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THE ROLE OF PUPIL CONSTRICITION
IN DISCOMFORT GLARE

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Vincent Mervin King, B.Sc., M.Sc.

* * * * *

The Ohio State University
1971

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INTRODUCTION

The purpose of this investigation was to determine the role played by pupil constriction in discomfort glare. Discomfort glare is the unpleasant sensation produced by light which can extend from a threshold to an intolerable level. Illuminating engineers try to avoid discomfort glare in designing a lighting installation for a given environment. This means that they must be concerned with threshold levels of discomfort and accordingly this investigation has placed major emphasis upon threshold levels of discomfort.

A light source or lighted environment which is said to be glaring can produce two major effects which must be differentiated. The first of these is disability glare which involves the veiling effect of stray light produced by the glare source on the visibility of objects in the field of view. While disability glare may be distracting and frustrating to the observer these effects must be carefully differentiated from feelings of discomfort. The sensation of discomfort that is produced by the glare source is the second effect and is called discomfort glare.
Discomfort glare is a mild form of what clinicians call photophobia. In one form of photophobia, the iris is made more sensitive to pain from contraction because of an iritis which is a diseased condition of the iris. Another kind of photophobia is one in which referred pain from the cornea is combined with nerve impulses from the iris to produce discomfort or photophobia. Cold air, a foreign body, a newly fitted contact lens, or a chemical irritant spread over the cornea can lower a subject's threshold for discomfort produced by the response of the iris to light. In this study of discomfort glare, subjects with normal corneas and irides have been used to avoid these additional complications.

Drugs have been used in this study to manipulate the pupillary response to light, but, for the most part, the variations in discomfort which have been studied have been produced by manipulating the temporal and spatial patterns of light applied to the retina.
HISTORICAL REVIEW

Research on Discomfort Glare

For more than fifty years people interested in designing a comfortable and efficient lighted environment have been involved in research to determine the attributes of different light sources that are related to efficient and comfortable seeing.\(^1\)\(^{-7}\) Some work in the area of comfort in a lighted environment was done by Nutting\(^1\) who determined the effective limits of seeing. He determined the threshold of visibility, the threshold of contrast, and the threshold of discomfort. Prior to Nutting's research, Cobb\(^2\) had concluded from his work that a light source that is said to be glaring produces two different effects in the observer. The first is the actual decrement of vision caused by the presence of a glaring light source in the peripheral field of view and the second is the one of visual discomfort. Cobb found that these two factors were independent.

Nowakowski\(^3\) discussed some of the probable causes of the discomfort produced by a glaring light source.
He stated that the discomfort was due primarily to the local irritation of the retina by the light from the glare source and to some extent by the repression of the oculomotor fixation reflex which is the reflex movement of the eye to image the bright stimulus in the peripheral field of view on the fovea. Nowakowski also confirmed Cobb's assertion that there are two aspects of glare, a disabling aspect and a discomforting aspect.

In the same year as Nowakowski's publication, Holladay published data showing how visual comfort is related to the size of the glare source and the luminance of the background of the glare source. The degree of comfort is also related to the brightness of the source.

In 1949, a paper by Luckiesh and Guth presented data that illustrates how the threshold of discomfort (called the borderline between comfort and discomfort or BCD by them) is dependent on certain variables. They investigated the influences that the background luminance, the size of the glare source, the position of the glare source in the field of view, the number of sources, and the configuration of the glare source have on the BCD.

After this work appeared other work on discomfort glare has followed dealing with large sources and with
the influence of the immediate surround. The work mentioned in this section has dealt with the practical aspects of a lighting installation, that is, what characteristics of the installation are involved with discomfort glare. The following sections will cover the research that has been done to determine the physiological cause or causes of discomfort in the observer.

Production of Pain

Whenever tissue is damaged or is present in an environment that is potentially damaging a sensation may be produced that is called pain. This sensation is generally regarded as arising from the stimulation of free nerve endings of thinly medullated or unmedullated nerve fibers. Axons of these fibers synapse with other cells whose fibers are in the lateral spinothalamic tract of the spinal cord. The fibers of the lateral spinothalamic tract terminate in the thalamus on cells which primarily project to the cortex in the region of the postcentral gyrus.

This brief outline of the general pathway subserving pain must be extended to include the sensory innervation of the eye. Anatomical, physiological and electrophysiological evidence indicate that the fifth cranial nerve, the trigeminal nerve, is involved in
the pathway for pain from the eye.

Claude Bernard ascertained the importance of the trigeminal nerve in the production of pain from the eye when he noted that the eye became insensitive to mechanical stimulation after the ophthalmic branch of the trigeminal nerve was cut.

Anatomical evidence provided by Beatie and Stilwell shows that all nonvisual innervation of the rabbit eye occurs through the long and short ciliary nerves which are branches of the ophthalmic division of the trigeminal nerve. Fibers which have free endings originate from the cornea, sclera, epithelium of the ciliary processes and the anterior iris, and blood vessels. Clark found similar distributions of endings of the fibers of the trigeminal nerve in the cat eye. These endings were present in the cornea, in the connective tissue between the ciliary muscle and the ciliary epithelium, and in the connective tissue of the iris.

Tower recorded from the cat's long ciliary nerve while stimulating various regions in and around the globe and determined that mechanical stimulation of the cornea, sclera, iris, and lens produced activity in the long ciliary nerve.

That the optic nerve does not contain pain fibers was shown by Magendie who determined that section of
the optic nerve in man was not painful. Also, Bernard discovered that mechanical stimulation of the optic nerve of the dog and rabbit did not appear to produce pain after the branches of the ophthalmic nerve were cut away from the optic nerve. More recently, Nakagawa electrically stimulated the optic nerve stump of a conscious unanesthetized man. At no location of his electrode did he obtain a report of pain from the patient except with an extremely high current which may have spread through the tissues to branches of the ophthalmic nerve. Also, he cut the stump of the nerve and again the patient only reported a visual effect, no painful sensation was apparently produced.

The fifth cranial nerve or the trigeminal nerve thus appears to be the pathway for impulses initiated by painful stimuli occurring in and around the eye.

Photophobia

With the trigeminal nerve acting as the pathway for nonvisual sensory modalities, the question arises as to what part of the eye is involved in the production of pain by stimulation with light. An answer to this question may come from the study of the causes of photophobia which is the extreme limit of discomfort glare and its symptoms include, besides the sensation of pain, lacrimation and blepharospasm.
Three general theories have evolved in regard to the causes of photophobia. One theory presumes that the impulses in the trigeminal nerve arise when endings of this nerve in the retina are stimulated. Another theory assumes that pain impulses arise from stimulation of the free nerve endings in the iris when the pupil reacts to light stimulation of the retina. Finally, a theory has been proposed that considers the role of the central nervous system in the production of pain due to light stimulation of the retina.

Wilbrand and Saenger assumed that some chemical product of the light reaction in the retina was capable of stimulating the trigeminal endings in the eye. This chemical product is normally carried away from the retina by some liquid flow before it has a chance to act on the trigeminal endings. Similarly, Beacher attributed photophobia to a fatigue of the retina or a slowed production of the compound in the rods and cones which is responsible for the conversion of light energy into electrical activity in the optic nerve. Beacher did not state the specific mechanisms involved, however.

Claude Bernard noted that diseases of either the cornea or the iris were accompanied by photophobia and he felt that these structures were important in pro-
ducing the pain associated with light stimulation of the retina.

The importance of the iris in the elicitation of pain has been discussed by several German authors. Nagel used homatropine, which dilates and immobilizes the pupils, in both of his eyes to eliminate the photophobia accompanying a migraine headache. He stated that photophobia resulted from the stimulation of the pain fibers in the iris when it reacted to light stimulation. Fuchs also abolished the pain due to excess light with homatropine in his eyes. He also had the opinion that the pain resulted from the stretching of the nerve fibers in the iris when it contracted to light or eserine.

Siegwart determined that vision was necessary for the production of pain. He could not elicit pain from a blind eye even by focusing sunlight directly on the eye. But, if the consensual pupil response existed, he did produce pain in the blind eye if the normal eye was stimulated with light. Siegwart believed that the retina could be excluded as a cause of the photophobia because he noted that retinal diseases can occur which do not produce any pain.

In two papers, Lebensohn has summarized the evidence concerning the causes of photophobia. He cited an experiment in which one eye of a rabbit was
anesthetized and then oil of mustard instilled into both eyes. In the unanesthetized eye the pupil constricted and the symptoms of photophobia occurred. However, the anesthetized eye remained normal. Lebensohn found that instillation of epinephrine, which is a vasoconstrictor, in eyes with conjunctivitis or iritis reduced or eliminated photophobia that accompanied the diseases. The eye of a patient on the side which had the superior cervical ganglion removed which produced vasodilatation in that eye had photophobia which was abolished with the use of epinephrine. In 1951, Lebensohn determined the luminance level required to produce photophobia in patients who had conjunctivitis, corneal or iridic disease, or head injuries or migraine headaches before and after treatment with epinephrine. The use of epinephrine elevated the photophobia pain threshold. This evidence led Lebensohn to the view that local vasodilatation of the iris vessels is a prerequisite factor for the production of photophobia. According to his view, the trigeminal pathway has to be intact to produce the vasodilatation and then the movement of the iris caused by the light reflex causes the pain. The pain can be abolished by epinephrine which does so by constricting the blood vessels.

