THIS BOOK IS OF POOR LEGIBILITY DUE TO LIGHT PRINTING THROUGH OUT IT'S ENTIRETY.

THIS IS AS RECEIVED FROM THE CUSTOMER.

PUPILLARY RESPONSE VISIBILITY METER: FUNCTION, OPERATION AND APPLICATION

by

BALAJI RAMARAO

B.E.(Honors), Madras University, India, 1979

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1981

Approved by:

Corwin A Bennett
Major Professor

To

My beloved family and loved ones

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I would like to convey my deepest sense of gratitude and appreciation to Dr. Corwin A. Bennett for his guidance,help and interest in this work. My appreciation to Francis B. Doll for his design in putting the optical pieces of the instrument together. My thanks are due to Prof. J.J. Smaltz, Dr. Byron Jones, Dr. Mike Rubison and Dr. Alvin Compaan for their help and consent to serve on my committee. To all those who played an important role in the work I owe a big thankyou. Special mention should be made about Bradley Kramer, Vinay Vasudev and Greg Gideon for their help in conducting the experiments.

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (cont.)

LIST OF FIGURES (contd.)

LIST OF FIGURES (contd.)

INTRODUCTION

Ability to see objects through the atmosphere, underwater or in space is limited by the availability of light, its distribution on the object of regard and its background, the reflective properties of the object of regard and its background, the transmission characteristics of the intervening media, the properties of any magnifying or filtering optical devices employed and the characteristics of the human visual system (Duntley, Gordon, Taylor, White, Boileau, Tyler, Austin and Harris, 1964).

For many years researchers have striven to find answers to several questions relating to the characteristics of visual systems, questions like: Can some particular object be seen? How far can it seen? How rapidly can it move and yet be visible? How dim can the illumination become before the object is lost to view? Is magnification necessary to make the object visible? What is the optimum procedure for visual search? What is the probability of success in sighting an object searched for? Under what circumstances can it be recognized? Is identification possible? How is visual performance affected by fatigue, discomfort, distraction, apprehension, motivation, etc..? This field of research was referred to as visibilty research and regarded as a professional speciality within optics (Duntley, et al., 1964).

There have been several interpretations of the word "visibility" and a general lack of consensus regarding its definition was the result (Bennett, 1931; Cottrell, 1951). It is, therefore, necessary to explain the use of the term visibility. In this research visibility will be used to denote the human capability to detect, recognize and identify objects by means of the human visual mechanism. Thus at different levels of visual performance, an object may be detected as a shapeless

THIS BOOK CONTAINS NUMEROUS PAGES WITH THE ORIGINAL PRINTING BEING SKEWED DIFFERENTLY FROM THE TOP OF THE PAGE TO THE BOTTOM.

THIS IS AS RECEIVED FROM THE CUSTOMER.

spot, recognized as an alphabet i.e. character, and, finally, identified as the letter "a". Another definition of visibility was expressed by Cottrell (1951). In his paper the term visibility was used to refer to that special quality of a seeing task which depended on a combination of the brightness contrast, the subtended angular size of the detail, the brightness of the background and the time of observation. If any one of the above factors were varied the visibility of the task would also be varied. Hence, visibility was frequently specified by determining the threshold of one or more of the factors mentioned and expressing the index of visibility as the reciprocal of the threshold; or to set up an arbitrary scale of visibilities based on a selected reference task considered to be at "unit visibility".

Feree and Rand (1931) pointed out that the three most important physical factors in the visibility of objects are size of visual angle of the detail to be discriminated, difference in co-efficients of reflection between the object of regard and background (contrast) and the intensity of illumination. Their findings could be summarized as follows: a) With a given co-efficient of reflection the visual or sensation difference is greater in the case of light objects on dark backgrounds than it is in the case of dark objects on light backgrounds, b) the sensation differences increase rapidly with increase of intensity of illumination, and c) the increase in sensation with increased illumination is more rapid for white objects on black backgrounds or light objects on dark backgrounds than it is for dark objects (black) on light (white) backgrounds. In their study, Feree and Rand rated visibility in terms of the visual angle subtended by the object at the eye and measured visibility by speed of vision (needed to see the object). They found that visibility as measured by speed of vision varies greatly with intensity of illumination and with relation of object to background and that visibilities as measured by speed are, in general, greater than visibilities rated in terms of visual angle. Table 1 illustrates a part of their findings. The first column gives the increase of one disc over the former in terms of the visual angle. Thus 2 and 1 would mean that the second disc presented to the observer was twice the size of the first. The second column is the ratio of the two discs and is the visibility rated in terms of the visual angle. Thus for a increase of visual angle 2 and 1 the ratio would be 2.0 and this is the visibility rated in terms of the increase in visual angle. The third column presents the ratio of the speeds of vision needed to see the discs under different levels of illumination.

An object is said to be visible if it is at a particular threshold of detection, recognition and identification. The object being viewed is said to be above threshold of visibility if its details can be easily recognized. The threshold value is that value of either luminance, speed or visual angle when the object being viewed is just visible. The "above thresholdness" of the object of interest is frequently referred to as "suprathresholdness". This suprathresholdness of an object has been used as an index of visibility.

The object being viewed will be called a "display". If a display is produced by an electronic imaging system such as a cathode ray computing terminal it will be called a "information display". The whole visual system will be referred to as "information transfer in a display-to observer system" (Clauer and Bates, 1970).

Generally, a display is above the observer's threshold and it is desirable to measure the display's visibility in terms of how much it is above threshold. Apart from the measure of visibility (recognition) of an object, a measure of the quality of an information display is required, particularly for displays produced by electronic imaging systems (Clauer and Bates, 1970).

Table 1

Visibility as Rated in Terms of Visual Angle and Measured by Speed of Vision (Feree and Rand, 1931)

Visual angle in mins of arc	Ratio of visibility: visual angle scale	Ratio of visibility as measured by speed of vision Foot-candles of illumination							
		1.25	2.5	5.0	7.5	10.0	15.0	20.0	30.0
2 and 1	2.0	5.27	4.55	5.00	5.58	5.90	5.63	5.20	4.60
4 and 2	2.0	2.55	2.78	2.30	2.04	1.82	1.57	1.51	1.49
2 and 1	2.0	5.27	4.55	5.00	5.58	5.90	5.63	5.20	4.60
3 and 2	1.5	1.77	1.87	1.73	1.52	1.40	1.26	1.24	1.23
4 and 3	1.33	1.44	1.43	1.34	1.34	1.29	1.24	1.22	1.21
5 and 4	1.25	1.33	1.29	1.26	1.25	1.22	1.21	1.20	1.20
2 and 1	2.0	5.27	4.55	5.0	5.58	5.90	5.63	5.20	4.60
3 and 1	3.0	9.30	8.50	8.65	8.45	8.27	7.13	6.40	5.65
4 and 1	4.0	13.40	12.10	11.50	11.70	10.70	8.84	7.83	6.90
5 and 1	5.0	17.80	15.70	14.50	14.20	13.00	10.70	9.40	8.20
3 and 2	1.50	1.77	1.87	1.73	1.52	1.40	1.26	1.24	1.23
4 and 2	2.0	2.55	2.60	2.30	2.04	1.82	1.57	1.51	1.49
5 and 2	2.50	3.38	3.46	2.90	2.55	2.20	1.90	1.82	1.79
4 and 3	1.33	1.44	1.43	1.34	1.34	1.29	1.24	1.22	1.21
5 and 3	1.67	1.91	1.84	1.68	1.68	1.58	1.50	1.48	1.46

The optical signal which reaches the observer's eyes after modification by the optics of the environment constitutes the raw material of visual discrimination. The visual performance capabilities of the observer will govern whether the available signal provides an adequate basis for the discrimination of interest (Duntley, et. al., 1964). A measure of this signal for an adequate basis for discrimination is desirable to measure the threshold of visibility.

This research describes a device built to measure visibility of electronic imaging displays such as CRTs'. Several instruments were devised to measure suprathresholdness of information, allowing the reduction of visibility to threshold and using a measure of this reduction as a measure of suprathresholdness. Principles of reduction such as contrast reduction, brightness reduction, total reduction and partial reduction were used. A brief discussion of each of these devices follows most of which are unavailable now.

Visibility Meters

Jones' Visibility Meter (Jones, 1920)

As early as 1918 Lyod A. Jones described a visibility meter which was used primarily to evaluate the visibilities of ships at sea and to check the adequateness of their camouflage as a protective measure from German submarines during WW1. Figure 1 illustrates the principle of operation of this visibility meter.

The meter consists of a veiling brightness source which could be moved either farther away or nearer the optical axis thereby decreasing or increasing the brightness of the diffusing glass. A partial mirror in the principle optical path transmits part of the light (incident flux) from the object being viewed and reflects part of the light from the veiling glare source. A neutral non-diffusing optical wedge was arranged to move across the path of the incident flux and linked to the veiling source so that the wedge was moved into the path (increasing reflectance) of the

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

THIS IS AS RECEIVED FROM CUSTOMER.

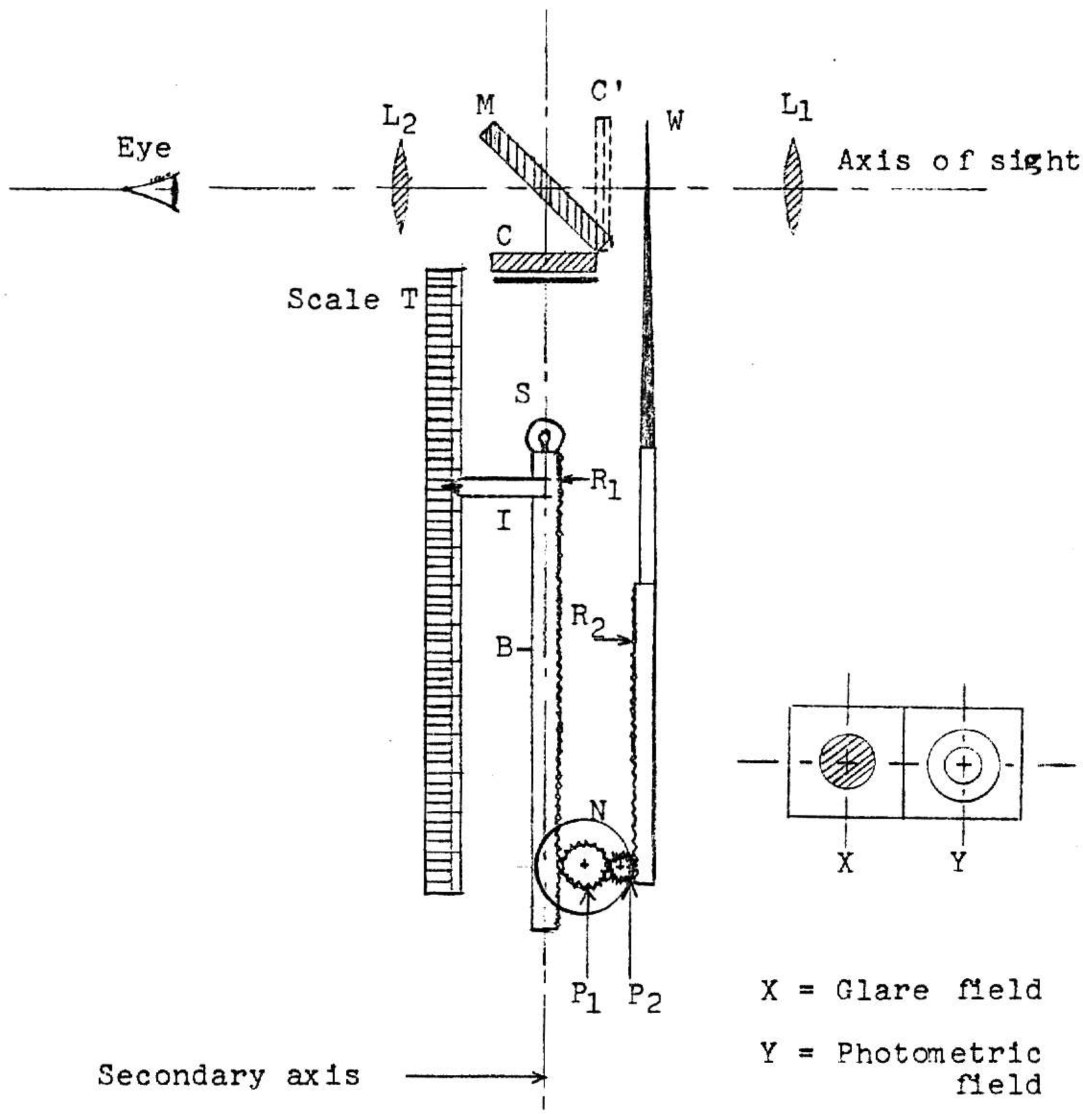


Figure 1. Diagrammatic illustration of Jones' visibility meter (Jones, 1920).

incident flux when the source moved nearer to the diffusing glass. In this manner the veiling luminance was increased while the object or incident flux was decreased. This principle would reduce the change in contrast between the veiling source and the background of the object.

The scale "T" (Figure 1) was calibrated to read the transmittance of the wedge and brightness of the veiling source. Visibility was expressed by the relation

$$V_b = \frac{B_v}{B_1}$$

where B_v is the brightness of the veiling source which when superimposed over the background of the object and the object would reduce the contrast to threshold and B_1 is the brightness of the background.

<u>Bennett's Visibility Meter</u> (Bennett, 1931)

In 1931. M.G. Bennett reported a visibility meter designed for use in meteorology and illuminating engineering. This device consisted of twenty one obscuring glass lenses (discs) of equal obscuring power. These discs could be brought into the field of view one at a time until the object being viewed was completely obscured. The visibility of the object was expressed in terms of the distance and the number of obscuring glass discs used. If a tree was the object and was being viewed at a distance of 100 feet, and 14 glass discs were used to obscure the tree from the field of view, the visibility would be expressed as 14, at a distance of 100 feet.