Eckardt, McLean and Goodell reported that pulling
on the iris during surgery with incomplete anesthesia results in severe localized ocular pain. These authors also stated that breaking iris adhesions to the lens with mydriatics produces pain. They used the blink rate as a measure of ocular pain and found that when a foreign body was placed in the eye the blink rate was decreased with a corneal anesthetic but increased with a cycloplegic. They believed that photophobia was the result of the combination of activity in the trigeminal nerve caused by the movements of the iris or corneal irritation and the activity in the optic nerve caused by the light stimulus. Sensory innervation proceeding along the mesencephalic root of the trigeminal nerve excites the midbrain and lowers the threshold for incoming optic nerve impulses. The enhancement of the impulses due to the lowered threshold is interpreted as pain from the eye.

The view expressed by Eckardt, McLean and Goodell considers the possible role played by the central nervous system in the production of pain from the eye. Wolff has also expressed the opinion that the cerebral cortex and brain stem are involved. He arrived at this notion from the fact that patients with Argyll Robertson pupils experience an intensification of light and pain. These sensations result from the involvement of the
cerebral cortex and the brain stem with the disease lesions.

A similar notion is shared by Bessiere, et al, who consider photophobia as the result of a summation of input at the thalamic juncture of the trigeminal and visual pathways. Also, Kittel believes that photophobia results from the interaction of the trigeminal impulses and optic nerve impulses in the midbrain.

The results of the investigations cited in this section indicate that the integrity of the optic nerve and the trigeminal nerve is mandatory for the production of photophobia. With only a few exceptions, the iris has been implicated as the source of the pain impulses which arise either as a result of vasodilatation or as a consequence of its reaction to light stimulation of the retina. Suggestions have been made that the interaction at a higher level between the activity in the optic nerve and the trigeminal nerve is also a factor in the production of pain from the eye.

Discomfort in Normal Eyes

The investigations cited in the previous section have dealt with pathological cases of either diseased or traumatized eyes. A study of discomfort produced in normal, non-diseased eyes was undertaken by Bartley.
Presenting repetitive flashes of light to the subject, Bartley observed that the amount of discomfort felt by the subject increased as the number of flashes increased from one to six flashes per second. Beyond six flashes per second the feeling of discomfort decreased. Bartley proposed that the discomfort is produced by the breakdown of the reciprocal innervation between the sphincter and dilator muscles of the iris. This conclusion was based on the fact that the amount of constriction and dilation of the pupil to the flashes change at different rates as the frequency of the flashes change.

In his study of the brightness enhancement that occurs with slowly flickering lights, Halstead reported that his subject did not experience the discomfort produced by these lights while viewing them with dilated pupils. Halstead had used 0.5 percent scopolamine which produces mydriasis by paralyzing the sphincter muscle. This result indicates that pupillary changes are of significance in the production of discomfort produced by intermittent light stimuli.

The results of another experiment that implicate pupil movements in the production of discomfort were obtained by Sachs. He determined the time required for a large field of fixed luminance to become com-
fortable after a 15 minute period of dark adaptation. The time required for a suddenly exposed field with a luminance of $29.4 \times 10^4$ nits to become comfortable was an average of 20.0 seconds for seven subjects. After these same subjects received privine in both eyes which causes mydriasis by activation of the dilator muscle, the average time required for a field with a luminance of $363 \times 10^3$ nits to become comfortable was $18.4$ seconds. Therefore, the discomfort threshold at a given time was elevated by mydriasis of the pupils.

Fugate and Fry\textsuperscript{28} also found that the threshold of discomfort can be elevated by paralyzing the sphincter muscle of the iris with homatropine. The homatropine must be instilled in both eyes of the subject to have an effect, and its effect on the discomfort threshold lasts as long as the pupil is immobilized.

The results of the experiments done by Bartley, Halstead, Sachs, and Fugate and Fry were obtained with intermittent stimulation by a light source or with sudden exposure to a bright field. These conditions produce a pupillary light reflex consisting of rapid constrictions and dilatations of the pupil which could excite the endings of the trigeminal nerve in the iris causing discomfort.\textsuperscript{28} Exposure of the eye to a steady stimulus does not produce such rapid and extensive re-
responses of the pupil. Attempts have been made to find a relation between the pupil response and the discomfort produced by a steady stimulus.

Cadiergues noted in his review of the literature on both pupil data and discomfort glare data that there was a remarkable correlation between the variation in the BCD and in the diameter of the pupil. Citing Flaman's work on the pupil, Cadiergues stated that the pupil area fluctuates between 50 and 160 percent around the average pupil area. This magnitude of fluctuation was compared to the variation of the BCD data around the mean for different subjects in Luckiesh and Guth's work (40-180 percent) and the variation for one subject in Petherbridge and Hopkinson's data (45 - 170 percent). These similar values led Cadiergues to the assumption that discomfort glare is due to some activity involved in the pupil reflex.

However, Hopkinson could not discover any relation between the average diameter of the pupil and the degree of discomfort produced by a continuous glaring light stimulus. Although, he did remark that there were oscillations of the pupil which were most noticeable when the subject viewed a glare source that produced a high degree of discomfort. Hopkinson felt that these oscillations were the result of competition between the
sphincter and dilator muscles.

Experiments using normal subjects with healthy eyes have shown that the discomfort threshold to an intermittent stimulus is related to pupil movements and that this threshold can be manipulated by drugging the irides. Also, other experiments have shown that some aspect of the pupil response to a steady glare stimulus may be related to the discomfort produced by that stimulus.
APPARATUS

An optical system was constructed which provided (1) a means for stimulating the left eye and (2) a pupillometer for recording the consensual pupillary reflex of the right eye.

A schematic of the optical system is shown in Figure 1. Source $S_1$, a tungsten ribbon filament, acts as the source for the glare stimulus. Lenses $L_1$, $L_2$, $L_3$ and $L_4$ form an image of the tungsten filament in the plane of aperture $A_2$. An image of aperture $A_2$ is formed at $E_1$ by lenses $L_6$, $L_7$ and $L_8$. This is a circular image, 0.80 mm in diameter. Lenses $L_3$, $L_4$, $L_5$ and $L_6$ form an image of aperture $A_1$ in the plane of F.T., which also contains the primary focal point of the doublet $L_7$-$L_8$. Various apertures may be placed at $A_1$ providing for different glare stimulus diameters up to a maximum of $120^\circ$ subtended at the entrance pupil of the subject's eye. $T_1$ is a sectored disc which, when rotating, interrupts the glare stimulus beam and provides the following cycle - one second on, one second off, one second on, one second off, one second on, and five seconds off.
Another tungsten ribbon filament lamp, $S_2$, serves as the source for the continuous background. Lens $L_9$ forms an image of the filament in the plane of aperture $A_3$. An image of this aperture is formed at $E_1$ by mirrors $M_1$ and $M_2$, and lenses $L_{11}$, $L_7$ and $L_8$. This image was a rectangle, 0.7 mm by 0.3 mm in the early experiments, but the aperture was changed later to give a round image 0.8 mm in diameter in the plane of the pupil. Mirror $M_2$ is a first surface mirror, while $M_1$ is a piece of plate glass. The light from $S_2$ completely fills the aperture in the plane of F.T., which allows for a background of 120° diameter.

Each ribbon filament, $S_1$ and $S_2$, is powered by a DC voltage source whose output is varied by controlling the AC input with a variac. The luminous output of each lamp is adjustable by manipulation of the appropriate variac which alters the current through the filament. DC ammeters placed in the circuits of the lamps provide for visual monitoring of the current flow which can be related to the luminance of the imaged filament at $E_1$ by calibration curves.

The calibration of the luminances of the filament images of $S_1$ and $S_2$ at $E_1$ were made two different ways using a Macbeth Illuminometer. In one method the exit pupil of the Macbeth instrument was imaged at $E_1$ so that
it was coincident with the filament image. The proper converging lens was selected so that the image of the exit pupil of the Illuminometer was smaller than the filament image. With adjustment for the transmittance of the auxiliary lens, the Illuminometer readings were converted into luminance values. With the other method the illuminance produced by the filament image on a test plate at a given distance from the plane of \( E_1 \) was measured with the Illuminometer. The luminance of the image was then calculated from the illuminance values read with the Macbeth instrument. In order to do the calculation, the distance from the test plate to the image and the size of the image were measured. For example, if the distance from the test plate to the image is one foot and the illuminance on the plate is four footcandles, the filament image has an intensity of four candelas. Since the area of the image was 0.5 square millimeters, the image luminance for this example is 8,000 nits.

Since the diameter of the beam entering the subject's eye was known, the retinal illuminance was specified in trolands which, for the example used above, would be 4,000 trolands.

The source for the infrared pupillometer is \( S_3 \). Lenses \( L_{12} \) and \( L_{13} \) form an image of the ribbon filament
of $S_3$ in the plane of $T_2$. $T_2$ is an aluminum disc with 30 holes in its periphery. An image of these holes is formed at $E_2$, which is in the plane of the entrance pupil of the right eye, by mirrors $M_3$ and $M_4$, and by lenses $L_{15}$ and $L_{16}$. The diameter of these images is 0.5 mm. The image moves over a horizontal span of 2 cm in the plane of $E_2$ when the disc $T_2$ is rotated. The disc $T_2$ is rotated at approximately 30 rps, which means that the pupil of the subject's right eye is scanned approximately 900 times per second. To provide for alignment of the scanning system on subjects with different interpupillary distances, mirror $M_4$ is fixed relative to the subject, but the rest of the scanning system can be moved in a direction parallel to the line from $S_3$ to $M_3$. $P$ is a thick plate of glass which can be rotated about a horizontal axis which is perpendicular to the light path through the plate. Rotation of this plate moves the image of the scanning dot up or down at $E_2$ providing for vertical alignment of the dot on the center of the subject's pupil. An infrared filter, $F$, is put in the scanning beam so that this beam will not produce a constriction of the pupil.