<u>Luckiesh and Moss Visibility Meter</u> (Luckiesh and Moss, 1935)

The Luckiesh and Moss visibility meter is illustrated in Figure 2. The meter essentially consists of two colorless photographic filters with precise circular gradients of density which may be rotated simultaneously by means of a rack and pinion arrangement. The gradient filters reduce the apparant brightness of the visual field due to the absorption and lower the contrast between the object of regard and its background

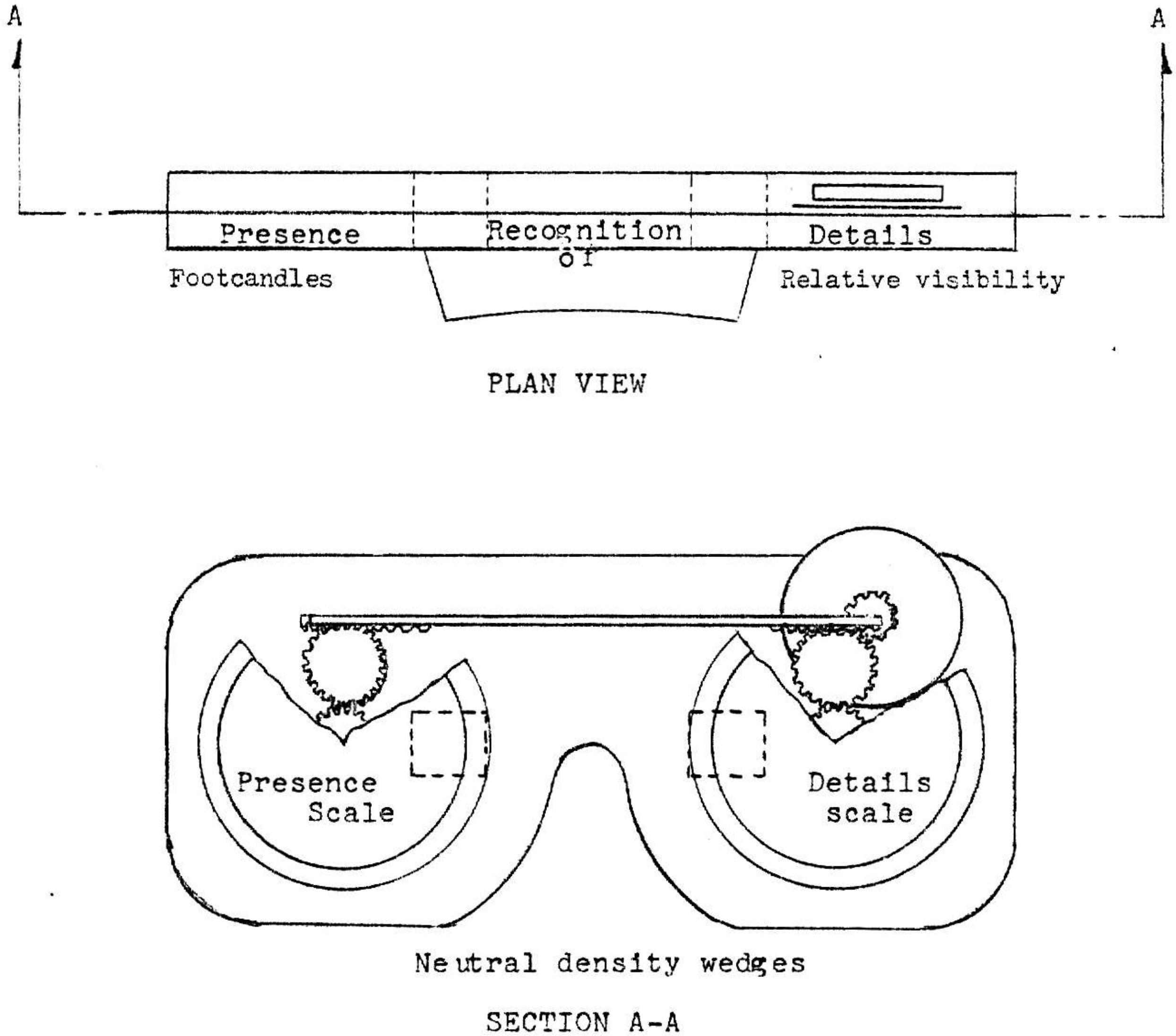


Figure 2. Diagrammatic illustration of the Luckiesh-Moss visibility meter(Finch and Palmer, 1955).

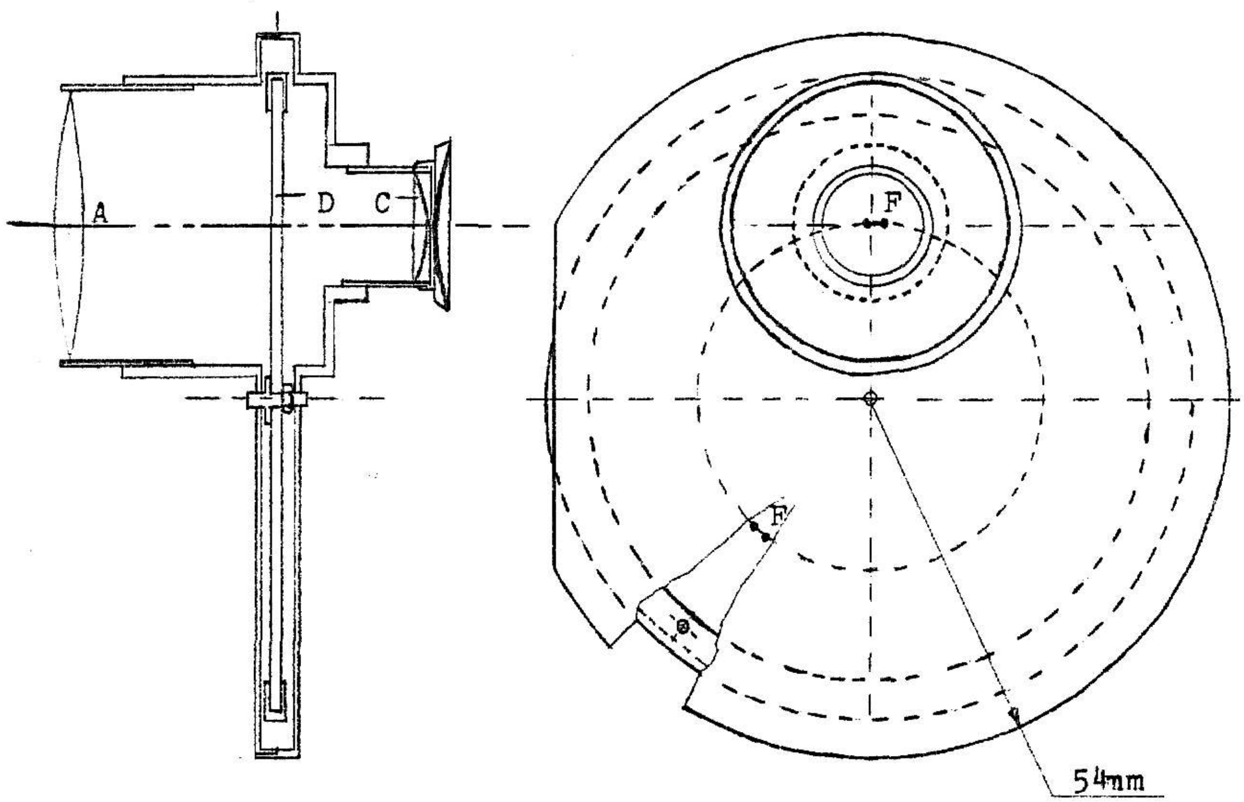
due to the diffusing characteristics of the filter. Rotation of the discs reduce the brightness of the object and background to threshold conditions by scattering the light from the more bright areas to the less bright areas.

A calibration scale on the scale of relative visibility is in terms of a pair of black parallel bars separated by their width, viewed against a uniformly bright white background. The reduction of visibility to threshold conditions by this meter employs the use of a reduction in the brightness difference, the contrast and the visual acuity of the object. The whole field of view is reduced in brightness level and fogged until the predetermined degree in difficulty of seeing is achieved. The setting gives the visibility in terms of the relative visibility.

Although extensively used and studied, questions were raised regarding the effect of the progressive change in apparant brightness of the task as seen through the filters, on the adaptation of the eye (Cottrell, 1951).

Phillips Visibility Meter (Finch and Simmons, 1953)

The Phillips Visibility meter was reported by Bouma and Host in 1936 and was the first instrument to be designed specifically for street and highway lighting use. Figure 3 illustrates the instrument which consists of 1:1 magnification system and a large disc upon which a series of 50 dots are placed on a circle. The dots are rotated so that they are seen successively in the same position in the center of the optical path and projected upon the roadway but with different transmittance (Finch and Palmer, 1957). The instrument is aimed at the spot to be tested and the disc is rotated until a black spot is selected which permits the target to be just perceptible against its background. The transmittance of the spot is used as a measure of relative visibility. The eye maintains a constant adaptation. The meter measures the brightness difference threshold.



A = Objective

C = Lens

F = Spots

D = Disc

Figure 3. Diagrammatic illustration of the Phillips visibility meter (Finch and Palmer, 1957).

Duckler Visibility Meter

In 1939 a visibility meter was described in a French periodical and was called the "Duckler Visibility Meter". This instrument is similar to the Luckiesh-Moss visibility meter except that a series of variable density glass discs are used (Finch and Simmons, 1953; Finch and Palmer, 1957). Threshold is determined when the object observed is no longer seen through a glass disc of slated absorptive power. The instrument is a brightness difference threshold meter and eliminates the influence of glare.

Annular Ring Visibility Meter (Finch and Simmons, 1953)

The "Annular Ring Visibility Meter" was first reported in 1940. It consists of a series of paper rings having external and internal diameters of 0.8 and 0.2 inches respectively, placed side by side on a glass plate which can be mounted on a windshield of a car. The rings are lit by an adjustable incandescent source. The visibility of the road surface is observed by selecting the rings which most closely match the lighted road surface.

The Street Lighting Evaluator (Finch and Simmons, 1953)

Used primarily to evaluate visibility on road surfaces, the instrument consists of three parts: A miniature pavement bed mounted over the hood of the car; a glare integrator mounted over the windshield; and a control box in the operator's compartment. The pavement bed is fitted with a piece of simulated pavement, which by inspection, is matched to the street texture. Miniature pedestrains or obstacles are positioned on the pavement. Brightness and Luckiesh-Moss visibility readings are made on the pavement strip and obstacle. The readings are entered on a nomograph.

Basically, the three measurements made are (1) The brightness of the pavement, (2) The brightness of the representative obstacle on or near the pavement in question and (3) the glare effect from sources in the field of view. These three readings are integrated into one overall value of relative visibility which can be read off the nomograph.

Horton's Visibility Meter (Finch and Palmer, 1957)

This visibility meter is very similar to the Phillips Visibility Meter and works on the brightness-difference threshold principle. It consists of a lens system (Figure 4) with a 1:1 magnification and a transparant disc in the focal plane of the eyepeice. A series of transparant circular dots of varying transmittance are arranged around the periphery of the disc and are made such that the dots would obscure objects at approximately 200 feet ahead of the observer. The disc is rotated until the difference between the object brightness and its background brightness is below the brightness difference threshold.

Cottrell Visibility Meter (Cottrell, 1951)

Figure 5 is a schematic drawing of this contrast - brightness threshold meter. The device consists of a light source which is superimposed on the optical path by a system of mirrors and lenses. A variable polaroid filter controls the brightness of this veiling luminance. A circular neutral gradient filter is placed in the optical path and the brightness of the object is varied as the transmittance of the neutral gradient. When the transmission is 1.0 (maximum) the brightness of the total field is the brightness of the veiling glare source plus the brightness of the actual field. The equipment is adjusted so that the brightness of the veiling glare source is equal to that of the actual field. Therefore, under these conditions the total brightness is twice the brightness of the background. When the gradient is rotated until the transmission is a minimum (0.0) the brightness of the veiling luminance is equal to the brightness of the background.

For a visibility measurement the circular neutral gradient is rotated until the object in question is at the threshold state under the particular conditions of viewing described above. The veiling brightness is

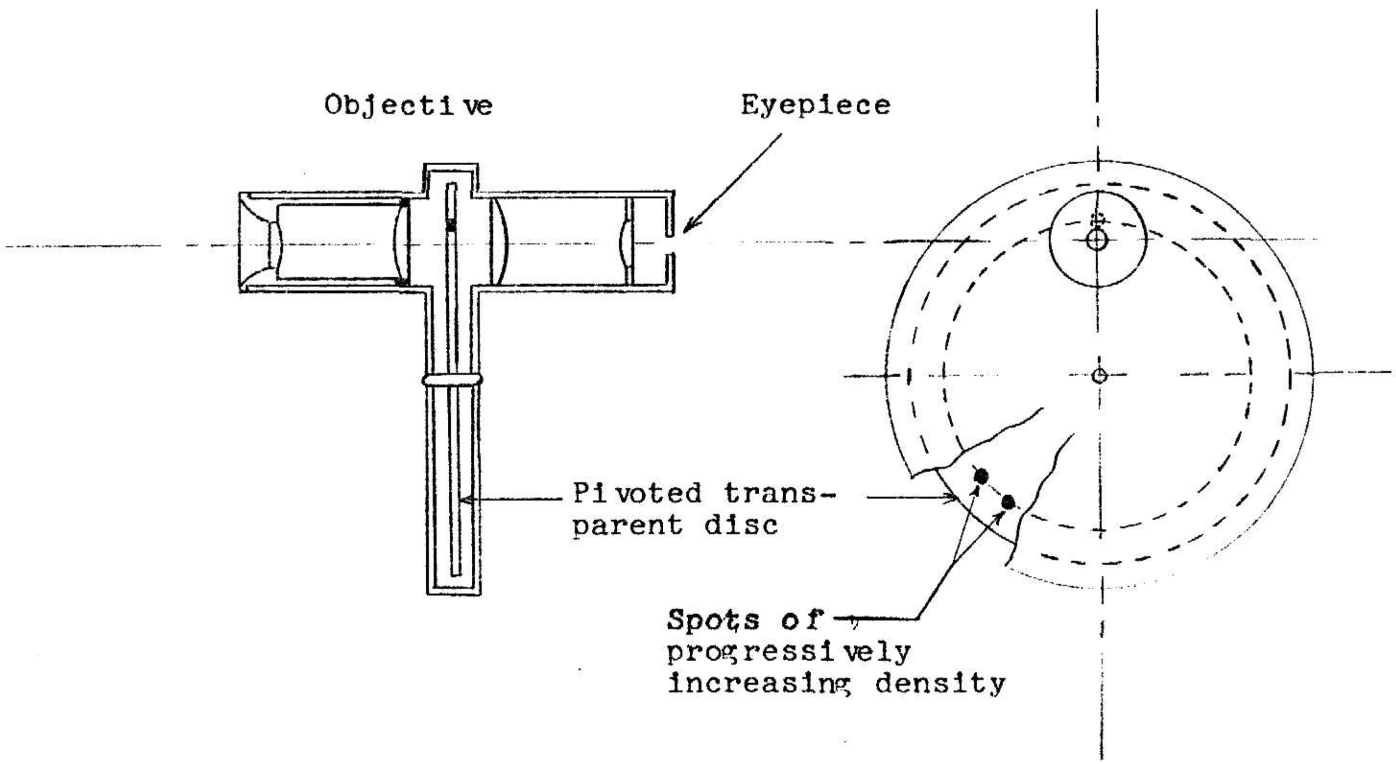


Figure 4. Diagrammatic illustration of the Horton's visibility meter (Finch and Palmer, 1957).