An image of the subject's right eye is formed by a lens and mirror $M_4$ on a ground glass surface which
lies a short distance in front of the cathode of an infrared sensitive photomultiplier tube. The lens and photomultiplier are not shown in the figure. The optical axis of this portion of the recording system which passes through $E_2$ is depressed downward about $30^\circ$ below the line of sight. This helps to prevent light specularly reflected by the cornea from reaching the photomultiplier.

The output of the photomultiplier tube is analyzed by an electronic circuit that converts the signal generated by the scanning beam into a DC voltage which is proportional to the pupil diameter. The system is similar to the one described by King\textsuperscript{31} except that in the system used in the present study the scan line remains at a constant level. The DC voltage is monitored with an oscilloscope and also recorded by a chart recorder.

The pupillometer was calibrated by positioning artificial pupils of known diameter at $E_2$ and determining the deflection on the chart recorder for the different diameter pupils. The calibration indicated that the apparatus is capable of making absolute diameter measurements with an error of less than $\pm 0.1$ mm and relative diameter measurements with an error of less than $\pm 0.05$ mm.
The subject is positioned by means of a biting board and a forehead rest so that the center of the pupil of his left eye is at $E_1$. The scanning system is moved so that the center of the scan line coincides with the center of the pupil of his right eye. Fixation and accommodation are controlled by a small dot on a piece of plate glass or by cross hairs put in the plane of F.T.
PROCEDURE

Even though the subject in making his judgments selects a criterion of discomfort which cannot be rigidly controlled by the experimenter, he was given prior instruction so that he might be familiar with the concept of a discomfort threshold. That is, he was told that at the borderline between comfort and discomfort (BCD) the glare source should produce an environment that would be annoying to him, and he should feel that if the luminance of the source were decreased slightly it would no longer bother him. Furthermore, the subjects were asked to put their criteria in words. Their descriptions match those given by the subjects used in the work reported by Fugate and Fry.28

Also, Dr. Guth32 sent a written description of the instructions given to his subjects to the author's adviser and these instructions were given to the subjects used in later portions of this experiment.

Each subject was instructed to increase the luminance of the glare source, which he did by increasing the current through the filament of source $S_1$ by means
of a variac, until it produced a feeling of discomfort. He was allowed as many cycles of the glare stimulus as he needed to reach the threshold of discomfort. When the subject stated that the glare source was uncomfortable, the changes in the pupil diameter were recorded for two complete cycles of the momentary glare. Figure 2 is an example of such a recording.

Usually, five determinations of the BCD were made for each condition. In addition, the experiments were repeated at a later date, so that for each experimental condition the subject made at least ten settings of the glare luminance at the BCD. Changes were made in these procedures for some parts of the experiment. These changes will be described in the pertinent sections.

The five subjects participating in this investigation were students in the College of Optometry who were between 20 and 25 years of age. Their refractive errors ranged from one diopter of hyperopia to two diopters of myopia with less than one-half diopter of astigmatism present in some cases. No attempt was made to correct the refractive errors during the experiment.
RESULTS

Experiments were conducted to determine the effects of glare size and background luminance on the BCD and on the consensual pupil response to an intermittent glare source with a luminance at the BCD level. Another parameter that was investigated was the retinal location of the glare source. Also, results were obtained using various drugs to immobilize the pupil. Finally, the effects of steady stimulation with a glare source were determined on the BCD and on the consensual pupil response.

Effect of Glare Size

Data for one subject are shown in Figures 3, 4, and 5 which demonstrate the effect of the size of the glare source on the BCD and on the pupil diameter with three different background luminances. The lines marked $\Delta$ in the graphs refer to the change in diameter of the pupil which occurs for the initial flash in a cycle of the glare stimulus presentation. Figure 6 shows how this value is measured. Each point is an average response to 20 of these flashes. The line designated with IPD refers to the initial pupil diameter which is the
diameter of the pupil just prior to the rapid constriction in response to the initial flash. Each of these points also is the average for 20 responses. Each of the points on the line denoted by BCD is the average of 10 settings by the subject of the glare source at the borderline between comfort and discomfort. In terms of angle subtended at the subject's entrance pupil, the diameters of the glare sources were 10°, 20°, 40°, 60°, 80°, and 120°.

Some idea of the variability of the data can be gathered from Figure 3. The limits marked by the brackets on the graph represent the range of the BCD data over all sessions of the stated condition for the subject D. L. These ranges are somewhat misleading since the intrasession variability is much less. For example, the range of the BCD data for one day is about 0.20 log unit. Correspondingly, the variability of the pupil data for a given session is also much less than that given in the graph. However, the graph does show the rather large change in sensitivity of the subject from day to day and it also shows how this change is reflected in the pupil data, particularly in the initial pupil diameter, the ranges of which are marked with arrows. Also the range limits for the BCD data illustrate another aspect of the data which
is the reduction in variability with an increase in glare size. The subjects in this experiment commented that it was easier for them to determine a discomfort threshold with the larger glare sources.

Figures 7-9 show some of the intersubject variability of the data. The BCD data show a spread of approximately one log unit for a given glare size for the three subjects whose data are included in the figures. Plotted in Figure 10 are the average data of the three subjects. It can be seen from the graph that the BCD changes about one log unit over the range of glare sizes used.

Figure 11 presents the average pupil data for the three subjects for three background luminance levels. It can be seen from this figure that the pupillary constriction for a given background luminance is relatively constant for all glare sizes at the BCD.

**Effect of Background Luminance**

The effects of the background luminance on the borderline between comfort and discomfort for three subjects and four glare sizes are demonstrated in Figure 12. The BCD data for four glare sizes of 10°, 20°, 40°, and 80° diameters have been averaged over the three subjects used in this portion of the experiment.

Figure 13 presents the averaged pupil data for the three subjects with the same conditions that were present
when the subjective BCD data were obtained. It is obvious from this figure that the change in pupil diameter is not constant for different luminance levels of the background, but the $\Delta$ values decrease with increasing luminance. No attempt was made to demarcate the various curves for the change in pupil diameter because of the close proximity of all curves. There is almost a linear relation between the $\Delta$ values and the logarithm of the background luminance.

To further clarify the pupillary activity at the borderline between comfort and discomfort, the $\Delta$ values were plotted against the corresponding initial pupil diameters for three subjects. These plots are given in Figures 14, 15 and 16. It is apparent that the amount of constriction, $\Delta$, is linearly related to the initial pupil diameter at the BCD. Even though the slopes of the regression lines drawn through the data points are different for the three subjects, their pupil data can be made to conform if the change in diameter is expressed as a percentage of the initial pupil diameter and then this percentage is plotted against the initial pupil diameter. Figure 17 is such a plot, but, for clarity, the averaged pupil data for each condition for each subject were used, not each data point as in the three preceding figures. The relation-
ship between the percentage change of pupil diameter and the initial pupil diameter appears to be curvilinear over the range of the data that were collected.

**Effect of Peripheral Glare**

Apertures were designed to be placed in the apparatus in the plane of $A_1$ such that they would produce an annular pattern in the plane of F.T. (Figure 1). Figure 18 shows the pattern as seen by the subject. The outside of the ring subtended $80^\circ$ at the entrance pupil. The inside diameter was selected so that the area of the annulus equaled the area of a central glare source used in the experiments which have been described. For example, the $10^\circ$ glare source subtends a solid angle of $0.025$ steradians and an annulus was made such that its lighted area corresponded to the same solid angle (that is, the solid angle of the $80^\circ$ diameter circle, $1.47$ steradians, less the solid angle subtended by the opaque center, $1.445$ steradians). Annular targets were made in areas equal to $10^\circ$, $20^\circ$, $40^\circ$ and $60^\circ$ diameter sources.

The results for one subject are shown in Figure 19. From the figure, it can be seen that the BCD level for a peripheral source (designated by BCD-P in the figure) is higher than that of a central source (designated by BCD-C). Also, it is evident that the pupil responses
to the two conditions are different. That is, less change occurs for the peripheral glare source than for the central glare source.

**Effect of Immobilization of the Iris**

If it is assumed that the discomfort produced by a glare source is caused, in part, by changes occurring in the iris tissue, then if these changes are prohibited the threshold of discomfort should be altered. Two drops of 0.5% tropicamide solution, which paralyzes the sphincter muscle, were used in both eyes in an attempt to block a light response of the pupil. The BCD was determined with a 1.75 log td background and the 120° intermittent glare source immediately before instillation of the drug and then at various times afterwards. Figure 20 shows the change in the BCD during the recovery from paralysis of the irides. This plot also shows the changes which occur in the initial diameter of the pupil as well as the change in diameter following the first flash of the train of three flashes of the glare source.

There does seem to be a change occurring in the BCD, but this change may be overshadowed by the variability of the BCD data. To obtain somewhat independent measures of the BCD, independent because the subject cannot use color or brightness of the source to influence his criterion of the discomfort threshold, three glare
sizes were selected (10°, 40°, and 120° in diameter) for the next subject who received the same dosage of tropicamide. Figure 21 shows the subjective data for the three glare sizes at different times following instillation of the drug and it also shows the change in pupil diameter with the 10° glare source. Each curve indicates that there is some change in the BCD that corresponds to the change in pupil response. To overcome some of the variability, the BCD data obtained with the 10° and 40° glare sources were shifted downward so that the first point of all three data curves coincided. An average of all three of these curves was determined and this average is shown in Figure 22. Also shown in the figure are averaged pupil data for both the initial pupil diameter and the change in pupil diameter obtained with the three different glare sources. It is evident that there is a change in the BCD during the action of the drug.

It might be argued that the changes in BCD that are apparent in Figures 20, 21 and 22 are due to variations in the discomfort threshold that occur throughout the day. To determine if the discomfort threshold changes during the day, BCD data and pupil data were obtained on one subject every hour during one day. The results of this experiment are shown in Figure 23.
There are no apparent continuous changes of the BCD during a day, particularly during the first part of the day where the major portion of the change has occurred in the drug experiments.

Tropicamide paralyzes the sphincter muscle by blocking the action of acetylcholine on the muscle. To see if activation of the dilator muscle by administration of a sympathomimetic drug produces a different effect on the BCD, three drops of 10% phenylephrine hydrochloride were used to dilate the pupils by causing the dilator muscle to contract. Figures 24 and 25 show the results for subjects D. L. and G. P. There is a gradual increase in the BCD which is unlike the effect produced by tropicamide with its rapid initial alteration of the BCD. It is obvious that the pupil response to light has not been abolished in either case. It has even been accentuated for subject D. L. for the first several hours after drug instillation and accentuated for subject G. P. after several hours.

Immobilization of the pupil can also be done by constricting it maximally. This can be done by using a parasympathomimetic drug such as pilocarpine which acts directly on the sphincter muscle causing it to contract. Figure 26 shows the pupil data and the subjective data for subject D. L. before and after administration of
three drops of 2% pilocarpine solution in both eyes. The averaged BCD data for 20°, 40°, and 120° glare stimuli has been elevated one hour after instillation of the drug, but these data rapidly drop back to the pre-drug level. A small amount of constriction occurred in response to the glare stimulus even at the first determination one hour after instillation of the pilocarpine so the pupil has not been immobilized by the drug.

Effect of Steady Presentation of Glare

In this section of the experiment a comparison was made between intermittent and continuous glare for a constant background luminance of 1.75 log td.

In the case of continuous presentation, after the subject has set the glare luminance at his BCD, the glare source may become comfortable again since adaptation occurs. To be consistent in the determination of the BCD a time limit of two minutes was established. Every fifteen seconds from the time the subject notified the experimenter that the glare source was at the BCD, the experimenter asked the subject if it was still uncomfortable. When the luminance reached a level at which the subject did not have to increase it during a two-minute period, this luminance value was recorded as the BCD, and then while the glare source remained
constant at this level, the pupillometer was turned on for 30 seconds to record the pupil diameter.

Figure 27 shows the average of the results of three subjects. Two of the subjects were unable to obtain discomfort with the two smallest glare sizes (10° and 20° in diameter) for the continuous glare condition because their thresholds exceeded the light output limits of the apparatus. From the graph, it is apparent that the BCD values for continuous glare (BCD-C) approximately parallel those of the intermittent glare (BCD-I), but are elevated about one log unit. It can also be observed that the pupil diameters obtained for the four glare sizes for steady stimulation are approximately constant.

For the pupil data, the plotted points do not represent maximal constriction, but are an average of the pupil diameter over a 10 second time period. Figure 28 is an example of the recording taken following the two minute adaptation to the glare. Because the pupil shows a fluctuation in its size for the continuous glare source, several points were read from the recordings to determine a representative diameter. At an arbitrary point in time after the beginning of the recording, ten consecutive one second intervals were marked off on the record, and the
pupil size read at these time intervals. In the case of the figure shown, the pupil sizes were read at the vertical time lines.

It was obvious from the records that the data show large rhythmic oscillations having a wavelength of about 10 seconds. There also appeared to be faster oscillations having wavelengths of 3 seconds and 1 second. In order to segregate the various components, the data were digitized. Values corresponding to the pupil diameter were read from the recordings at 0.2 second interval over a recording length of 30 seconds, and the digitized data were fed into an IBM 360/75 Computer. The computer was programmed to analyze the data into four components as shown in Figure 29. Curve A represents the raw data; C is the slow drift corresponding to the 10 second wavelength activity apparent in the raw data; E and G are the slow and fast components which correspond to the one second and three second activity; curve H is the residual noise, the oscillations left over after the three component curves, C, E and G, are subtracted from the raw data, curve A. The summation of the four curves, C, E, G and H, then produces the raw data, curve A. The scale of the ordinate on the left in the figure is linearly related to the pupil diameter which is given by the
scale on the right ordinate. The scale on the right applies only to the raw data and not to the other curves. The other curves are displaced arbitrary amounts to facilitate inspection and comparison of the separate curves.

Recordings of the pupil diameter were made while the subject was exposed to glare luminances that he had set at the BCD. The raw data were computer analyzed into separate components as previously described. The slowest oscillation probably represents a drift of the pupil and accordingly it was not considered in the following analysis. The residual curves, E and G, which contain the 1 to 3 second activity, were summed and an average diameter determined from this. Also, the deviations from this average were obtained. The average diameter and the average deviations, called hippus size, are tabulated in Table 1 for one subject. Also presented in this table are the retinal illuminances for various glare sizes which were at the BCD. Also given is the hippus ratio, which represents the amount of hippus relative to the average pupil diameter. It should be noted that this ratio does not remain constant.
Open Loop versus Closed Loop Conditions

Under normal viewing conditions, the pupil has control over the retinal illuminance. In systems engineering terminology, the pupillary reflex is an example of a negative feedback system; as the retinal illuminance increases, the pupil decreases in size which then decreases the retinal illuminance. In the experiments reported up to this point, the pupil has had no control over the retinal illuminance because the entering beam was always smaller than the pupil. This means the feedback loop was open. With ordinary viewing conditions, this loop is closed. This could imply that the pupil may drive itself which will increase the magnitude of the oscillations that were apparent in the recordings obtained under open loop conditions with steady stimulation. To determine if the pupil undergoes increased or different oscillation with the closed loop system an experiment was done using the natural pupil, the subject's pupil, as the aperture stop of the apparatus - subject combination.

In order to do this, the original apparatus had to be modified. A schematic of the apparatus is shown in Figure 30. The source is a coiled tungsten filament at A. The condenser lenses B and C form an image of the coil at D, but this image was broken up by placing
a ground glass plate between the two lenses B and C. The field stop E lies at the primary focal point of the lenses F and G. This field stop subtended an angle of 29° at the subject's entrance pupil. An image of an aperture at D is formed in the plane of the subject's entrance pupil and the diameter of this image was 11.3 mm. With the subject properly centered, the subject's pupil then limited the amount of light entering the eye.

Various luminance levels were presented to the subject by varying the current through the tungsten filament. A given luminance of the 29° source was presented to the subject for one minute, then a two minute recording made. During this period of time, the subject was asked whether the source was comfortable or close to his BCD. After the two minute recording, the luminance was increased to the next level, a one minute time period allowed to elapse, and another two minute recording made with another subjective estimate of the glare source. This procedure was followed for the different luminance levels presented in Table 2. The pupil data, analyzed as before, are also presented in this table. It was found that a luminance of 3,430 nits was close to or at the BCD for each subject.

The hippus ratio is approximately constant for all conditions and it is also not much different from
that determined in the experiment with an open loop condition. The component curves under the two different conditions of open loop and closed loop are presented in Figure 31. There is apparently no difference in the components for these two conditions.

Natural Viewing Conditions

It would be desirable to compare the subjective data of this experiment to the data of experiments carried out by other investigators. However, the subjective data obtained in this study and reported to this point were obtained with monocular viewing through a tiny artificial pupil. Other investigators who have worked on discomfort glare have allowed the use of both eyes with natural pupils. In order to make a comparison, an apparatus was designed which would allow the use of both eyes under natural viewing conditions. Figure 32 is a schematic drawing of this apparatus.

The subject inserts his head through an 8x10 inch rectangular hole in one side of a 20 inch cubical box, the corners of which are filled in with plywood triangles so that the box is a tetradecahedron composed of 6 squares and 8 equilateral triangles and approximates an integrating sphere. The inside of the box is painted flat white. A chin rest and a forehead rest hold the
subject's head in place so that his eyes are about two inches inside the box. In the opposite wall of the box there is a circular hole 10 inches in diameter. Ten inches from this aperture there is a 5 inch diameter lens held in a flat white screen so that the subject sees this lens centered in the hole in the end of the box. The lens \( L_1 \) produces images of the filaments of lamps \( S_R \) and \( S_L \) in the plane of the subject's eyes so that the subject sees the lens as being uniformly filled with light. A ground glass plate is placed before the lamps to break up the filament images in the plane of the subject's eyes. The five inch diameter lens subtends an angle of \( 10^\circ \) at the plane of the subject's entrance pupil. \( T_R \) and \( T_L \) are shutters which are operated by rotary solenoids and these shutters have the same temporal sequence as that of the other experiment, that is, one second on, one second off, and so on.

Lamps \( S_B \) and \( S_B' \) illuminate the interior of the box. These lamps are shielded from the subject by aluminum plates. Since the lamps are very close to the subject, ducts attached to exhaust fans are used to remove the warm air from around the lamps. Photometry of three places in the box, the wall opposite the subject, a center of a corner, and the center of a side wall, indicates that there are no bright regions and
the luminance of these three regions are well within 10 percent of each other. The luminance of the box is controlled by changing the voltage across the lamps.

Four lamps mounted on the outside of the box are used to illuminate the white screen holding the lens \( L_1 \). The luminance of the screen is also adjusted by means of a variac which controls the voltage across the four lamps.

A photoflood lamp is directed toward the shutters \( T_R \) and \( T_L \) so that the light reflected from the white shutters is focused in the plane of the subject's eyes. The subject adjusts the luminance of the reflected light until the brightness of the lens is the same as its immediate background. This arrangement prevents the lens from going dark when the shutters block off the light from the glare source.