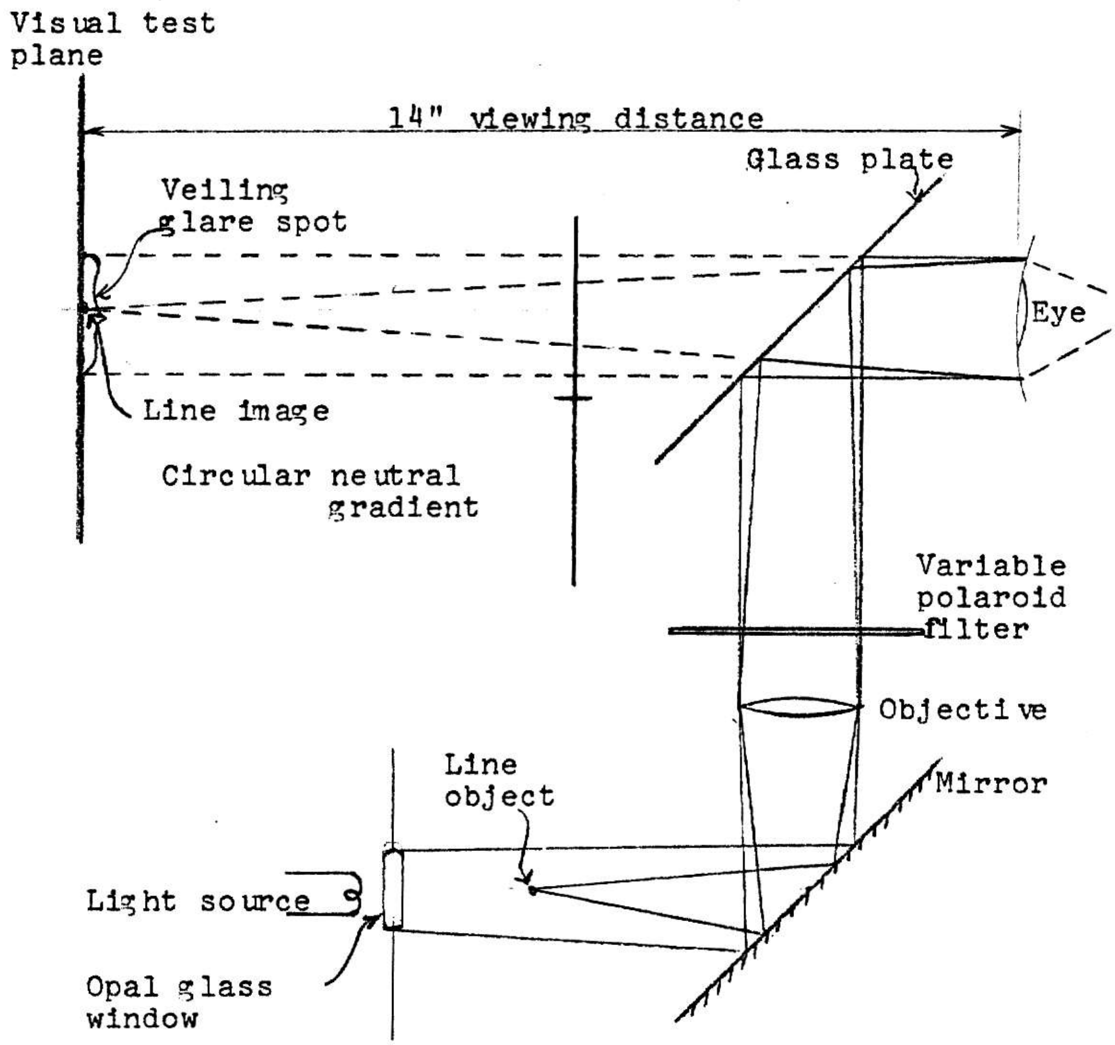


Figure 5. Diagrammatic sketch of the contrast-brightness threshold meter (Cottrell, 1951).

adjusted until it is equal to the background at maximum transmittance and the circular gradient filter is then turned until the target detail is just percieved. Visibility of the target is expressed in terms of the contrast threshold and inherent contrast of the object against its background.

<u>*Finch and Simmons Visibility Meter*</u>

In 1953, two researchers, D.M. Finch and A.E. Simmons, of the University of California reported a visbility meter designed specially to measure visibility at night on highways (Finch and Simmons, 1953). Figure 6 is a schematic drawing of the contrast threshold meter meant to measure visibility without much of subjective appraisal.

In this instrument the eye adaptation is kept constant, only a small central area (3°-5° in total visual angle) would be changed in making a measurement and the total visual field was approximately symmetrical and included sixty degrees total visual angle.

The optical system consisted of an upper and lower monocular optical system. The upper monocular system consisted of an objective lens and an image erecting lens. The field of view as seen through the eyepiece shows in an outer annular ring. The central portion of the view is seen by the lower monocular system and has superimposed on it a veiling brightness source. The double neutral wedge reduces the central portion of the scene to contrast threshold by the dual action of the reduced brightness of the scene and the added brightness of the veiling source. The principal visual field is unaffected.

In operation the wedge is adjusted for full visibility of the scene and focussed. The wedge is now adjusted for full visibility of the veiling brightness source. This source is adjusted to match the brightness of the surround as viewed in the upper monocular system. The wedge is then rotated till the central portion is at threshold. Visibility is measured

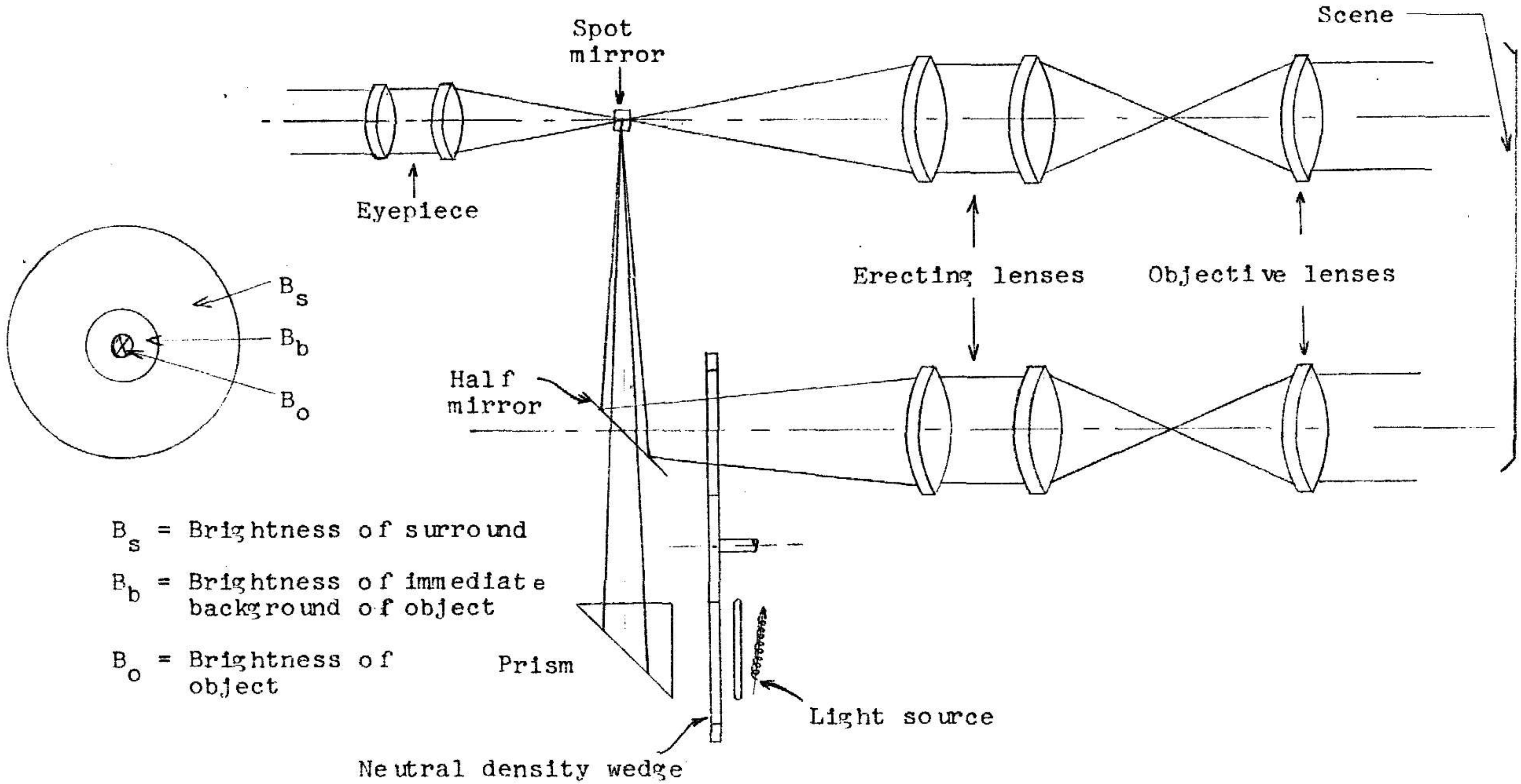


Figure 6. Diagrammatic illustration of a contrast threshold meter (Finch and Simmons, 1953)

in terms of the brightness of the background immediately surrounding the object, brightness of the object, transmittance of the wedge at the object and at the veiling source.

Finch and Simmons showed that the visibility could be expressed in terms of the transmittance of the wedge and they calibrated visibility to the transmission of the wedge.

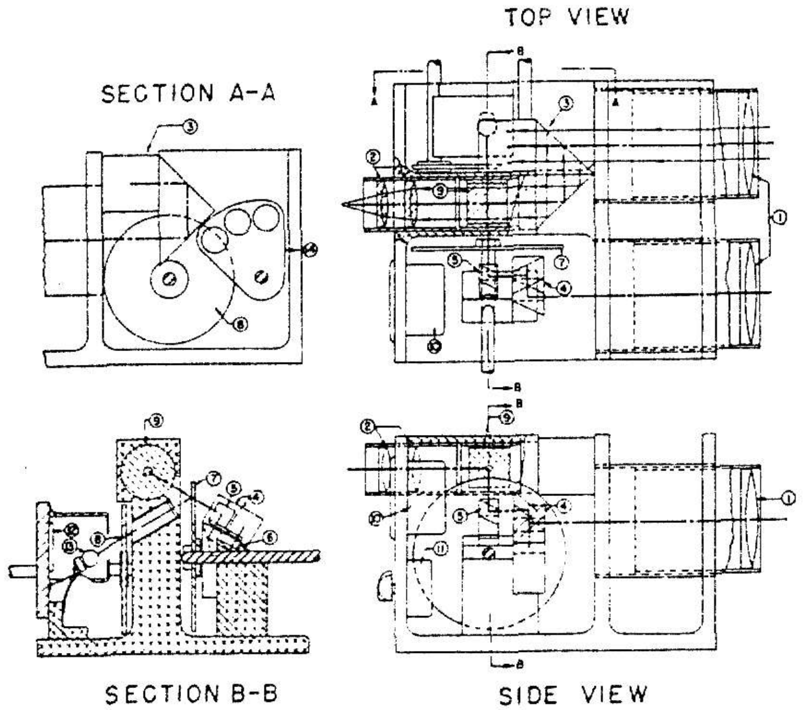
The U.C. Meter (Finch, 1957; Finch and Palmer, 1957)

Designed by Finch and Palmer and reported in 1957, this visibility meter operates on a principle similar to the Finch and Simmons meter. This device could also be used as a contrast-brightness threshold meter. Figure 7 illustrates this device. The U.C. Meter has an optical path having a central field area of approximately two degrees wherein the contrast can be varied by decreasing the field brightness and simultaneously adding an equal amount of veiling brightness.

The major problem with the Finch and Simmons meter was fulfilling the design requirements of the variable density neutral filter and an optical system exactly as much light flux to be added in the form of veiling glare as is subtracted from the central path. This design overcomes these problems by using a circular wedge made by depositing aluminium on a plane glass surface with a special evaporation technique so that the transmission varies linearly with angular position. The instrument was calibrated both as an average brightness meter and a visibility meter.

Blackwell's Visual Task Evaluator

The visual task evaluator is a type of visibility meter operating on the principle of contrast reduction to visibility threshold by means of a veiling luminance. There are four models of the VTE which were developed and all four operate on the same principle. The reduction to contrast is achieved without alteration to the task background.



1. Objective Lens—coated achromat 180 mm focal length.
2. Eyepiece Lens—coated achromat 122 mm focal length.
3. Binocular Prism 7 x 50.
4-6. Right Angle Prism.
7. Variable Transmittance Mirror (partial aluminum coating) — visibility index control.
8. Variable Density Wedge — background brightness control.
9. Object Mirror.
10. Ammeter — 100 milliamps.
11. Background Brightness Potentiometer.
12. Photocell-Round 1-inch dia., A-5.
13. Veiling Glare Source — 2.2-volt bulb.
14. Color Selector.

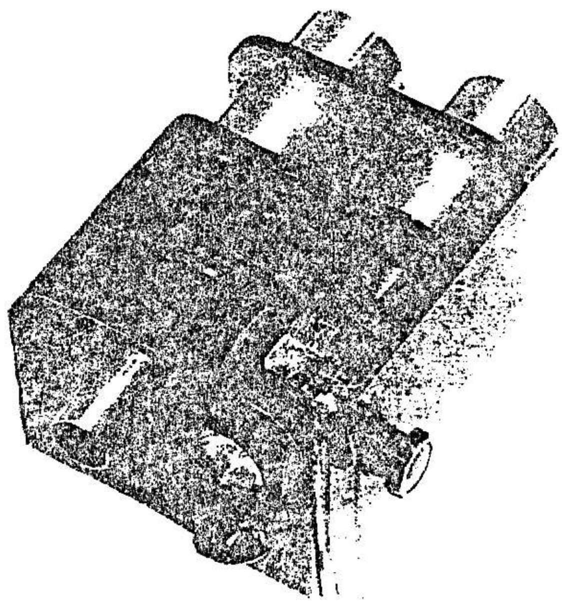


Figure 7. The U.C. meter (Finch, 1957)

Model 1. This model of the VTE is shown in Figure 8 and was used between 1957 and 1958 to evaluate interior illumination levels (Blackwell, 1959; 1970a). In operation, the first step was to bring the task under study to threshold by adjusting the intensity of the veiling luminance source to reduce contrast. The task under study is viewed through one of the two objective lenses and is seen in the inner circular field of the photometric comparator cube. The variable contrast wedge (sum of the reflectance and transmittance is a constant around the periphery) is then adjusted till the veiling brightness source, seen in an outer annulus around the inner circle of the photometric cube, matches the brightness of the task. The task can be defocussed to obviate the difficulty of matching a uniform veiling source with a non-uniform task brightness. Once the match is obtained the arrangement is left undisturbed and the removable mirror is inserted in the optical path thus obscuring the task. The mirror reflects a standard disc target "S" in place of the task. The standard target wedge is then adjusted until a match exists between the disc target and veiling source and the disc target is at threshold. Now the disc target and the target (task) have been adjusted for equivalence and the visibility is measured in terms of the physical contrast of the standard (4 minute) disc target which matches the object of interest.

Model 2. This instrument is a smaller and lighter version of model 1. There are a few modifications (Blackwell, 1970). The standard disc target was eliminated and so was the defocussing lens. A 10-power telescope was added to improve precision in matching small areas of background luminance to the annulus.