The glare source luminance can be adjusted by the subject. This also is done by changing the voltage across the glare lamps. The same procedure in determining the BCD was used with this experimental arrangement as in the prior one.

Experiments were completed which involved the use of a glare source 10° in diameter with background luminances of 1, 3, 10, 30, and 100 fL. Following an adaptation period of 10 minutes in the darkened room
and 3 minutes to the lowest luminance inside the box, the experimenter started the glare cycle and the subject increased the luminance of the glare source until it reached his BCD. Thirty seconds were allowed to elapse between the end of one determination and the beginning of another. After five determinations of the BCD were made, the subject was allowed a short rest period away from the box (room otherwise dark) while the background luminance was increased to the next level. The subject again was allowed three minutes to adapt to this new level before the BCD determinations were resumed. This procedure was carried out until determinations were completed with all five background luminances.

Figure 33 shows the data obtained with two subjects. The dashed line represents the BCD values obtained by Luckiesh and Guth\(^5\) for a glare source whose size was comparable to that used in this experiment. The temporal pattern of the stimulus was the same in this experiment as that used by Luckiesh and Guth.

Since D. L. and S. S. had made BCD settings for a 10° glare source on the system connected with the pupillometer at different background luminance levels, this data can be compared to that obtained with the box apparatus. To do this, the BCD settings have to be converted into comparable values.
Since the subject's pupil diameter is known in the case of the data obtained with the pupillometer, an equivalent field luminance can be calculated which will produce the same retinal illuminance through his natural pupil as that produced through the exit pupil of the stimulating system. To do this, the ratio of the area of the exit pupil of the system to the effective area of the natural pupil just prior to the onset of the glare source was calculated and then multiplied by the luminance values of the background and glare source. Table 3 presents the pertinent values and demonstrates the procedure for this calculation. The Stiles-Crawford correction factor is obtained from an equation presented by Schober and Fry\textsuperscript{33} which is:

\[
\text{Correction factor} = 1 - 0.0425x^2 + 0.000666x^4
\]

where \(x\) is the radius of the pupil. The BCD values with their associated background luminances which are given in the last two columns of the table are plotted as open circles in Figure 33.

Since the data from the pupillometer were obtained under monocular conditions and the data from the box apparatus were obtained under binocular conditions, some account for this difference must be made. Bourassa and Wirtschafter\textsuperscript{34} have shown that the luminance of a glare source has to be increased about 1.5 times to remain
at the discomfort threshold when one eye is closed. Therefore, the data derived from the pupillometer would have to be displaced downward an amount corresponding to the binocular facilitation of the discomfort threshold. This would bring the two sets of data closer together for subject D. L., but would separate them for subject S. S. It should be mentioned that Bourassa and Wirtschafter employed steady stimulus conditions and that the difference between monocular and binocular thresholds for their normal subjects ranged from 1.2 times up to 4 times. Therefore, no definite displacement can be made of the points shown in Figure 33, but the direction of the displacement can be ascertained as being downward.
DISCUSSION

The Borderline Between Comfort and Discomfort

Since the purpose of this research is to determine the role that pupillary movements play in bringing about the sensation of discomfort, it would be advantageous to compare the subjective results pertaining to the discomfort threshold with the results obtained by other investigators. This comparison will help to establish the criteria that the subjects used in this experiment.

The subjective data show dependence of the BCD on the size of the glare source and the background luminance. These relations are graphically presented in Figure 10 which shows that an increase of glare size brings about a decrease of the BCD level. Over the range of glare sizes used in this experiment, the BCD data change by about one log unit. A comparison can be made over a short range of glare sizes between the data presented in this study and the data given by Luckiesh and Guth\textsuperscript{5} who also used intermittent stimuli with the same temporal pattern as that used in this study. Their BCD data show a decrease of about 0.5
log unit when the glare size is increased from 10° to 20° of visual angle. The data in Figure 10 indicate a decrease of 0.4 log units with the same increase of glare size.

The BCD is dependent on the background luminance, also. This has been determined by Nutting and Luckiesh and Guth. Increasing the background luminance produces an elevation of the BCD level as depicted in Figure 12. An increase of the background luminance of 1.0 log unit is accompanied by an increase of the BCD of 0.24 log units. Luckiesh and Guth found a change of the BCD of 0.45 log units associated with a 1.0 log unit change of the background. However, Nutting found an increase of 0.32 log units of the BCD with a 1.0 log unit increase of the background.

The differences between the data shown in Figures 10 and 12 and the data given by Luckiesh and Guth and by Nutting can be considered to arise from the large differences in experimental conditions. Each of the previous studies employed natural viewing conditions with both eyes. The Luckiesh-Guth data were obtained with intermittent exposure to the glare source. Nutting's data were obtained with a sudden exposure to the glare source, not with a series of exposures.

Another evaluation of the criteria selected by the subjects of the present study can be made from the data
shown in Figure 3 which were obtained under conditions very close to those used by Luckiesh and Guth. The data for one subject almost correspond to the average data obtained by Luckiesh and Guth while the other subject's data are considerably higher. Both subjects had been given the instructions taken from Guth's protocol prior to this phase of the experimentation.

Even though the data of the experiments done with the pupillometer apparatus are in qualitative agreement with the data of other investigators, there are absolute differences between the subjective data of the present study and the data obtained by other workers, but these differences can probably be attributed to the different experimental conditions and they are not the result of the use of a different criterion of discomfort. Furthermore, the data obtained in the experiment with natural viewing conditions correspond to data obtained by Luckiesh and Guth under similar conditions, the differences in this case being due to subject differences. Therefore, the subjects whose data appear in this work were measuring the borderline between comfort and discomfort.

Several remarks should be made concerning the variability of the ECD data as shown in Figure 3. For the smaller sources, the variability of the data is about
one log unit which can be compared with Hopkinson's data. Hopkinson varied the luminance of the background of the glare source to determine a discomfort threshold and found that the variability of the background luminance was about one log unit. If his experiment had involved the adjustment of the glare luminance to obtain a discomfort threshold, the variability would probably be approximately half of a log unit. The data vary over this magnitude over a period of several days as Hopkinson's results show, but do not seem to change this much over a period of one day as the results of the present study show. It is possible that the variability of the data is due to slight changes in the criterion from day to day. It is also possible that different emotional states or fatigue may cause a change in the threshold of discomfort. It is also possible that other sources of discomfort such as slight headaches or a slight illness may influence the discomfort threshold. Whatever may be the cause of the variability, the effect of the scatter of the data can be minimized by averaging the data over two runs which are taken on different days. This is what was done in this experiment. For those experiments which were done on the same day, such as the drug experiments, changes occurred in the BCD data which took place within a day's time that do not happen under
normal conditions.

The subjects also reported that it was easier to determine a threshold of discomfort with the larger glare sources, and this is reflected in the decreased variability of the BCD for these sources. The variability for the larger sources, above $40^\circ$ in diameter, is less than 0.5 log unit. Perhaps it was easier for the subjects to determine the threshold for the larger sources because small eye movements will not have as pronounced an effect in causing the image of the source to fall on previously unexposed retina. Secondly, the border between the glare source and its background is easier to see with the smaller sources and perhaps the contrast between the two has some influence on the criterion for discomfort. Finally, the subjects set the retinal illuminances of the smaller sources quite high so that a significant change in the state of adaptation of the retina stimulated by the light from the glare source would occur. This means that if the subject found the threshold quickly, that is, took only several cycles of the glare to locate it, less adaptation would have occurred and the threshold would be lower. However, if he had difficulty and it took more than a few cycles to locate the threshold, the retinal region stimulated by the glare source would reach a higher level of light.
adaptation causing the threshold to be higher.

**Intermittent Stimulation by a Glare Source**

If a sensation of discomfort is produced when the pupil is brought down to a certain size, then the final pupil size would be constant at all levels of background luminance at the borderline between comfort and discomfort. That this is not true can be determined from a study of Figure 13. If the Δ values are subtracted from the IPD values, the final pupil diameter is the result. This value decreases as the retinal illuminance of the background increases. Therefore, the BCD is not related to a certain critical minimum diameter of the pupil.

Also, the amount of constriction is not important in this regard either. If discomfort were produced after the pupil had constricted a given amount, then the Δ values would be constant for all background luminance levels. Far from being constant, there is a progressive decrease of the Δ values with an increase of the background luminance as shown in Figure 13.

One of the major results of the experiments involving manipulation of the discomfort threshold by changing the size of the glare source and changing the luminance of the background is the remarkably constant relation between the initial pupil diameter
and the change in pupil diameter caused by the first flash in the train of three flashes. This relation is depicted in Figures 14, 15 and 16, and the curvilinear relation which exists between the percentage change of diameter and the initial pupil diameter is shown in Figure 17. The change in pupil diameter for the three subjects whose data are shown in Figures 14-16 indicate that as the pupil gets smaller because of an increase in background luminance, the amount of constriction at the BCD decreases. For all subjects, the amount of constriction is probably nil when the pupil diameter reaches 2 mm which is the approximate physiologic limit of constriction for the three subjects. The data for the subjects coincide if it is plotted as in Figure 17 which indicates that a 40% change in pupil diameter is associated with discomfort if the pupil has an initial diameter greater than 5 mm. Below this diameter, the percentage change decreases probably reaching zero when the initial pupil diameter reaches 2 mm.

A comparison can be made between the data presented in this study and the data found by Fugate and Fry using the same stimulus pattern but with glare sizes of 1.5 and 51 degree diameters. Fugate and Fry found that the pupil constricted about 1.5 mm to the first flash when at the BCD and on a background of 450 td.
With the present experiment however, a glare source with a luminance level at the BCD seen on a 450 td background would produce a 1 mm constriction of the pupil as obtained from Figure 13. A possible reason for the discrepancy in change in pupil diameter is that the initial pupil diameter in the present experiment was smaller than that for Fugate and Fry's experiment. This is probably the result of the difference in the sizes of the backgrounds used in the two experiments. The background used in this experiment was 120° while the background in Fugate and Fry's experiment was 51°. Fugate has shown that a larger field with the same luminance will produce more constriction of the pupil when momentarily presented. Also, data were obtained on one subject relating to the size of the pupil following three minutes adaptation to a 2.71 log td circular stimulus that took on different diameters. Figure 34 illustrates how the pupil diameter is related to the size of the continuous circular stimulus. A stimulus size of 51° and at a level of 2.71 log td would produce a pupil diameter of about 4.7 mm. This would then correspond to the initial pupil diameter if the subject had been exposed to a stimulus like that used in Fugate and Fry's experiment. Examining Figure 15, a 4.7 mm initial pupil diameter, for D. L., would have meant
that the pupil would constrict about 1.8 mm to a flash which was at the BCD, which is somewhat closer to Fugate and Fry's value.

Fugate and Fry also found that the change in diameter of the pupil at the BCD depended on the size of the glare source; more constriction of the pupil occurred to the presentation of a larger source. The results of the present study do not show this dependency, but the change in pupil diameter at the BCD appears to be relatively independent of the size of the glare source as the data in Figure 11 show. Not knowing what the initial diameter of the pupil would be for the smaller size glare source that they used (1.5°), an estimate of the amount of constriction cannot be made.

The discrepancy pointed out above could also be the result of some differential effect caused by stimulation of different retinal areas. The 1.5° stimulus would largely be confined to the foveal region of the retina and some other mechanism responsible for discomfort may come into play in this case. This experiment has shown a similar regional effect. If it is the amount of constriction of the iris relative to the initial diameter of the pupil that is important, then the BCD should be obtained when the requisite constriction is produced regardless of the retinal area stimulated.
This seems to be the case when the glare stimuli are presented centrally. However, if the glare is presented as a bright annulus around the central region of the retina, there is less constriction of the pupil at the BCD for a given initial pupil diameter as can be interpreted from Figure 19. It is possible that in addition to, or as an alternative to, the inclusion of another mechanism in this case, the subject's criterion could have changed. The subjects participating in this part of the experiment commented that the BCD was more difficult to determine and that the glare source produced a different feeling than in the previous experiments. Another possibility is that the fixation reflex also comes into play and the subjects have to work at repressing this reflex as Cobb and Nowakowski have suggested.

The results of the experiments in which the background luminance and the size of a centrally presented glare source were manipulated indicate that at the BCD there is a linear relation between the initial pupil diameter and the amount of constriction to the first flash in a train of flashes. This relationship does not hold, however, if the glare source is presented peripherally.
Analysis of the Forces Occurring in the Iris

In order to satisfactorily explain any relation that may exist between pupillary movements and discomfort produced by a glare source, some analysis must be made of the forces involved in constricting and dilating the pupil. The sphincter pupillae muscle, a band of smooth muscle fibers about 1 mm wide which encircles the pupil, causes a constriction of the pupil when the muscle fibers contract. The dilator pupillae muscle, which is a radial layer of tissue close to the posterior surface of the iris, is apparently responsible for dilation of the pupil. The dilator muscle may be aided in its task by the elastic tension exerted by the iris tissues.

Under normal conditions, the iris is influenced by the three mechanisms outlined above: the variable forces produced by contraction of the sphincter and dilator muscles and the spring-like force of the iris tissues. These forces are closely balanced as Mapstone has shown. If the two muscles are paralyzed by drugs such as thymoxamine, which paralyzes the dilator muscle, and cyclopentolate, which paralyzes the sphincter muscle, the pupil has a diameter of 6 mm. This indicates that with a pupil diameter smaller than this, the sphincter muscle has to supply a force greater
than the elastic force of the iris tissues. For pupil diameters larger than 6 mm, the dilator muscle has to supply the excess force. Conceivably, a diameter of 6 mm can be obtained by the complete relaxation of both muscles under normal physiological conditions.

With the pupil being capable of constricting to 1.5 mm and dilating to 10 mm in diameter, it is quite apparent that large changes must occur in the disposition of iris tissues, particularly the nerves and blood vessels. van Alphen has found that miosis causes a straightening of the nerves and blood vessels. With extreme miosis the nerves are straight, thin and radial in course. The nerves are thicker and follow a highly tortuous course with extreme mydriasis. With this displacement of the nerves, it is highly possible that discomfort sensations can arise when the iris oscillates as it does to a glare stimulus.

That the forces involved in moving the pupillary edge of the iris are not linearly related to the pupil diameter has been shown by Loewenfeld and Newsome. If these forces were linearly related to the pupil diameter, the pupil would constrict or dilate with a constant velocity. That is, the pupil diameter would decrease or increase with a steady, unbroken motion. Loewenfeld and Newsome found that the pupil does not
constrict in this fashion, but there is a change in rate of constriction or dilation at a definite limit of the pupil diameter. The limits of the linear change in pupil diameter for the six subjects used in their study were 5.7 mm and 3.2 mm. Between these limits the pupil changes in size at a constant rate. Beyond these limits the pupil moves at a slower rate, as though some mechanical force has been applied.

In a subsequent paper, Newsome and Loewenfeld describe the changes of the anterior iris tissues during various stages of constriction and dilation in the same six subjects of the previous experiment. For their measurements on the photographs taken of the eyes of the subjects, they divided the iris into two portions, a ciliary portion which extends from the limbus to the collarette and a pupillary portion between the collarette and the inner edge of the iris. Their results show that the size of the ciliary ring is linearly related to the size of the pupil. The pupillary ring is not linearly related to the diameter of the pupil, however. Between the limits found in the preceding experiment (5.7 mm and 3.2 mm) the inner pupillary ring does not change in size. Beyond these limits, it decreases in width. These changes in shape occur regardless of how the pupil was changed in size.
They occur whether the pupil was constricted by sympa-thetic paralysis or parasympathetic activation for constriction and vice versa for dilation.

Loewenfeld and Newsome explain the difference of behavior of the pupillary portion of the iris with different pupil diameters as due to a limit of contractility of the two muscles, the sphincter in miosis and the dilator in mydriasis, or as a result of an increasing difficulty in compression of the iris stroma, or as a result of a limit of the distensibility of the muscles, the sphincter in mydriasis and the dilator in miosis. Whichever it may be, there is a mechanical limit to the smooth changes of the iris tissue. This limit affects both large and small pupil diameters and represents a change in the forces required at these limits.

Another of their findings that is of importance for this study, is the fact that the blood vessels did not appear to move with the pupillary edge, but seemed to lag behind. This indicates that the blood vessels are passively carried along by the iris stroma in which they are embedded. This would seem to imply that the nerves are carried along also, but at a somewhat slower rate than the pupillary edge of the iris. This could act as the stimulus to cause the nerve fibers to fire.
Finally, the forces involved in the dilation of the pupil seem to depend on whether the pupil has reached its initial diameter from a state of mydriasis or miosis. Abrams, using a magnetic hook over the lower iris edge of the rabbit eye, has shown that the force required to pull the iris down a given amount is not directly related to the diameter of the pupil. More force is required when the pupil reaches its diameter from mydriasis than from miosis to bring about a given dilation of the pupil.

These results imply a changing level of forces depending on the diameter of the pupil and whether it is in the process of constricting or dilating. These would also seem to indicate that the movement of the iris tissues such as the stroma, blood vessels, and nerves play a significant role in establishing the forces required for a given movement or the speed of movement for a given force. The result of these changes could be increased tension on the free nerve endings which would result in discomfort until adaptation of the tissue takes place. These results also indicate that there is not a suddenly applied mechanical limit to the movements of the iris which would appear to correspond to the finding of the present study that there is not a critical minimum diameter of the pupil.
which is associated with discomfort. The gradual change of tension and the lagging of the stroma behind the pupillary edge, although the amount is quantitatively unknown at present, correspond to the finding of this experiment that a certain amount of constriction is not associated with discomfort, but a variable amount dependent on the diameter of the pupil just prior to constriction.

**Immobilization of the Pupil**

If the changes in the disposition of the tissues in the iris are responsible for the uncomfortable sensations produced by light, then stopping the movements of the pupil should also abolish the discomfort or change the BCD level. Fugate and Fry found with binocular instillation of homatropine an elevation of the BCD above the level that could be measured with their apparatus for the period of time after instillation of the drug in which pupillary movements were prevented. The BCD level returned to normal as the pupillary reflex returned to normal. This would indicate that the movements of the iris are responsible for discomfort in the subjects in which the homatropinization produced an elevation of the BCD.