In this model (Figure 9) the operator views the external world through the telescopic system. This view fills the inner circular comparator cube and subtends an angle two degrees in diameter. An

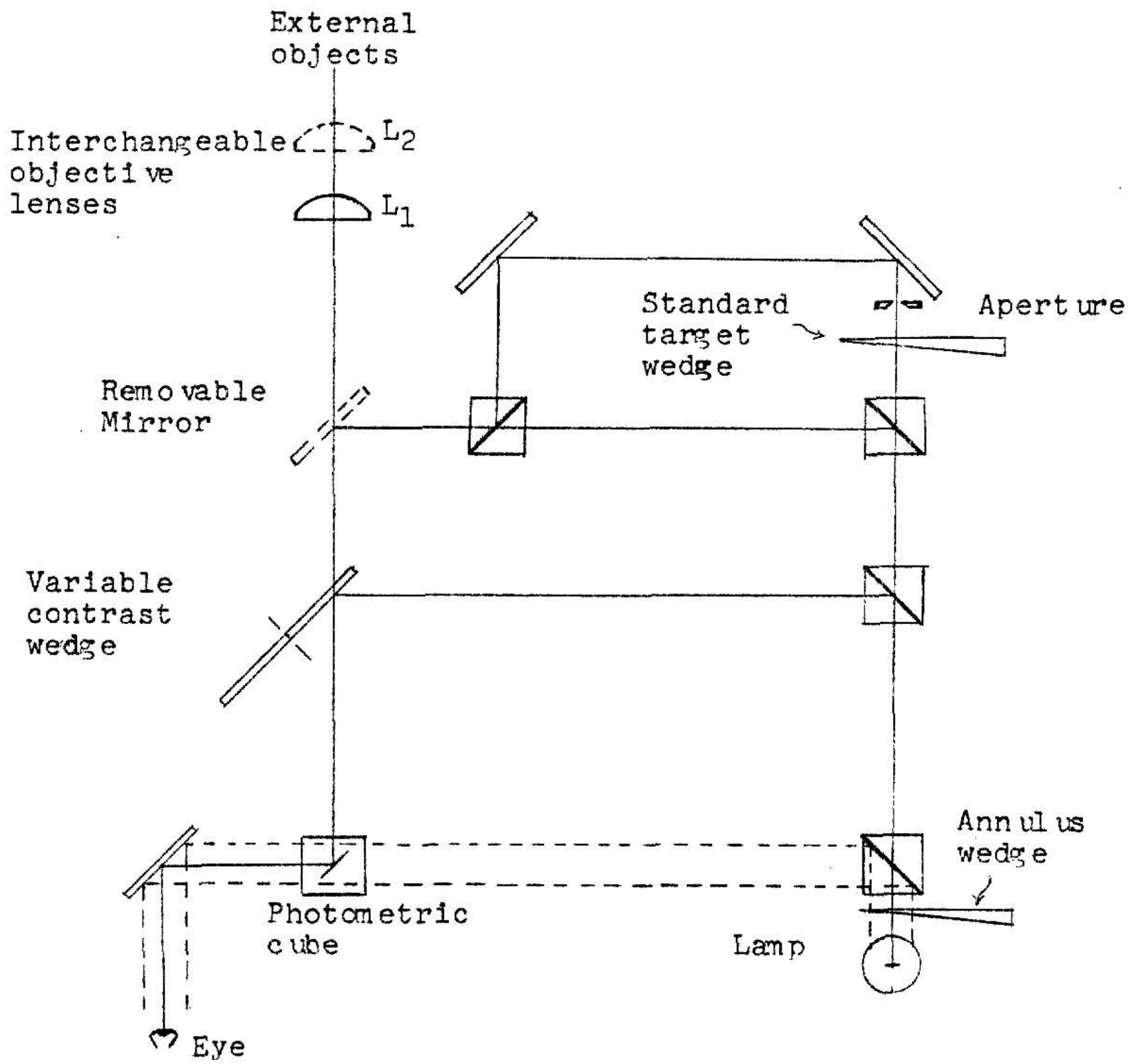


Figure 8. Schematic optical diagram of Blackwell's VTE, Model-1 (Blackwell, 1970).

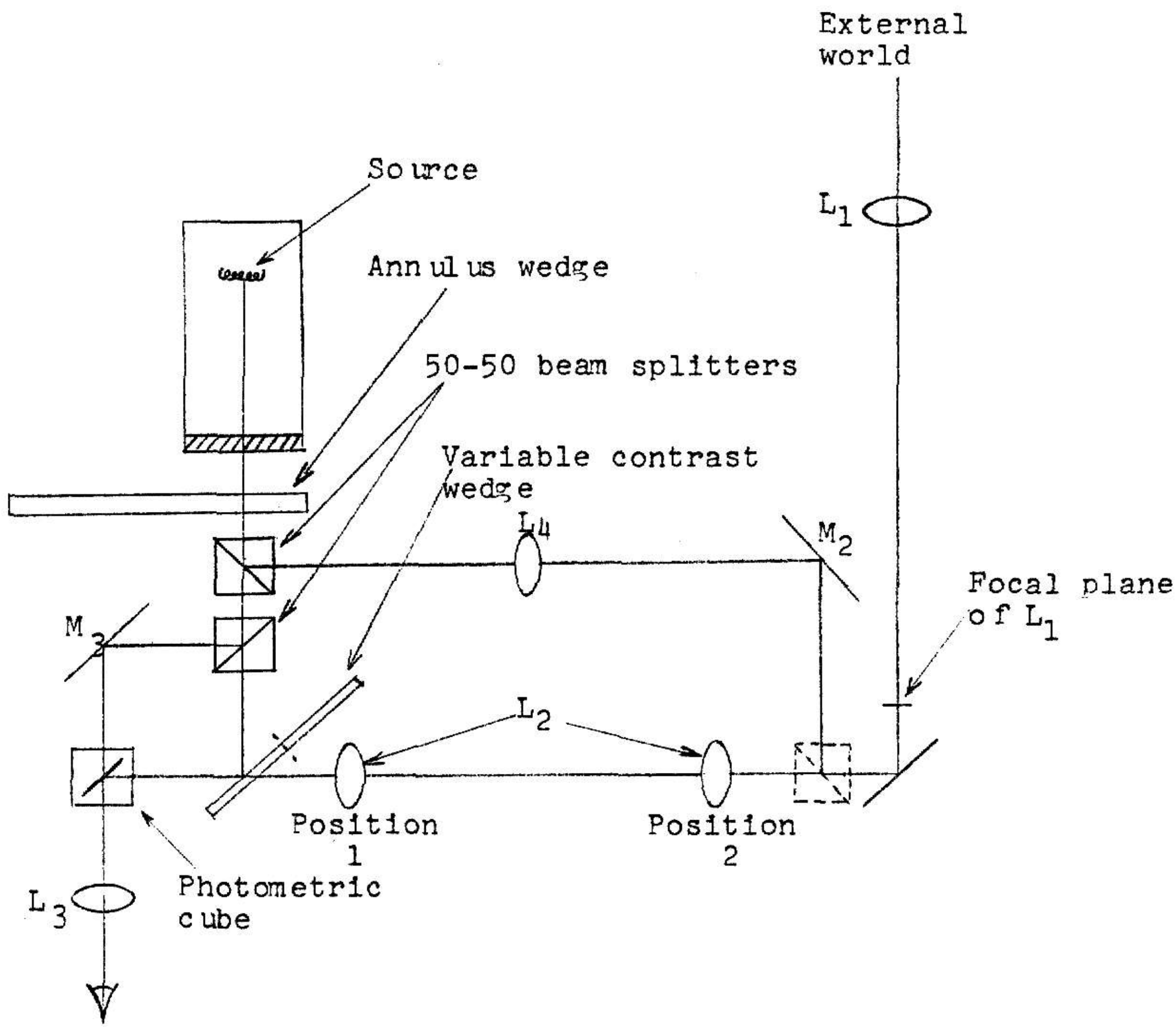


Figure 9. Schematic optical diagram of Blackwell's VTE, Model-2 (Blackwell, 1970).

internal lamp is used to supply veiling luminance.

Model 3. VTE model 3 was a total redesign of model 2 but adopting the same principles of operation. Figure 10 shows the optical features. Model 3 is about half the size of model 2 and is a portable model. It provides a wide continuous range of contrast rendition (Blackwell, 1970), and equivalence of luminance for all values of contrast rendition. Further, the instrument is fitted with an eight millimeter exit pupil so that the natural pupil of the eye of the VTE operator will be the limiting stop in the entire man-machine system. Figure 10 is a schematic optical diagram of Blackwell's VTE model-3.

Model 4. This model (Figure 11) was developed for situations in which cues received through binocular vision will have important effects upon task difficulty involving moving tasks or tasks which are large in angular size. The variable contrast wedge used in earlier models has been replaced by mechanically linked variable filters. The variable filters in the veiling luminance beams are directly driven and reduce task contrast in each of the two eyes continuously as the contrast control is rotated. The variable filters mounted directly over the eyes of the VTE operator alter the luminance of the combined beams produced by the focussed lights and the unfocussed light veil. These filters serve only to adjust the luminance of the combined beam so as to maintain a constant adaptation level. The measure of contrast rendition is obtained as before.

Eastman's Contrast Threshold Visibility Meter

Eastman's contrast threshold visibility meter is a portable visibility meter which uses the contrast reducing principle but does not require an internal light source (Eastman, 1968). Figure 12 is a schematic representation of the optical system of this instrument. The visual task is reduced to threshold by superimposing the task background or standard

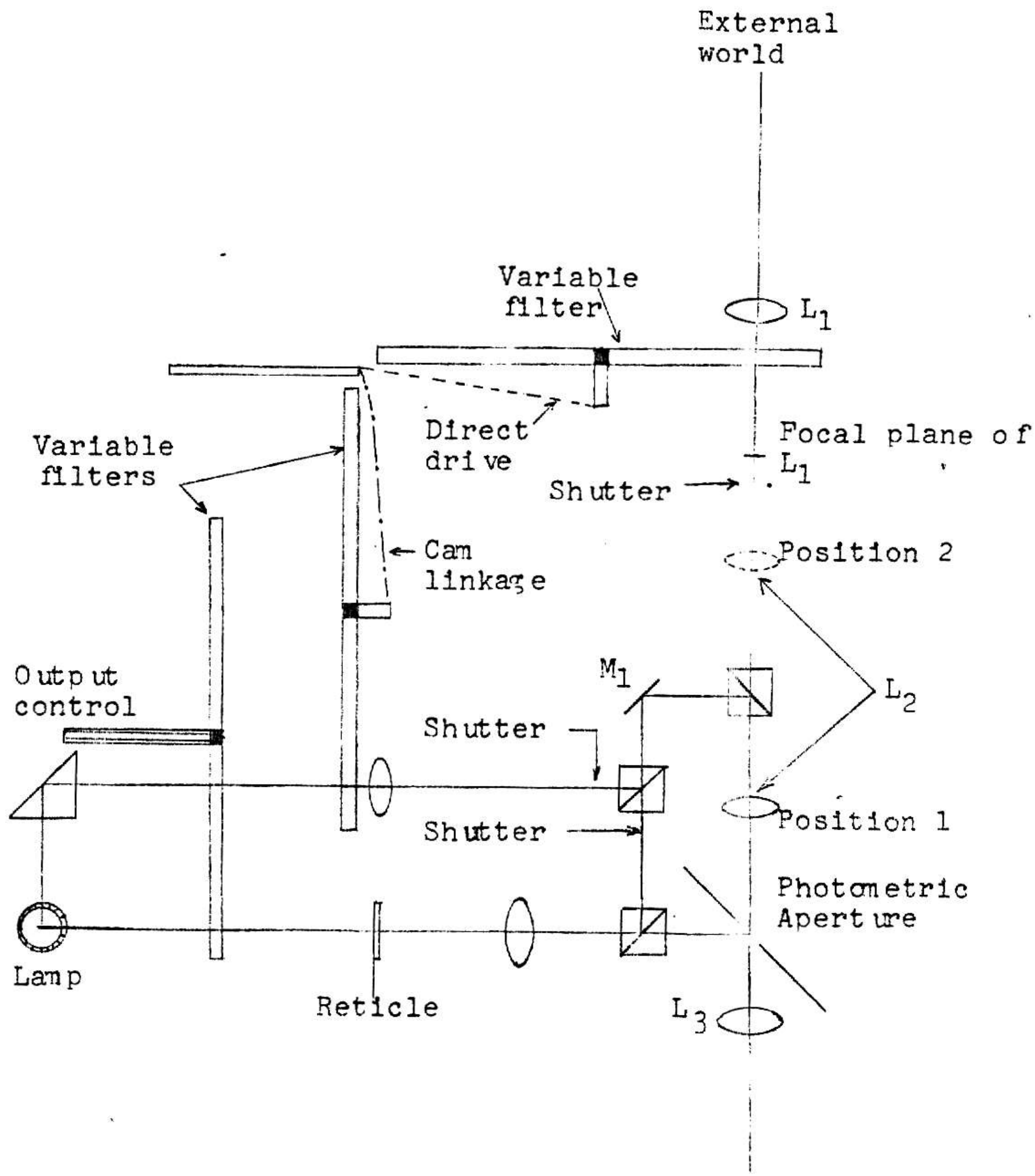


Figure 10. Schematic optical diagram of Blackwell's VTE, Model-3 (Blackwell, 1970).