The drug experiments in the present study were done with the intention of determining whether a differential
effect may exist depending on whether the sphincter muscle is paralyzed or activated or the dilator muscle is activated since these are all ways of immobilizing the pupil or altering the relations between the forces between the two muscles. The sphincter was paralyzed by using tropicamide. Figures 20-22 illustrate the results obtained with the use of tropicamide. For the two subjects used, tropicamide elevated the BCD during the period of time that the pupil was immobilized or almost immobilized. However, the BCD was not elevated two log units above the normal as it was in the case of Fugate and Fry's experiment. A reason for this difference could be due to the different rates of action of the drugs homatropine and tropicamide. These drugs block the myo-neural junction but do so for different periods of time. An homatropinized eye does not return to normal for more than 60 hours as Fugate and Fry determined. On the other hand, an iris acted upon by tropicamide is normal after 24 hours. This quick action of tropicamide could mean that not all myo-neural junctions are blocked at the same time and that some distorted contraction of the iris could take place. This distortion of the tissues could bring about discomfort also.
Two subjects were given bilateral doses of phenylephrine hydrochloride which acts directly on the dilator muscle causing it to contract. Variable results on the BCD were the outcome of this experiment as shown by Figures 24 and 25. The BCD data for both subjects show a gradual rise throughout the day but the change is not seemingly related to the change in pupil diameter. In neither case was the pupil totally immobilized by the drug, however. If it is assumed that the amount of tension produced between the two pupil muscles is related to discomfort, then phenylephrine, which dilates the pupil and thereby increases the force required by the constrictor muscles to produce a certain diameter of the pupil, should aggravate the discomfort. However, this does not seem to be the case for the two subjects used since the BCD has not been lowered by the use of phenylephrine.

One subject was given pilocarpine which acts directly on the sphincter muscle causing it to contract. The results of this experiment are shown in Figure 26. Again, as long as the pupillary light reflex was blocked, or almost so, the BCD was elevated. One obvious result of this experiment is that maximal constriction of the pupil does not produce discomfort if the constriction is brought about by drugging the
irides. This could be due to the gradual adaptation of the iris tissues to the extreme miosis. No discomfort is produced by the drug from the time of instillation until maximum miosis because the drug action is relatively slow giving the tissues adequate time to adapt to the increasing constriction.

The results of the drug experiments indicate that the threshold of discomfort can be manipulated by pharmacologically changing the activity of the dilator and sphincter muscles of the iris. The most significant changes in the BCD occurred when the iris was immobilized by paralyzing the sphincter muscle. Activation of the sphincter muscle or activation of the dilator muscle produced some changes in the BCD but either not as large as those with paralysis of the sphincter muscle or not obviously related to the pupil response. Finally, increasing the tension between the sphincter and dilator muscles does not seem to lower the discomfort threshold which is contrary to the results expected for the mechanisms proposed by Bartley and Hopkinson.
The Steady State Response

Under ordinary conditions, the eye is not exposed to a flashing bright environment but to an approximately continuous environment in terms of changes of brightness levels. This means that the pupil will not be responding to a sudden exposure to a bright glaring light but will be responding to an approximately continuous exposure to the glare source, disregarding any eye movements. The results of the experiments using a steady glare source indicate that the pupil is not stable in its response to a continuous stimulus but is constantly varying in size. The oscillations can be subdivided into separate components as is done in Figure 29; the major components consisting of oscillations with frequencies around 1 and 0.3 Hz. These oscillations are probably similar to those noted by Hopkinson who determined their frequency at about 2 Hz. But, since he did not make a determination of their magnitude, a more detailed comparison between his results and the results of the present investigation cannot be made.

The data on the magnitude of the oscillations relative to the average pupil diameter, the hippus ratio, presented in Table 1 do not seem to show any clear relation between the magnitude of the hippus ratio and the BCD. According to the data for momentary expo-
sure it would be expected that smaller oscillations
would be associated with discomfort with smaller pupil
sizes. For G. P. the largest oscillations occurred
with the smaller pupil diameter at the BCD.

The data presented in Table 2 illustrate that as
the source luminance increases the pupil diameter de­
creases and so does the hippus. This mutual decrease
keeps the hippus ratio approximately constant over the
luminance levels studied. There seems to be no differ­
ence between the pupil response at levels below the BCD
and those at or above the BCD. No conclusions can be
drawn from this data concerning the relation between
the magnitude of the hippus and discomfort.

The relation between hippus and the average diameter
may be a complicated one. At this time it is not known
whether the dilation or the constriction or both are
the important parameters, or whether it is the rate
of change or the number of oscillations in a given period
of time that are important in relation to discomfort.
The experimental work of Abrams\textsuperscript{41} and Loewenfeld and
Newsome\textsuperscript{39} indicate that the forces required to produce
a given pupil size are constantly changing. Especially
important in this connection is the finding that a given
force applied to dilate the pupil causes greater dilation
if it reached its state from one of miosis. This could
lead to two different conclusions about the production of discomfort. First, since the constant force gives a greater change in diameter, this could lead to distortion of the nerves and to discomfort. The second interpretation is that the iris tissues are more flexible and easier to move in this case and, therefore, less distortion of the tissues would take place which would then not produce discomfort. More work is required on the forces in play in the iris and also on the characteristics of hippus before this problem can be solved.

Natural Pupil versus Artificial Pupil

Since the pupil system has control over its own input under normal situations, it might be expected that the oscillations that occur to a steady stimulus under the open loop conditions are either attenuated or have different frequency components under the closed loop, or normal, condition. In a sense, the pupil system may drive itself. This, however, does not seem to be the case for the 0.3 and 1 Hz components as the data presented in Figure 31 indicate. There does not appear to be any difference in magnitude of the two frequency components between the open loop and closed loop condition which could be the result of the small gain factor for the pupil system that Stark\textsuperscript{42} has found. The differences that do seem to exist are the result
of the curves being plotted on an arbitrary scale. Furthermore, there does not seem to be any change in the relative amounts of oscillations in the two different components with the open and closed loop conditions. With the method of analysis used, the results of the experiments using the natural pupil and a small artificial pupil indicate that there are no apparent significant differences between the open loop and closed loop conditions.
SUMMARY AND CONCLUSIONS

An attempt was made to relate certain aspects of the pupillary light response to intermittent and steady stimuli which also produced a threshold sensation of discomfort. The glaring stimuli were presented to the left eye and the consensual pupillary reflex of the right eye was recorded with an infrared pupillometer. The subject's task was to adjust the luminances of the glare sources to the threshold of discomfort, or BCD. Various sizes and configurations of circular glare stimuli were presented intermittently or steadily on a large circular background which was varied in luminance. A study was made of 1) the effects of immobilizing the pupil with various drugs and 2) the effects of activating the two muscles of the iris with drugs. A study was also made of the oscillations of the pupil which occur to a steady glare stimulus. The subjective data of this study were compared with the discomfort glare data of other investigators.
Several conclusions regarding the relation between the pupil movements and discomfort can be drawn from the results of this study.

1. The pupil does not constrict a set amount to the flash of a glare source at the BCD, but the amount of constriction varies with the initial diameter of the pupil.

2. The size to which the pupil must be constricted in order to produce discomfort is not a constant. The discomfort varies with the initial diameter of the pupil.

3. The discomfort threshold can be elevated by immobilizing the pupil with a drug such as tropicamide.

4. Increasing the tension between the sphincter and dilator muscles by the use of drugs does not aggravate the discomfort produced by a flashing glare source.

5. In the case of steady stimulation, the amount of hippus and the average size of the pupil both vary with the luminance of the stimulus and it has not been determined how these variables are involved in producing discomfort. It should be possible to isolate the effects of these two variables but this has not been accomplished in this study.

6. There are no apparent differences of the oscillations of the pupil to a steady glare stimulus at the BCD as viewed through a small artificial pupil or through the natural pupil.
TABLE 1

BCD DATA FOR G.P. FOR STEADY FIXATION OF GLARE SOURCES OF VARIOUS SIZES. THE RETINAL ILLUMINANCE PRODUCED BY THE BACKGROUND WAS 51.4 TROLANDS.

<table>
<thead>
<tr>
<th>Glare Source Size (Degrees)</th>
<th>Retinal Illuminance produced by the Glare Source (troland)</th>
<th>Average Pupil Diameter</th>
<th>Hippus Size</th>
<th>Hippus Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1,363,000</td>
<td>2.06 mm</td>
<td>.25 mm</td>
<td>.121</td>
</tr>
<tr>
<td>60</td>
<td>474,000</td>
<td>2.13</td>
<td>.14</td>
<td>.053</td>
</tr>
<tr>
<td>80</td>
<td>326,900</td>
<td>2.42</td>
<td>.15</td>
<td>.064</td>
</tr>
<tr>
<td>120</td>
<td>265,700</td>
<td>2.16</td>
<td>.25</td>
<td>.130</td>
</tr>
</tbody>
</table>
TABLE 2

DATA OF D.L. AND R.W. FOR STEADY FIXATION OF A 29° GLARE SOURCE. THE LUMINANCE OF THE BACKGROUND WAS ZERO.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Luminance of Glare Source</th>
<th>Hippus Size</th>
<th>Average Pupil Diameter</th>
<th>Hippus Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.L.</td>
<td>34 nits</td>
<td>.581 mm</td>
<td>5.67 mm</td>
<td>.102</td>
</tr>
<tr>
<td></td>
<td>343</td>
<td>.362</td>
<td>4.00</td>
<td>.090</td>
</tr>
<tr>
<td></td>
<td>3,430*</td>
<td>.269</td>
<td>2.57</td>
<td>.105</td>
</tr>
<tr>
<td></td>
<td>10,290</td>
<td>.201</td>
<td>2.87</td>
<td>.070</td>
</tr>
<tr>
<td>R.W.</td>
<td>34 nits</td>
<td>.512 mm</td>
<td>5.35 mm</td>
<td>.096</td>
</tr>
<tr>
<td></td>
<td>343</td>
<td>.446</td>
<td>4.04</td>
<td>.114</td>
</tr>
<tr>
<td></td>
<td>3,430*</td>
<td>.284</td>
<td>3.25</td>
<td>.087</td>
</tr>
</tbody>
</table>

* 3,430 nits was found to be at or near the BCD for each of the two subjects.
**TABLE 3**

THE BCD DATA FOR D.L. AND S.S. CONVERTED FROM THE PUPILLOMETER APPARATUS TO NATURAL VIEWING CONDITIONS. THE SIZE OF THE GLARE SOURCE WAS 10° IN DIAMETER.