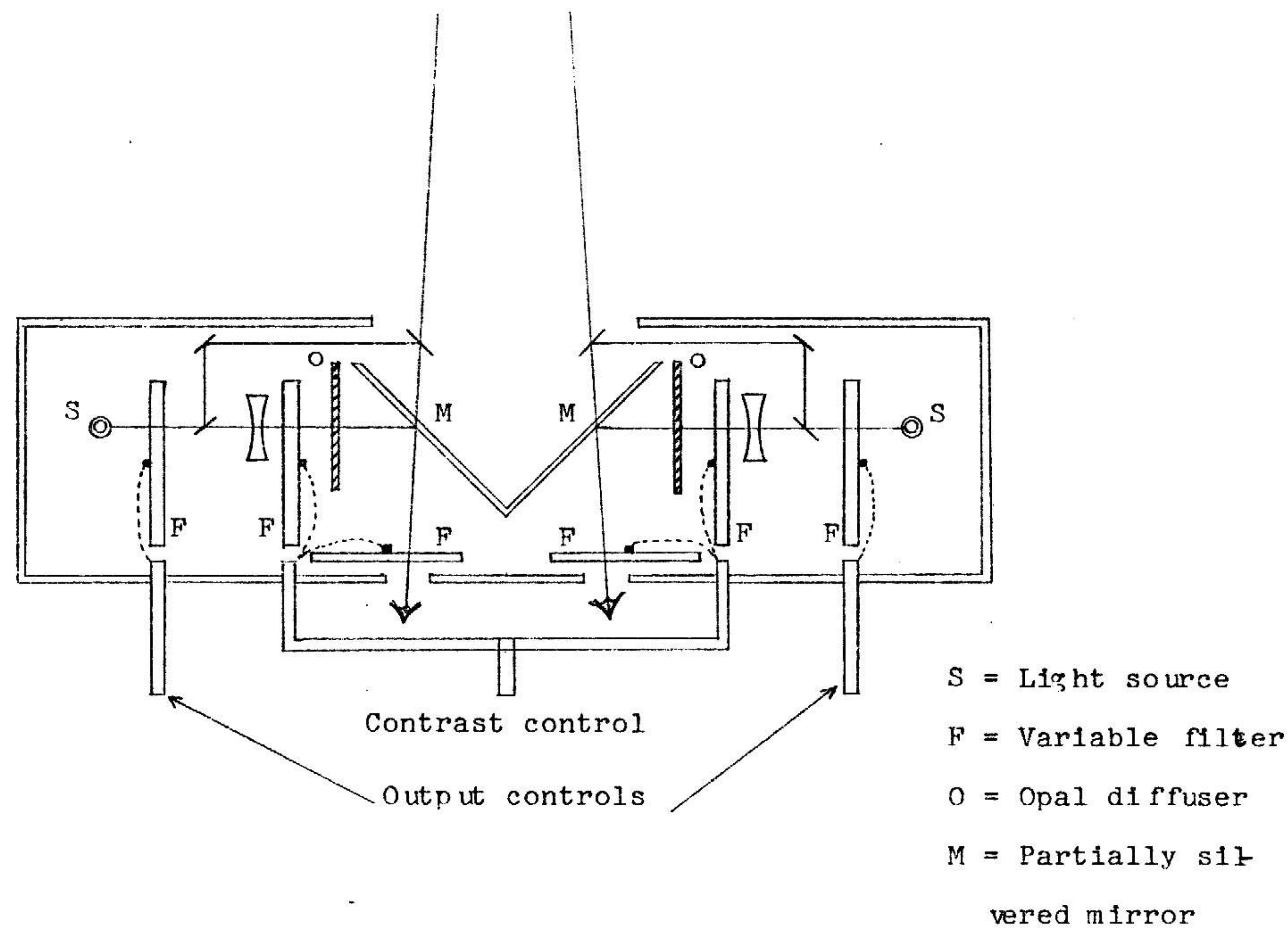
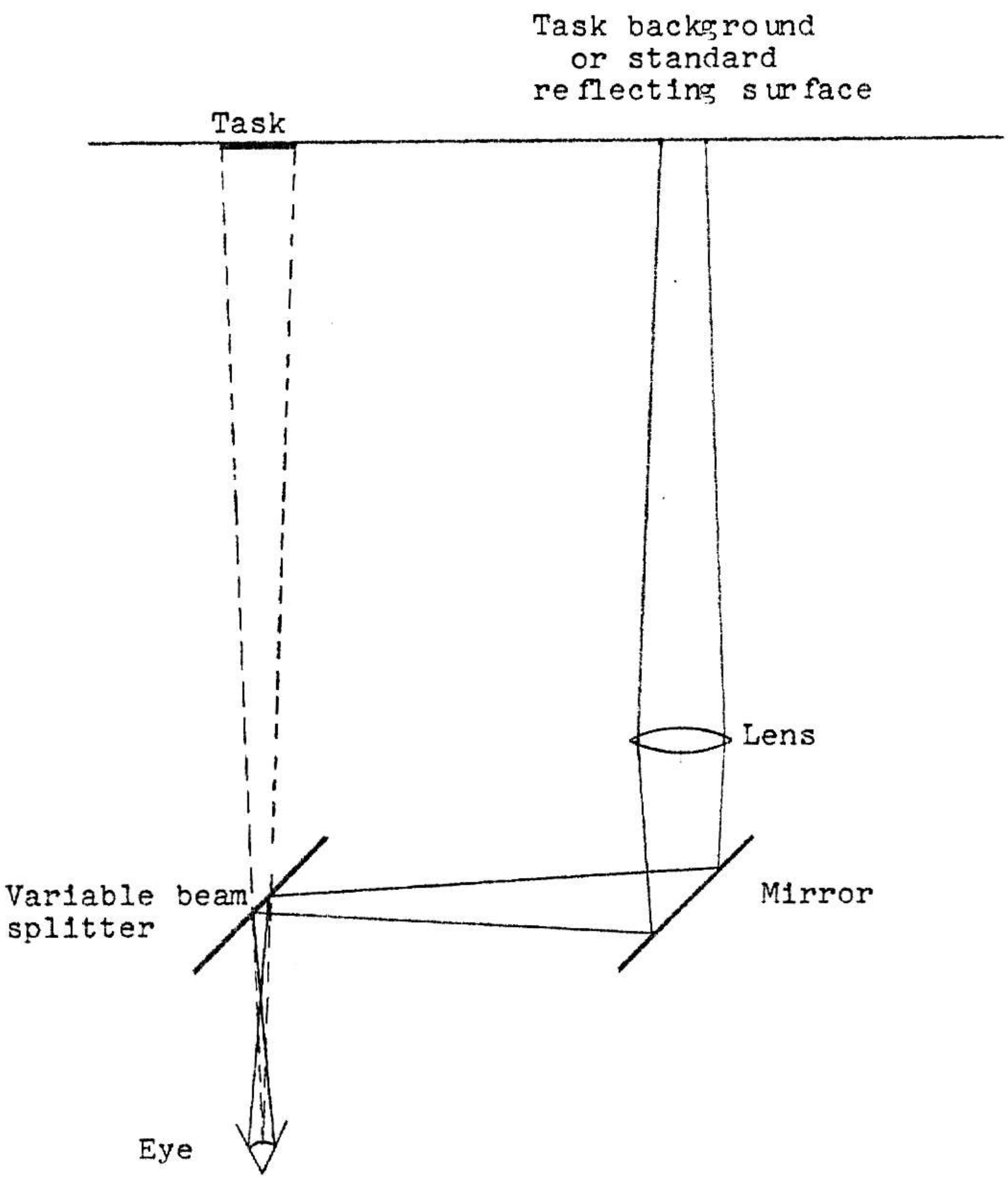


Figure 11. Schematic optical diagram of Blackwell's VTE, Model-4 (Blackwell, 1970).



<u>Figure 12. Schematic optical diagram of Eastman's visibility meter (Eastman, 1968).</u>

reflecting surface over the task by a system of lenses and mirrors. The threshold is reached by changing the transmittance and reflectance of the variable beam splitter till the task is reduced to threshold. Visibility is expressed in terms of the transmittance and reflectance of the beam splitter by calculating a contrast multiplier which is the ratio of the transmittance to the sum of the transmittance and reflectance.

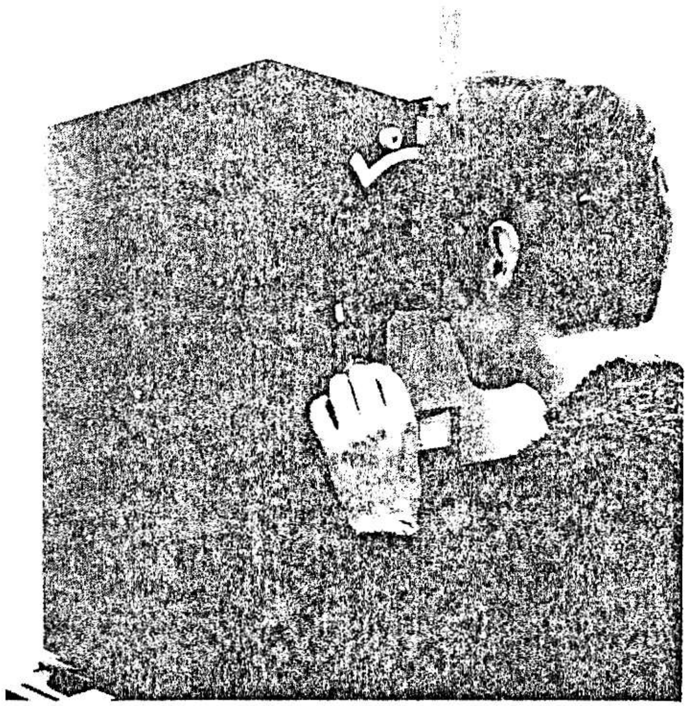
When this meter was designed, it was designed with the intention of using it in automobiles so that drivers would have an indication of night visibility on roadways.

Discernibility Meter (Clauer and Bates, 1970)

The "Discernibility Meter" was proposed by C.K. Clauer and A.D. Bates, the former a psychologist at International Business Machines Corporation and the latter an optical consultant at Cupertino, California. The device was reported in a laboratory report of IBM Corp. The discernibility meter was proposed so as to measure the quality of information (visual) produced by electronic imaging displays in a display to observer information transfer system. To measure the quality of suprathreshold information it is necessary to find out how much it is above observer's threshold.

The technique described provides for the recognition of the effect of observer distance and angle, ambient illumination, noise and such influences as **discrete** quantisization of information by means of dots or raster lines.

The instrument has been described as a calibrated contrast attenuator and is shown in Figure 13. The observer's action of rotating the front polarizer from vertical to horizontal has an effect of exchanging light from the display to light from the veiling source.



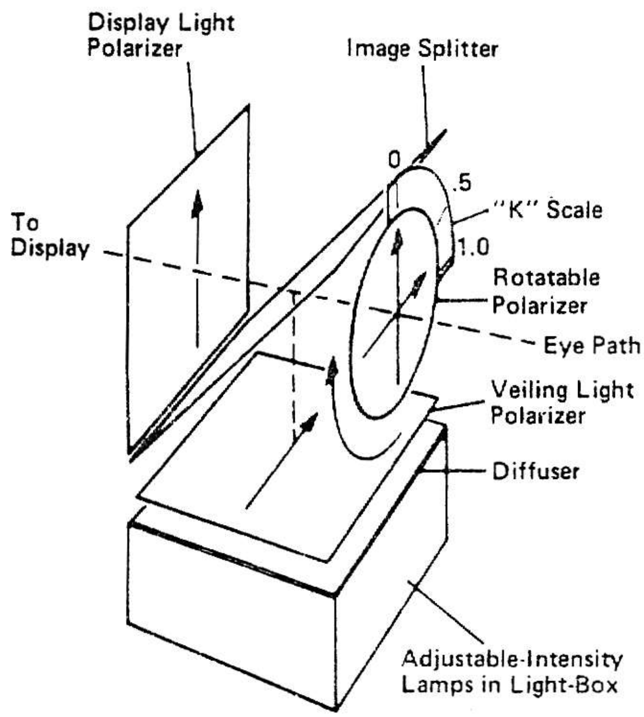


Figure 13. Discernibility meter (Clauer and Bates, 1970)

The "K" scale is calibrated as the sine squared of the angle from zero degrees. With an appropriate setting of the veiling luminance to match a reference luminance of the image, the K setting gives the contrast atten - uating factor for the image seen through the instrument. The observed image contrast is (1-K) times the contrast at zero setting, called object contrast. Discernibility is expressed as the negative logarithm to the base ten of (1-K).

Levy's EB Meter

The EB meter is made by EB instruments, Chippenham, Wiltshire, England. The visibility meter is of the contrast reducing type and is used for the measurement of relative visibility. Figure 14 illustrates the optical setup. Contrast reduction is achieved by the addition of veiling light to the image. The addition occurs at a twin rotating disc chopper of variable space to mark ratio. This arrangement allows the background luminance to remain sensibly constant over the whole range of adjustment. There is a refective shutter to control the task exposure time. This is also arranged to cause minimal luminance changes when it is operated. Use of the shutter improves repeatability of measurements.

The task is viewed along path A through the telescope formed by the objective and eyepiece. The graticule maintains visual focal accomodation when the task is invisible. Path A is clear when the clear part of the chopper is in front of the objective. Veiling light travels along path B and is reflected twice into the telescope. The first reflection is at the fixed mirror and the second is at the chopper. The chopper rotates fast enough so that the changes between reflecting and transmitting is not perceived through the telescope. All that is seen is the image of the task, reduced in contrast by an amount dependent on the ratio of the task light to veiling light entering the telescope. This ratio can be varied by varying the space to mark ratio of the chopper, using the chopper ratio control.

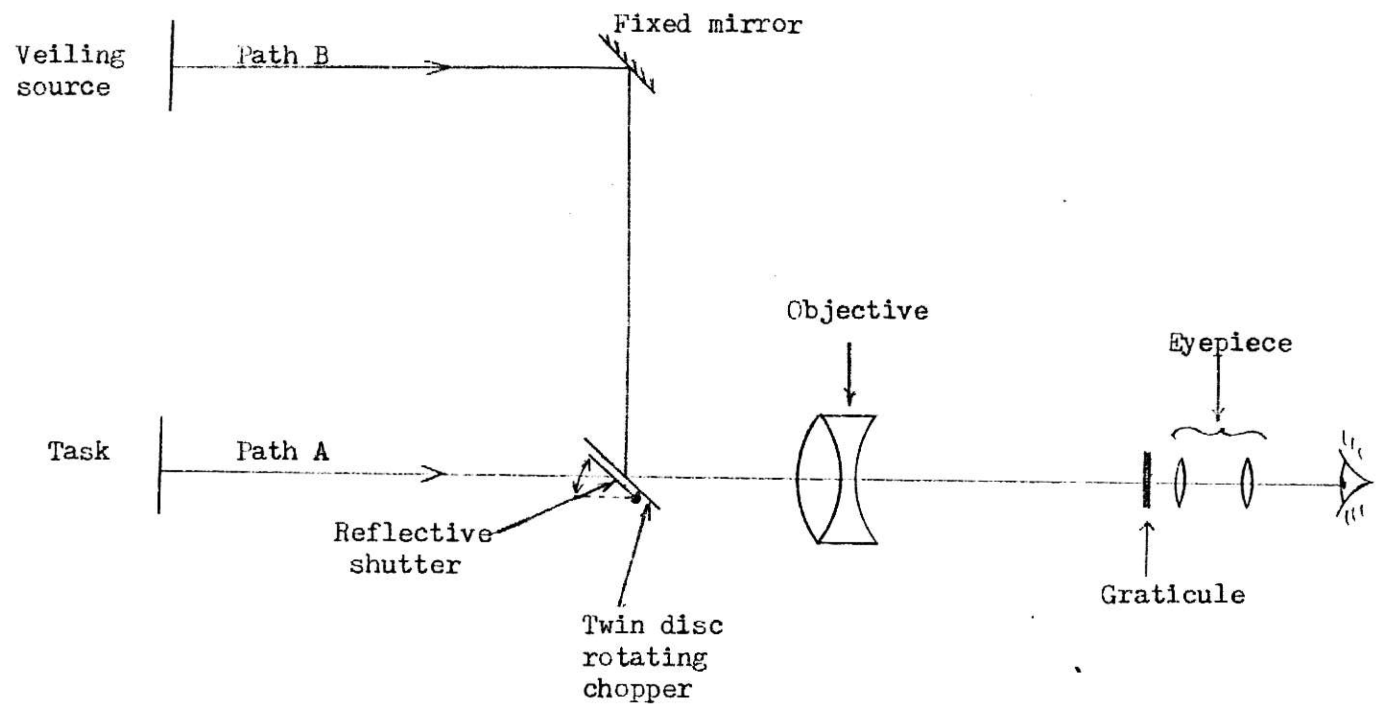


Figure 14. Optical system of the Levy's EB visibility meter.

The chopper consists of two optically worked glass discs. Each of these bears a half disc aluminium reflecting film. The chopper can be adjusted between transmitting for half its rotation, reflecting for the remaining half of its rotation and totally reflecting for the whole of its rotation.

The shutter when open is parallel to path A and displaced laterally from it, forming no part of the optical path. When closed it is parallel to the chopper disc thereby blocking off path A and reflecting the veiling light from path B. Thus the shutter cuts off task light while reflecting veiling light. In this way background luminance is maintained approximately constant and hence adaptation changes of the eye are minimized.

In use, the task is viewed through path A with the shutter kept open and path B closed with a cardboard strip. The task is brought into focus at a distance varying from 15-20 inches form the front of the device. Focussing is achieved by adjusting the eye lens ring (the smaller of the two rings) for best focus of the graticule and then bringing the task into focus by adjusting the outer, larger of the two, eyepiece focussing ring. The cardboard blanking strip is then transferred to the task window to make sure that none of the task detail is visible in the veiling source. Presence of task detail will introduce error and confusion in measurements. The cardboard strip is removed and the timer switched on. The chopper is connected to the main switch and works when the power switch is activiated. After these measurements the chopper ratio control is adjusted till the task is reduced to the threshold selected.

Visibility is calculated in terms of the task luminance, the veiling luminance, the transmittance and reflectance of the disc chopper and the transmittance and reflectance of the gradient filter (chopper ratio control). The expression used to calculate relative visibility is

$$R_v = \frac{(L_t - L_b)}{L_b} \quad \frac{(L_t f_1 T_t + V f_2 T_v + V\ f_1 T_{vt}) - (L_b f_1 T_t + V\ f_2 T_v + V\ f_1 T_{vt})}{(L_b f_1 T_t + V\ f_2 T_v + V\ f_1 T_{vt})}$$

where

L_t is the task luminance.

L_b is the background luminance.

f_1 is the fraction of task light transmitted by the chopper.

f_2 is the fraction of task light reflected by the chopper.

V is the veiling source luminance.

T_t is the transmittance of the task path A.

T_v is the reflectance of the veiling path B.

T_{vt} is the spurious transmittance of the veiling light during the time the chopper is transmitting task light. This is due to the small amount of reflection from the otherwise clear parts of the chopper discs.