<table>
<thead>
<tr>
<th>Subj.</th>
<th>Background (fL)</th>
<th>BCD (mm)</th>
<th>IPD (mm)</th>
<th>Area (mm²)</th>
<th>SCCF*</th>
<th>Area xSCCF</th>
<th>Glare Ratio</th>
<th>Back- Corrected Background</th>
<th>Corrected Glare Ratio</th>
<th>(fL)</th>
<th>(fL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>30</td>
<td>240</td>
<td>4.11</td>
<td>13.32</td>
<td>0.834</td>
<td>11.11</td>
<td>0.0450</td>
<td>0.0189</td>
<td>0.567</td>
<td>10,800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>282</td>
<td>3.86</td>
<td>11.69</td>
<td>0.853</td>
<td>9.97</td>
<td>0.0502</td>
<td>0.0211</td>
<td>2.11</td>
<td>14,100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>348</td>
<td>3.78</td>
<td>11.22</td>
<td>0.860</td>
<td>9.65</td>
<td>0.0518</td>
<td>0.0218</td>
<td>9.25</td>
<td>18,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>426</td>
<td>3.54</td>
<td>9.83</td>
<td>0.875</td>
<td>8.60</td>
<td>0.0581</td>
<td>0.0244</td>
<td>24.4</td>
<td>24,800</td>
<td></td>
</tr>
<tr>
<td>SS</td>
<td>30</td>
<td>4.57</td>
<td>6.69</td>
<td>35.06</td>
<td>0.608</td>
<td>21.32</td>
<td>0.0234</td>
<td>0.0234</td>
<td>0.701</td>
<td>107</td>
<td></td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>5.37</td>
<td>6.23</td>
<td>30.57</td>
<td>0.648</td>
<td>19.81</td>
<td>0.0252</td>
<td>0.0252</td>
<td>7.56</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>4.57</td>
<td>2.83</td>
<td>6.50</td>
<td>0.915</td>
<td>5.95</td>
<td>0.0840</td>
<td>0.0840</td>
<td>25.5</td>
<td>384</td>
<td></td>
</tr>
</tbody>
</table>

*SCCF (Stiles-Crawford correction factor) = 1 - 0.0425X² + 0.000666X⁴

where X is the radius of the pupil.
Figure 1. Schematic of the apparatus used in the major portion of the experiment.
Figure 2. Tracing of the pupillometer recording which illustrates the pupil response to the glare stimulus.
PUPIL DIAMETER (mm)
Figure 3. Relationship of the BCD and pupil data to glare size for subject D.L. The retinal illuminance of the background was 0.86 log td. The range of the BCD data is indicated with brackets and the range of the pupil data is denoted with arrows.
Figure 4. The relationship of the BCD and pupil data to glare size with a background retinal illuminance of 1.86 log td.
Figure 5. The relationship of the BCD and pupil data to glare size with a background retinal illuminance of 2.86 log td.
Figure 6. Tracing of the pupillometer recording which demonstrates how the change in pupil diameter (Δ) is measured. The arrow points to the initial pupil diameter.
INITIAL PUPIL DIAMETER
Figure 7. The relationship of the BCD data to glare size for subject W.P. The retinal illuminances of the background was 0.36, 1.36 and 2.36 log td.
Log Retinal Illuminance of Glare (td)

Log Size of Glare (Steradians)

Source W.P.

2.86

1.86

0.86
Figure 8. The relationship of the BCD data to glare size for subject D.K. The retinal illuminance of the background was 0.86, 1.86 and 2.86 log td.
Log Retinal Illuminance of Glare (td)

Log Size of Glare Source (Steradians)

D.K.

2.86
1.86
0.86
Figure 9. The relationship of the BCD data to glare size for subject D.L. The retinal illuminance of the background was 0.86, 1.86 and 2.86 log td.
Figure 10. The averaged data of three subjects showing the relationship between the BCD and glare size with three background retinal illuminances.
LOG RETINAL ILLUMINANCE OF GLARE
(MEAN OF 3 SUBJECTS)

LOG SIZE OF GLARE SOURCE
(STERADIANS)
Figure 11. The averaged data of three subjects showing the relationship between the pupil responses and glare size with three background retinal illuminances.
PUPIL DIAMETER (mm)

MEAN OF 3 SUBJECTS

<table>
<thead>
<tr>
<th>IPD</th>
<th>0.86</th>
<th>1.86</th>
<th>2.86</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td></td>
</tr>
</tbody>
</table>

LOG SIZE OF GLARE SOURCE (STERADIANS)

PUPIL DIAMETER (mm)
Figure 12. The averaged data of three subjects showing the relationship between the BCD data and background retinal illuminance with four glare sizes.
Figure 13. The averaged data of three subjects showing the relationship between the pupil responses to a glare stimulus and the background retinal illuminance with four glare sizes.
MEAN OF 3 SUBJECTS

PUPIL DIAMETER (mm)

LOG RETINAL ILLUMINANCE OF BACKGROUND (td)

IPD

-1.60
-1.03
0.17
0.42
Figure 14. Plot of the change in pupil diameter against the initial pupil diameter for subject D.K.
CHANGE IN PUPIL DIAMETER (mm)

INITIAL PUPIL DIAMETER (mm)
Figure 15. Plot of the change in pupil diameter against the initial pupil diameter for subject D.L.
CHANGE IN PUPIL DIAMETER (mm)

INITIAL PUPIL DIAMETER (mm)

D.L.
Figure 16. Plot of the change in pupil diameter against the initial pupil diameter for subject W.P.
CHANGE IN PUPIL DIAMETER
(mm)

INITIAL PUPIL DIAMETER
(mm)

W.P.
Figure 17. Plot of the percentage change in pupil diameter against initial pupil diameter for three subjects.

CHANGE IN PUPIL DIAMETER (%)

INITIAL PUPIL DIAMETER (mm)
Figure 18. Drawing to illustrate the stimulus pattern viewed by the subject in the experiment on peripheral glare.
GLARE

BACKGROUND
Figure 19. Plot of the BCD and pupil data for one subject which compares this data for the condition of peripheral presentation of glare (-P) and central presentation of glare (-C).
Figure 20. The BCD and pupil data immediately before and at various times after instillation of tropicamide in both eyes of subject D.L.
Figure 21. The BCD and pupil data immediately before and at various times after instillation of tropicamide in both eyes of subject S.S. Three glare sizes were used to obtain the data.
Figure 22. The BCD and pupil data of subject S.S. for three glare sizes. The BCD data for the smaller glare sizes have been shifted downward so that the first data points coincide. The pupil data are the average of the three glare sizes. The data were taken immediately before and at various times after instillation of tropiccamide in both eyes of the subject.
Figure 23. The BCD and pupil data recorded during one day for subject D.L. with no drugs administered.
LOG RETINAL ILLUMINANCE OF GLARE (td)

TIME (hrs)
PUPIL DIAMETER (mm)

PUPIL DIAMETER (mm)

DL 1.75 LOG td glare NORMAL

120°
Figure 24. The BCD and pupil data immediately before and at various times after instillation of phenylephrine in both eyes of subject D.L.
D.L. 1.75 LOG td BACKGROUND
120° GLARE PHENYLEPHRINE

LOG RETINAL ILLUMINANCE (td)

PUPIL DIAMETER (mm)

TIME (hrs)

DRUG
Figure 25. The BCD and pupil data immediately before and at various times after instillation of phenylephrine in both eyes of subject G.P.
Figure 26. The BCD and pupil data immediately before and at various times after instillation of pilocarpine in both eyes of subject D.L. The data are averaged from the data collected with three glare sizes, 20°, 40°, and 120°.
Figure 27. The averaged BCD and pupil data of three subjects for different glare sizes using continuous glare stimuli (-C) and intermittent glare stimuli (-I). The curve denoted by pupil diameter refers to the average pupil diameter during the pupil's response to the steady stimulus.
LOGL RETINAL ILLUMINANCE OF GLARE (td)

MEAN OF 3 SUBJECTS

- BCD-I
- BCD-C
- IPD
- Pupil Diameter

LOG SIZE OF GLARE SOURCE (STERADIANS)

LOG RETINAL ILLUMINANCE OF GLARE (td)

PUPIL DIAMETER (mm)
Figure 28. Tracing of the pupil data recorded during stimulation with a continuous glare source.
Figure 29. Drawing of the computer plots which illustrate the raw pupil data and the various components extracted from the data.
Figure 30. Schematic of the apparatus used to stimulate the left eye using the natural pupil.
Figure 31. Comparison of the hippus components of the pupil data obtained with a small artificial pupil and the natural pupil.
ARTIFICIAL PUPIL

NATURAL PUPIL

AVERAGE PUPIL DIAMETER 6.1 mm

LUMINANCE = 343 NITS

LUMINANCE = 34 NITS

ARBITRARY SCALE

TIME (Seconds)
Figure 32. Schematic of the apparatus used in the experiments with natural viewing conditions.
Figure 33. BCD data for two subjects with the apparatus shown in Figure 32. The open circles represent data derived from the previous experiments with a glare source of the same size as that used with natural viewing. The dashed line represents the average data of Luckiesh and Guth with a 10° glare source.
DATA OBTAINED WITH NATURAL VIEWING CONDITIONS

DATA DERIVED FROM PUPILLOMETER
Figure 34. The relationship between the pupil diameter and the size of the source. The source produced a retinal illuminance of 2.71 log td.
D.L. 2.71 LOG td

PUPIL DIAMETER (mm)

LOG SIZE OF SOURCE
(STERADIANS)
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