The equipment was calibrated by the manufacturer and the values of T_t, T_v and T_{vt} were found to be 0.57, 0.27 and 0.05 respectively.

If the task and background luminances are derived from the same surface as is often the case then the expression for relative visibility reduces to

$$R_v = \frac{f_1(T_t + T_{vt}) + f_2 T_v}{f_1 T_t} \quad .$$

Substituting the values for T_v, T_t and T_{vt} the relative visibility was calculated by using

$$R_v = \frac{0.62\ f_1 + 0.27\ f_2}{0.57\ f_1}$$

where f_1 and f_2 covary so that $f_1 + f_2 = 1$.

Table 2 summarizes the visibility meters, their inventors and the principles of operation.

Pupillary Response Visibility Meter

There is an increasing activity in the area of standards to cover human factors aspects of equipment design and use, a common one being to specify certain physical parameters in an attempt to provide a perceptible display or control nomenclature.

The lack of a convenient device to measure quality of information displays led to the development of a pupillary response visibility meter employing pupillary dynamics to measure task visibility. The instrument was designed by Bruce Rupp and Calvin Clauer at the IBM corporation and modified and built at the Kansas State University, Manhattan, Kansas.

The pupillary response visibility meter is a contrast reducing visibility meter designed to measure quality of presentation of contemporary displays with inexpensive instrumentation.

Theory. The principle of operation of a simple contrast reducing visibility meter is not very complicated (Figure 15). A veiling luminance is set to match the task luminance. A variable beam splitter is then used to adjust the brightness of the lights from the task luminance, L, and veiling source, V, until the details of the task are just visible. The visibility of the task (display in this case) may be calaculated and stated in terms of the number of times it is above threshold. The measurement will allow one to place a figure of merit on the display configuration.

One reason why this type of equipment was neglected was due to the difficulty of establishing an equivalent luminance level to be used as a reference point and to establish the maximum veiling luminance level for a complex visual field.

Table 2

Summary of Visibility Meters: Inventor, Year and Principle of Operation

Inventor	Year	Principle of Operation	Remarks
Jones, L.A.	1918	Contrast reduction between veiling source and background.	Used in WW1 to measure adequateness of camouflage of ships at sea.
Bennett, M.G.	1931	Total obscuration of the object by means of a system of lenses.	
Luckiesh, M. and Moss, F.K.	1935	Contrast reduction between object of regard and its background.	One of the most researched and widely used instruments.
Bouma and Host	1936	Contrast reduction between object of regard and its background.	First instrument to have been designed for street and highway lighting use.
Duckler	1939	Contrast reduction between object of regard and its background.	This instrument is a brightness difference threshold meter.
Finch, D.M. and Simmons, A.E.	1940	Comparison of object to standard.	This instrument was designed to measure the visibility of road surfaces.
Horton	1957	Brightness difference threshold principle	This device is similar to the instrument devised by Bouma and Host.
Cottrell, C.L.	1951	Contrast reduction between object of regard and its background.	Designed for roadway lighting use.

Table 2 (contd.)

Summary of Visibility Meters: Inventor, Year and Principle of Operation

Inventor	Year	Principle of Operation	Remarks
Finch, D.M. and Simmons A.E.	1953	Contrast reduction between object of regard and its background	Designed for roadway lighting use.
Finch, D.M. and Palmer, J.D.	1957	Contrast reduction between object of regard and its background.	This instrument is similar to the Finch and Simmons meter.
Blackwell, H.R.	1957 - 70	Contrast reduction between object of regard and its background.	Called Visual Task Evaluators, four models were developed over a period of fourteen years. These instruments were the most researched.
Eastman, A.A.	1968	Contrast reduction between object of regard and its background.	This instrument was designed for use in automobiles to measure night visibility on highways.
Clauer, C.K. and Bates, A.D.	1970	Contrast attenuation between object of regard and its background.	This device was a proposal.
Levy, A	1971	Contrast reduction between object of regard and its background.	Probably the first instrument to be made on a commercial basis.

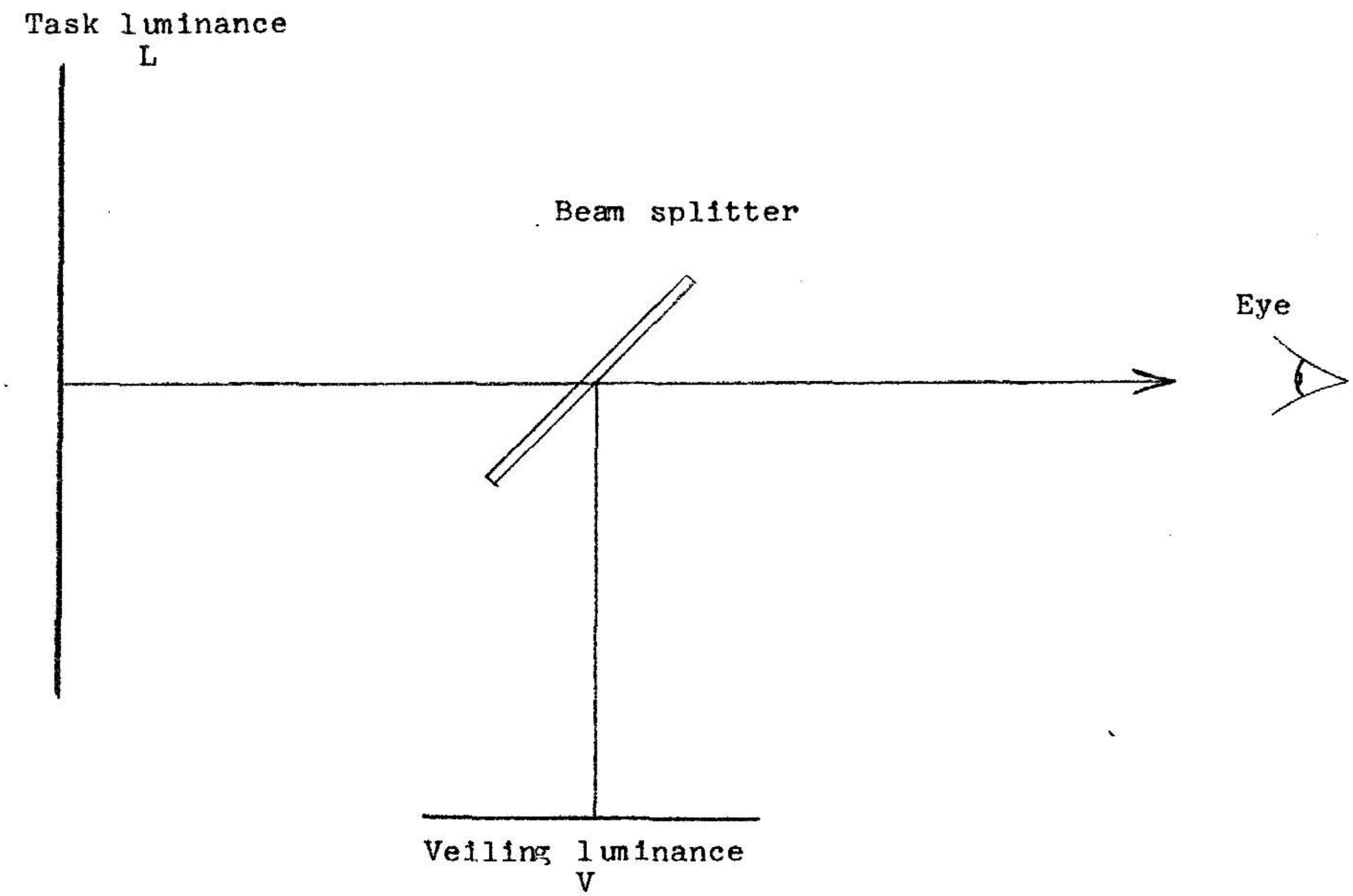


Figure 15. Illustration of the principle of a contrast reducing threshold meter.

A regular photometer would be useless as it would not spatially integrate the various luminances within the visual field the same way the eye would. This fact led to the conclusion that the eye could be used as a measure of overall luminance levels. Pupil size varies with luminance (Kaufman, 1972) and hence a measure of pupil size would be a measure of luminance.

The pupils of the eye have a consensual luminance reflex. The size of the pupils in both of the observers eyes will be the same whether one eye receives more or less light than the other; the eye receiving more light will dominate and control pupil size of both eyes. This eye will be referred to as the dominant eye.

In operation pupil size may first be determined when viewing the display, a reference luminance may then be adjusted to produce the same pupillary response as the display. Filters may be used to restrict the luminance to a range in which the pupil is most active. Pupil size may easily be measured by presenting two parallel points of columnated light to the eye. When the separation of these points is larger than the pupil diameter they will be seen as two different points. When the separation is less than or equal to the pupil diameter the points will be, due to the eye's refractive power, seen as a single point. This will be true only if the eye is acommodated at infinity. The separation of the parallel beams when they just begin to merge may be used as a measure of pupil diameter. Figure 16 illustrates the instrument proposed by Clauer and Rupp.

As the measure of visibility depends on contrast reduction measured by the response of the pupil, the device was called a "Pupillary Response Visibility Meter", abbreviated PRVM.

Theory of operation of the PRVM. A given visual task has some

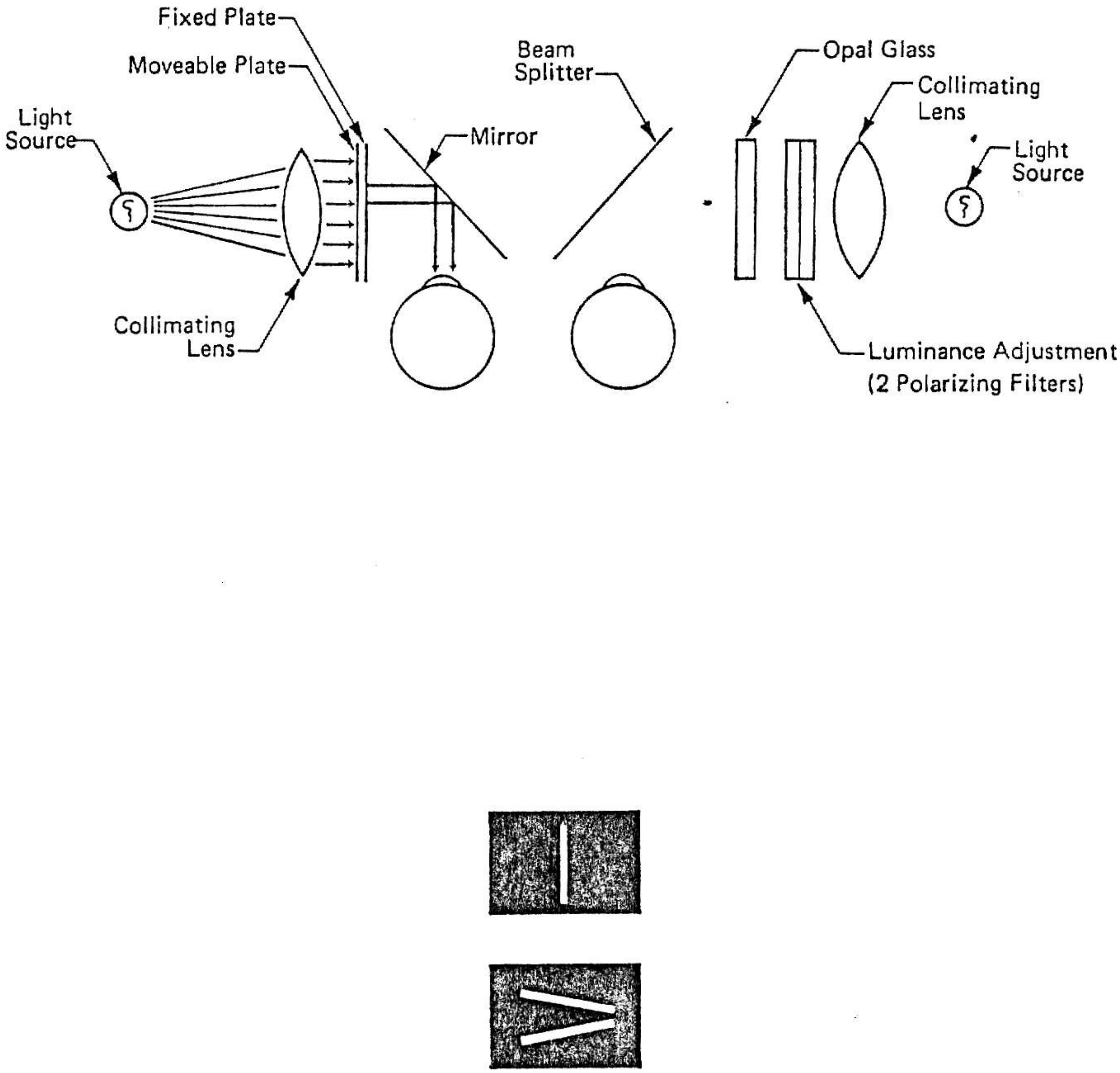


Figure 16. Schematic diagram of the proposed pupillary response visibility meter.

visibility which places it over the visibility threshold. This suprathreshold luminance of the task may be measured by having the operator view the task directly with the right eye. By virtue of the consensual pupillary response, if the luminance of the right eye is greater than that of the left eye, pupil diameter of both eyes will be governed by the dominant eye. The diameter of the pupil of the left eye can be measured. This measurement is called the task luminance diameter, or "TLD".

A uniform luminance is then set using an internal light source so as to produce an equivalent pupillary response to that produced by the suprathreshold task. To accomplish this the task is occluded and a uniform light source is directed into the right eye. This is the equivalent source. The luminance of this source is adjusted till an equivalent pupillary response to that obtained by the task is obtained. To get a uniform light source a ground glass plate was used; the plate diffuses light and produces a field of uniform luminance. The light is varied by means of a variable polarizer whose angle can be used to measure the transmitted luminance. The equivalent amount of luminance is measured and is called equivalent luminance or "EL".

The task is once again brought into view and the internal veiling source is superimposed on the task and adjusted till selected details of the task are reduced to threshold. The percentage of equivalent luminance is a measure of the degree to which the visual task is above threshold, or the percentage of equivalent luminance at that point is the "task visibility" or TV.

In the proposed design the pupil diameter measurements would have been made by measuring the deviations of the two plates (Figure 16) till the two spots seen at the left eye were coincident. Diffusion was achieved with opal glass.

Reviewing the proposed design by Clauer and Rupp of IBM, Corwin A. Bennett and Alvin Compaan of Kansas State University suggested a few modifications. The first was the elimination of the light source and optical system used to measure pupil diameter. Instead, a pupil spot display would be used. The pupil spot display consists of two tips of fibre optics which receive their illumination from the light source used to obtain equivalent and veiling luminances. In other words a single light source would serve both purposes. The tip positions of the fibre optics are adjustable by a control and rest against a groundglass plate. The reason for this modification was because the collimated approach to measure pupil size may be ultra sensitive to eye position and dependent upon having acommodation at infinity. In addition to this, tests have shown that the spots would get larger or smaller depending on the pupil size. The point of tangency of the spots was used as the criterion for establishing pupil diameter. The idea of using one light source would lead to considerable savings in cost and size. Hence the idea of using a fibre optic package seemed more feasible than the original design.

Figure 17 is a schematic drawing of the pupillary response visibility meter. The device consists of a light source "A" cooled by a fan "B". The luminance from the source passes through a focus control "C", through a pair of polarizers "F", through an opal glass diffusing plate "J" and is superimposed on the task or viewed with the right eye after being reflected by a partial beam splitter "K".

A pair of fibre optics "D" connect "C" to a pupil spot display "M". One tip is fixed while the other is movable by means of a pupil diameter control "N". The image display is viewed through an eyeport "O" and through an opening "E" providing an approximate visual angle of 5-10 degrees. The polarizers can be adjusted by a control "G" for zero luminance (to determine task luminance diameter) or increasing masking luminance (to determine equivalent luminance). "H" is an occluding plate to prevent stray

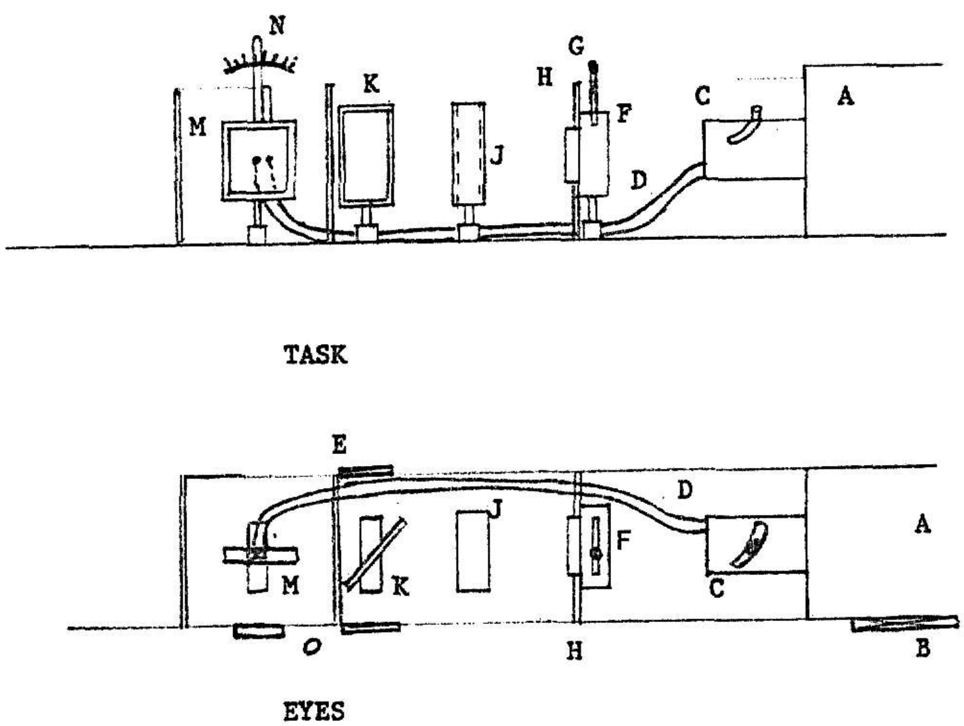


Figure 17. A diagrammatic sketch of the pupillary response visibility meter.

light form reaching the eye.

The entire setup is built into a box with the controls "G", "N" and "C" projecting above the top for easy handling and accessibility.

Operation of the PRVM

Preliminanry settings.

1. Position the PRVM so that "E" is open and control "G" is adjusted for zero transmittance of the polarizers. The scene to be evaluated is seen through "O" and "E".
2. Plug in light source "A" and fan "B".

Determinantion of task luminance diameter.

1. Turn transformer on.
2. Adjust position of the PRVM until the two spots on the pupil spot display are seen superimposed on the scene.
3 Adjust the control "N" until the two spots are tangent. Note the reading. If the reading is less than 4 mm, replace the beam splitter "K" with one having a higher reflectance and repeat this step.

Determine equivalent luminance.

1. Close "E" to occlude task.
2. Adjust "G" so that the defocussed light from "A" (defocussing is achieved by adjusting "C") produces tangency of the two spots or an identical pupillary response as produced by the task.
3. When a match is obtained, the equivalent luminance is measured by angle "G". This angle is called "ϕ_E".

Determine threshold visibility.

1. Open "E" and view the task. Adjust "G" until the luminance from source "A" makes selected details of the task just disappear or not visible or, in other words, reduces the task to threshold.
2. Record the angle made by "G" and call this"ϕ_T".
3. By means of a chart (remote) determine the values sine$^2(\phi_E)$

and $\text{sine}^2(\phi_T)$. The ratio $\text{sine}^2(\phi_T)/\text{sine}^2(\phi_E)$ is the visibility of the task or "V_{pr}".

PROBLEM

The aim of this research was to test the designed pupillary response visibility meter in order to determine whether the device worked in principle. The PRVM would be used to measure visibility of cathode ray tubes in order to determine its effectiveness in its intended application.

1. Pupillary Calibration

The visibility meter would be calibrated so that the fiber optic bundle could be used to measure the pupil diameter and, therefore, the luminance as pupil size would be calibrated with lumiance.

2. General Tests

To determine whether the PRVM worked in principle, observers would use the instrument to measure visibility of targets of different resolutions. It was expected that the settings would be good and that individual differences would not play an important role in making the use of the instrument restricted. The observers would also use the EB meter to make the same settings and the two instruments were to be pared. A high degree of compatibility was expected.

3. Visual Display Terminal Tests

The same observers would use the PRVM and the EB meter to measure visibility of dispalys produced by cathode ray tubes. This will be the final phase of testing conducted to test the applicability of the instrument.

METHOD

This research consists of three sections. Calibration of the pupil spot display with pupil diameter (to measure luminance), tests to determine whether the PRVM works in function and operation called general tests and finally, tests to determine whether the PRVM works in application. The first two phases are laboratory simulated while the third was performed in the computing laboratory of the department of Industrial Engineering.

1. Pupillary Calibration

The measurement of visibility involves pupillary dynamics and utilizes information on pupillary response to intensity of illumination in order to measure luminance levels. An experiment was performed to calibrate pupil diameter with luminance levels.

Apparatus. The apparatus used to calibrate pupil diameter with luminance was a model 1992S Eye View Monitor and TV Pupillometer system with Free Head Movement.

The series 1900 Eye View Monitor is a complete system for measuring a subject's eye position and pupil diameter while allowing some head movement. Figure 18 shows the system which consists of a CCTV camera viewing the subject's eye which is illuminated by an invisible infrared illuminator. The resulting picture of the eye is displayed on a 5" TV screen.

A special recognition circuit detects the pupil and the corneal reflection from the video signal and separates them from those of the eyelids, eyelashes and other noise. This circuit allows operation for a broad range of subjects under varying conditions with minimum operator adjustments.

Appendix 1 gives the complete specifications of the eye view

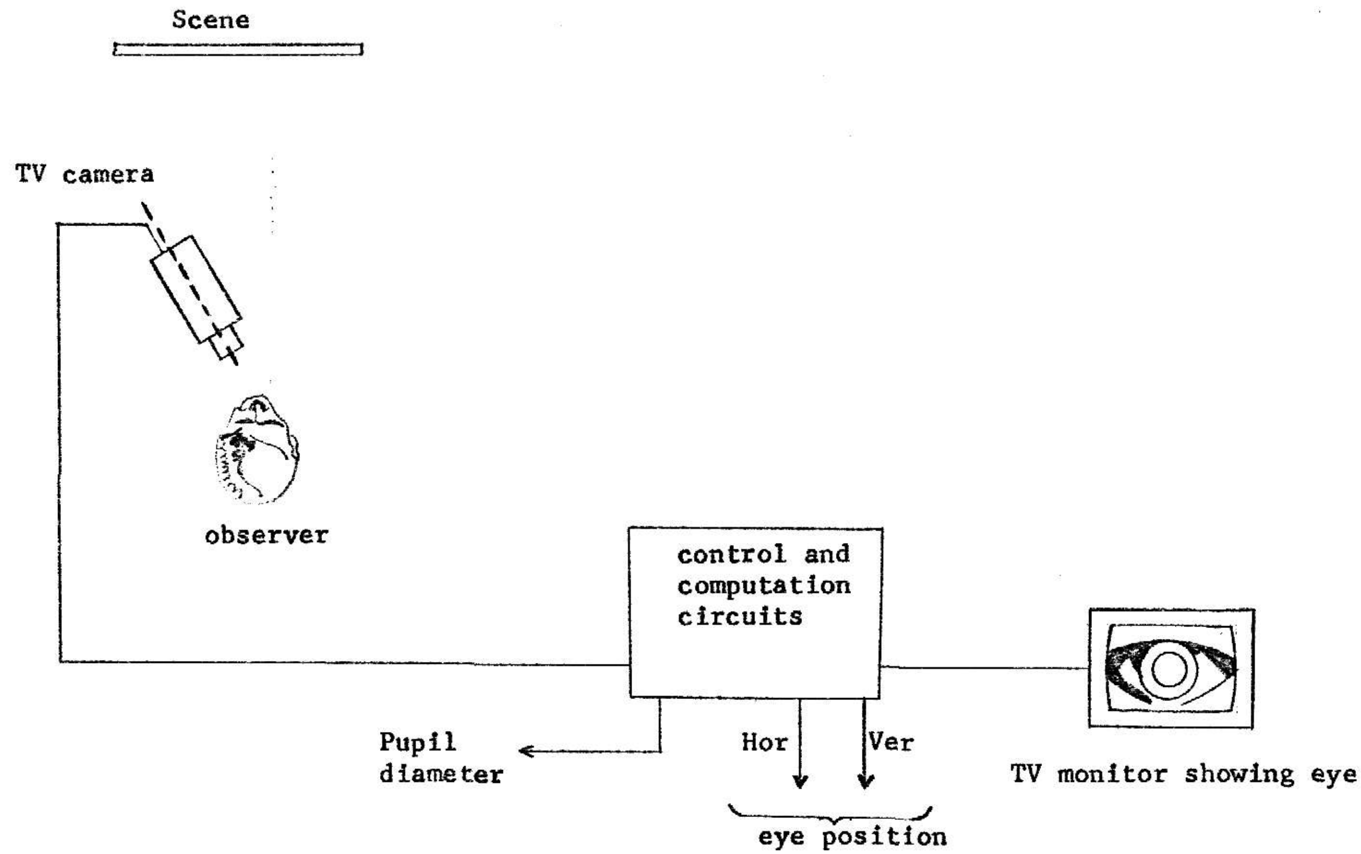


Figure 18. The eye view monitor system

monitor system.

The subjects were asked to place their heads on a face rest in front of the TV camera and look at a bar target kept at a distance of twenty inches from the eye. This distance was selected due to the limitations of the set up. A distance of fifteen inches would have been more suitable as this is the optimal distance while working in front of such a display.

The display itself was a USAF resolving bar target. This target consisted of groups of horizontal and vertical bars, each group made up of three bars seperated by a distance equal to their width. The groups varied in size and therefore in resolution. In this particular experiment the target played no special role in determining pupil size, only luminance, hence a bar target group of the largest resolution was chosen.

To simulate conditions during operation of the PRVM, an aperture 2" x 2" was cut out of cardboard and fixed onto the infrared source of the eye view monitor system. By doing this, it was ensured that the subjects eye would be adequately illuminated by the infrared source while at the same time seeing the bar target through the aperture in the cardboard.

Maximum object detectability occurs within the rod-free central fovea under conditions of high level (photopic) day time adaptation conditions, but at twilight (mesoptic) levels, detectability is practically uniform throughout the fovea, parafovea and peripheral retina (Duntley, et. al., 1964). The arrangement on the eye view monitor system ensured that light, reflected off of the target was uniform in the area of the central and peripheral retina and restricted to levels slightly below and above twilight conditions.

Figures 19, 20 and 21 show detais of the experimental set-up. Figure 19 is a front view of the set up (with the target removed) showing the aperture, the subject's position and the system arrangement. Figure 20 is a photograph of the set up as seen with the black cloth. Figure 21 is a rear view showing the complete set up without the black cloth that was used in order to prevent noise due to extraneous light sources.

A photometer was used to measure luminance and two light sources fitted with 120 V, 150 W, incandescent light sources were used to illuminate the target.

Experimental design. Twenty four subjects viewed the largest group of bars of a USAF resolving bar target with their right eye. The TV camera transmitted an image of this eye onto a 5" screen. The subjects looked at the target while the illumination was varied from 0.1ft-L luminance to 650ft-L in twelve steps. Table 3 lists the levels of luminance used. The range was restricted to the sensitive region of the pupil.

Procedure. Upon entering the laboratory the subjects were seated in front of a Titmus vision tester. They were read the following Instructions:

"In this experiment you will be requested to view a target through the opening in the cardboard while keeping your head on the face rest and under the black cover. The black cover is being used to shield out other sources of light. The target consists of a group of three parallel black bars seperated by a distance equal to their width. While you view the target the luminance will be varied and your pupil size will be measured using the eye view monitor system. There will be thirteen levels of luminance and each measurement will take approxi-

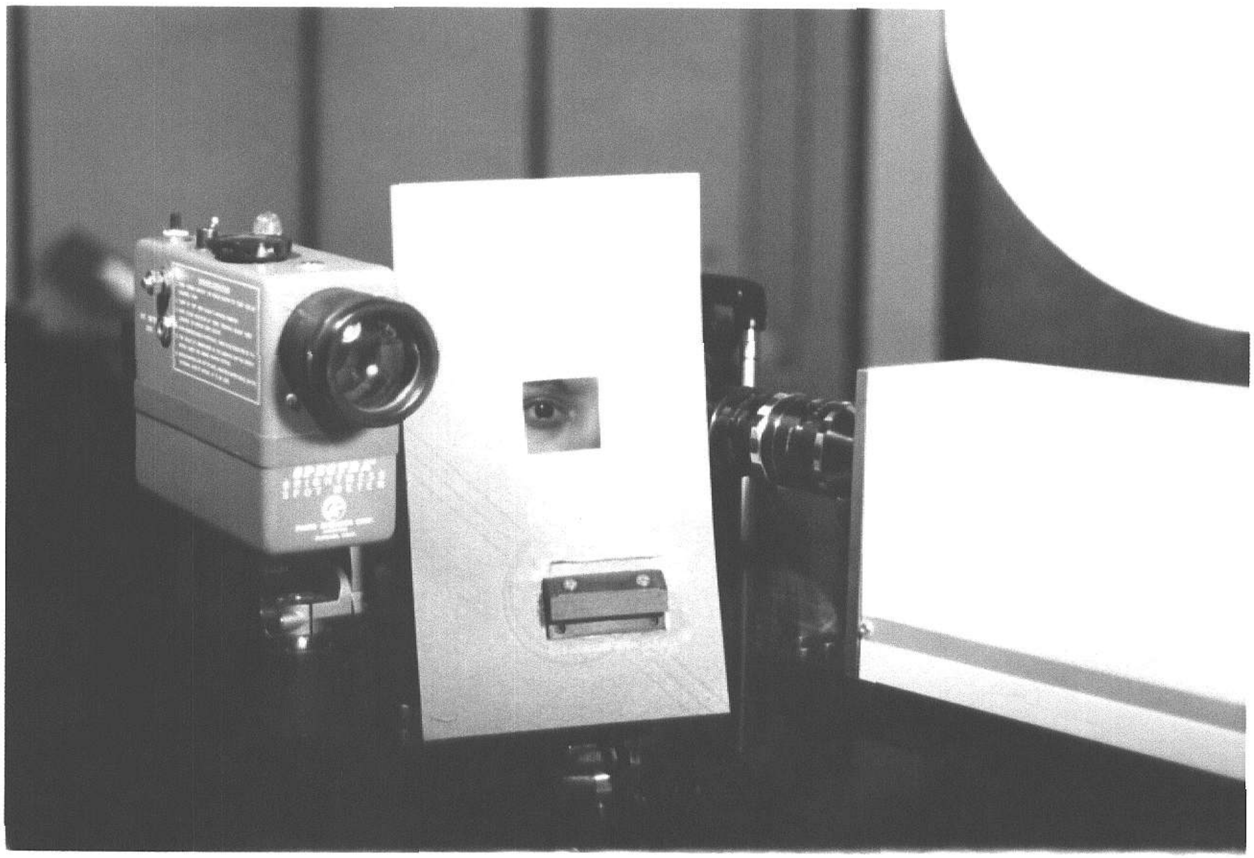


Figure 19. Experimental setup to determine pupil diameter under different luminances. View shows subject, 2"x2" aperture, TV camera and photometer.

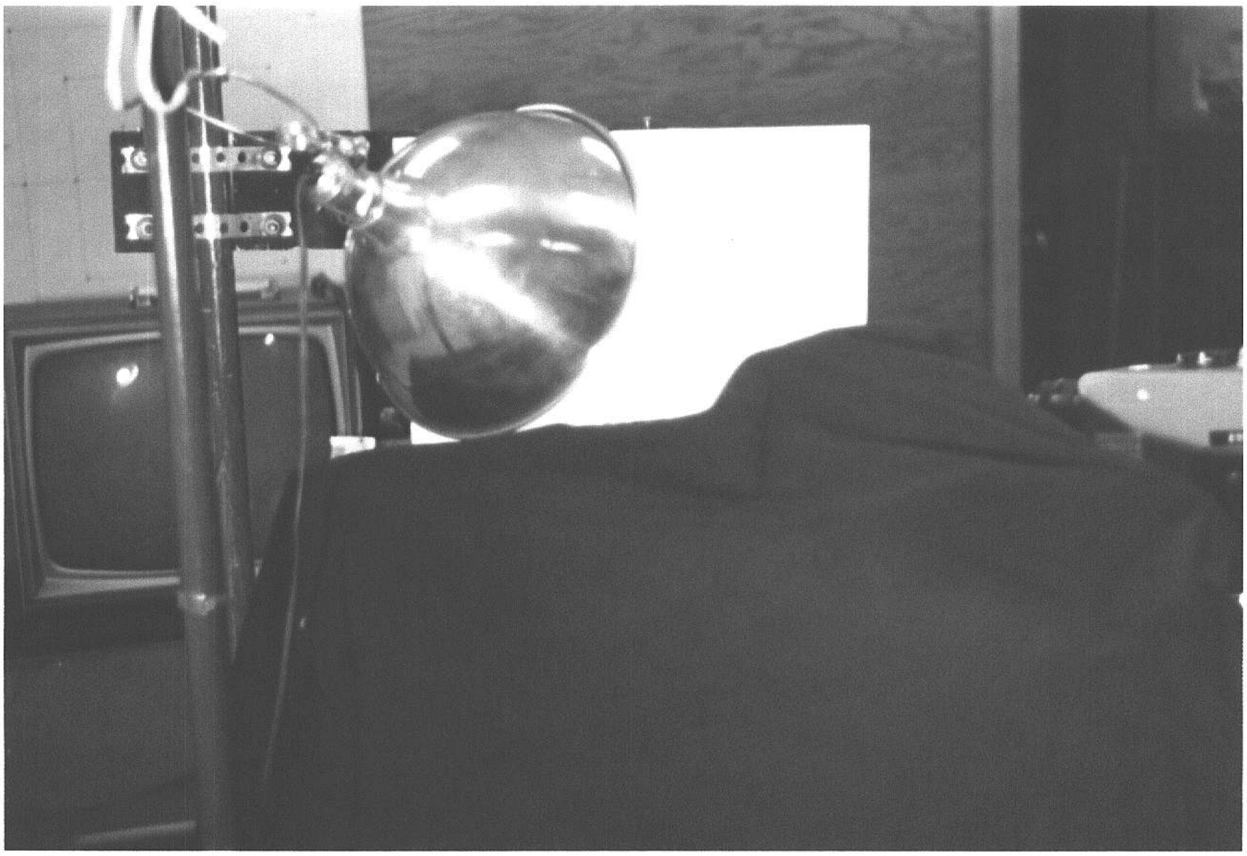


Figure 20. Experimental setup to measure pupil diameter under different luminances. View shows the source of illumination, the task background and the remaining part of the experimental setup under the black cloth.

Figure 21. The entire experimental setup to measure pupil diameter.

Table 3

Luminance Levels Used to Measure Pupil Diameters

Experimental sequence	Luminance levels in foot-lamberts
1	0.1
2	1.0
3	10.0
4	25.0
5	50.0
6	100.0
7	150.0
8	200.0
9	300.0
10	400.0
11	500.0
12	600.0
13	650.0

mately one minute.

There should be no discomfort or risk in this procedure. However, if you feel you do not want to participate feel free to leave. Naturally, I prefer that you complete the experiment so that I can get all the required data."

Subjects who consented signed the informed consent which read, "Having read the instructions and having been explained the procedures in the experiment, I hereby freely consent to be a subject in the research entitled 'Pupillary Response Visibility meter: function, operation and application'." Demographic and other data were collected from each subject. Table 4 lists these data.

The subjects eyes were then tested using the Titmus Vision Tester and the subjects ability to perform the task of using the PRVM was evaluated based on the results of the Titmus tester. The final decision is included in Table 4 under the heading "ability to perform".

For those subjects who were able to perform, their pupil diameters were measured using the experimental setup with the 1992S eye view monitor system.

<u>Subjects.</u> Twenty four subjects were used in this procedure. Nineteen were male and five female. Sixteen wore some form of visual aids such as glasses. Their ages ranged from 20 years to 51 years and the subjects were chosen on a whoever was available basis from the student population of the Kansas State University, Manhattan, KS.

<u>Results of the Titmus tester</u>. Of the twenty four subjects tested, only one was not suitable to be a person to use the PRVM. The reason was that the right eye of the subject was blind. Another extreme case was a subject with 20/40 vision but with severe phorias. All the other twenty two observers exhibited slight phorias but this was considered within acceptable limits for a task of this nature. Four subjects had

Table 4

Demographic and Other Data for Twenty Four subjects

Subject Number	Age (years)	Sex (M/F)	Visual aids worn (Yes/No)	Number of hours of close work done during the past week	Results of the Titmus vision tester in terms of ability to perform a visual task (Yes/No)
1	24	M	No	40	Yes
2	25	M	Yes	25	Yes
3	21	M	Yes	35	Yes
4	33	M	Yes	30	Yes
5	28	F	Yes	10	Yes
6	26	M	No	55	Yes
7	45	M	Yes	30	Yes
8	24	M	Yes	35	Yes
9	27	M	No	35	Yes
10	25	M	Yes	20	Yes
11	21	M	Yes	15	Yes
12	23	M	No	30	Yes
13	21	F	Yes	20	Yes
14	28	M	No	40	Yes

Table 4 contd..

Demographic and Other Data for Twenty Four Subjects

Subject Number	Age (years)	Sex (M/F)	Visual aids worn (Yes/No)	Number of hours of close work done during the past week	Results of the Titmus vision tester in terms of ability to perform a visual task (Yes/No)
15	51	M	Yes	50	Yes
16	27	M	Yes	40	No
17	30	M	Yes	20	Yes
18	22	M	Yes	15	Yes
19	20	M	No	20	Yes
20	25	F	Yes	30	Yes
21	24	F	Yes	15	Yes
22	24	M	No	30	Yes
23	21	M	Yes	40	Yes
24	23	F	No	50	Yes

below 20/20 vision with the left eye and another five had below 20/20 vision with their right eyes. The range was between 20/40 and 20/13.

All the twenty three observers possessed good color discriminability and the minimum standards for stereo depth perception.

2. General Tests

These tests include:

i) Optical-Mechanical tests,

ii) Functional tests and

iii) Operational tests.

Optical-Mechanical tests. The optical mechanical tests were intended to test pupil size with the pupil spot display. Figure 22 shows the optical diagram of the PRVM. Visibility threshold of the scene was measured by obtaining an equivalent response and a veiling luminance to mask certain selected details of the task. Pupillary response to light was used as the criterion of assessment. The deviation of the two fibre optic tips for a given task luminance gave the pupil diameter. This diameter was measured and used as a basis for the equivalent luminance setting. For different jobs the pupil spot display reading was noted and the luminance measured. These two values were cross checked using the calibration data.

The apparatus used was the PRVM. The observers were the same as those who performed the general tests, parts two and three.

Functional and operational tests. These two were combined into a single stage. In this part, two subjects used the PRVM to make several measurements. The results would indicate the effectiveness of the device both in function and in operation.

Apparatus. The apparatus used in this procedure consisted of the PRVM; an adjustable table; a 110V,60Hz to 12V,60Hz 100W transformer (Oriel corp.); two 120V, 150W incandescent light sources mounted on

P_1: Polarizing plate (movable)

P_2: Polarizing plate (fixed)

A: Partition

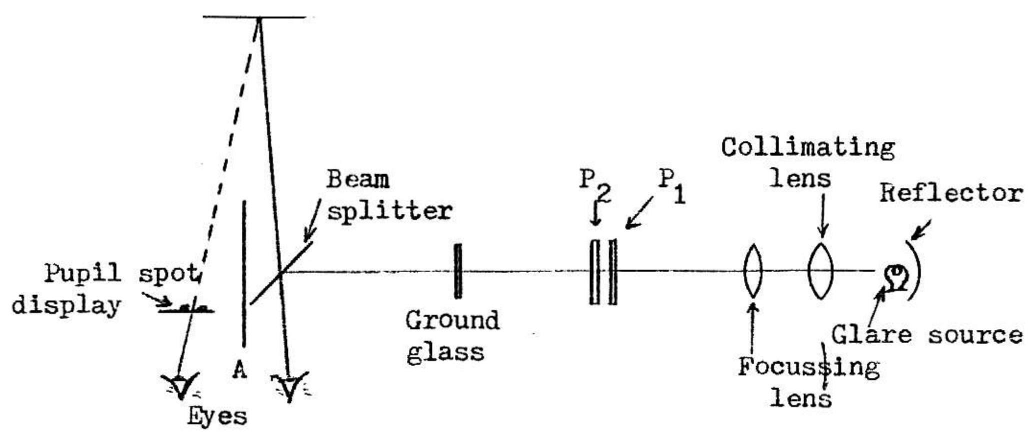


Figure 22. Optical arrangement of the pupillary response visibility meter

reflecters and stands; a photometer to measure the luminances and a black cloth cover to shield the subjects' eyes from extraneous light sources.

Figures 23, 24 and 25 show the experimental setup in three views.

Procedure. Subjects were asked to read a description of the PRVM and instructions on how to perform the experiment.

Description. "The pupillary response visibility meter is a device used to measure the visibility of an object or display using the contrast reducing principle (contrast between object and its background will be reduced to equivalence). Light reflected off of the object will reach your right eye after passing through the beam splitter. The pupil of your eye will adjust its size in order to accommodate the luminance. The pupil spot display control should then be adjusted till the two fibre optic tips you see superimposed over the scene become tangential. At this setting the pupil spot display will give a measure of pupil size. The object will then be occluded and the polarizer control will be adjusted till the light reaching the eye from the veiling glare source (projector) produces an identical response (tangency of the two spots) to that produced by the source. At this setting the task luminance and veiling luminance are equivalent.

The object is once again brought into view and luminances from the task and veiling glare source are superimposed. The polarizer control is once again adjusted till selected details of the task just disappear. The ratio of veiling luminance to equivalent luminance is the visibility of the task."

Instructions. "In this experiment you will be requested to view three letters of different sizes each under three contrasts for a total of nine conditions. Perform the experiment according to the following instructions and procedure.

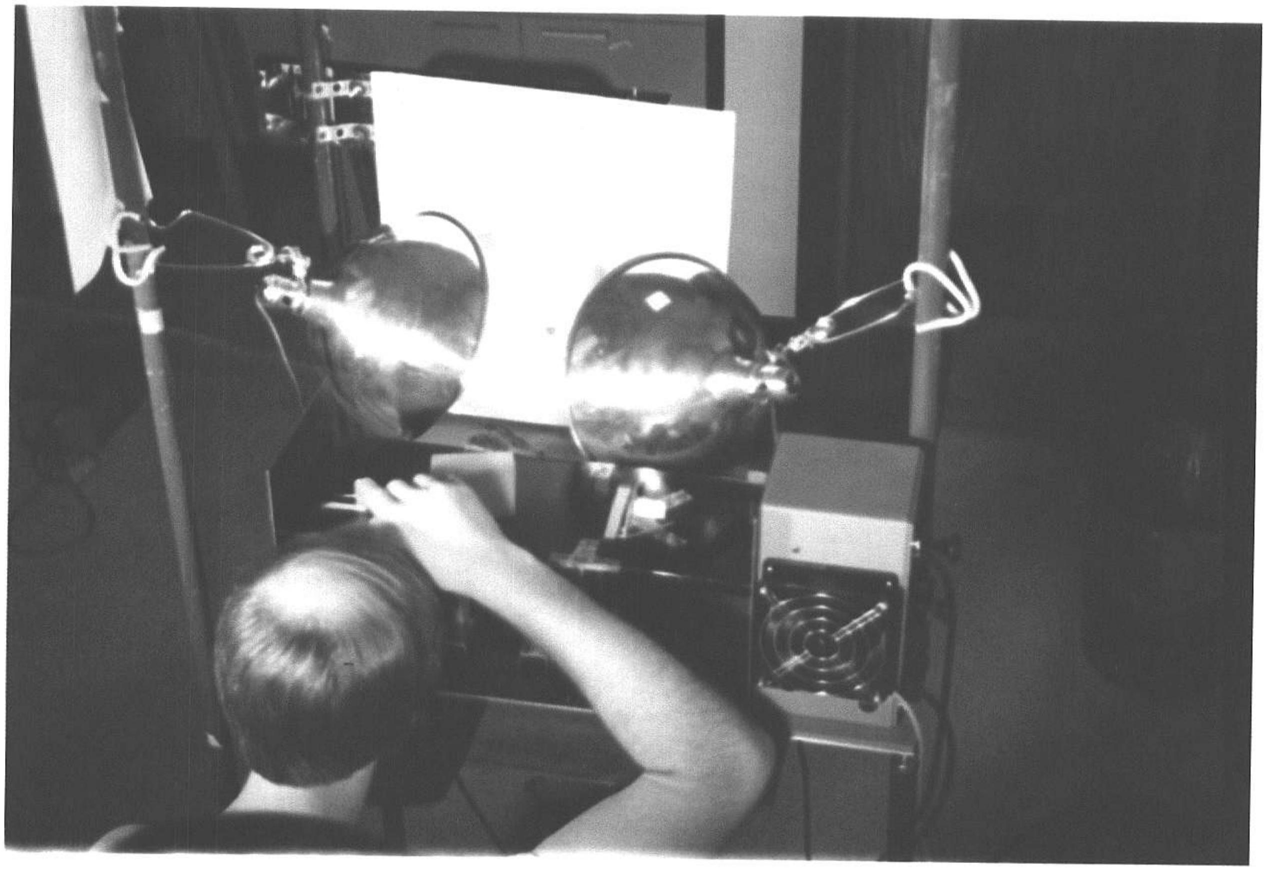


Figure 23. Experimental setup to test the pupillary response visibility meter: View from the back and above observers eye plane.

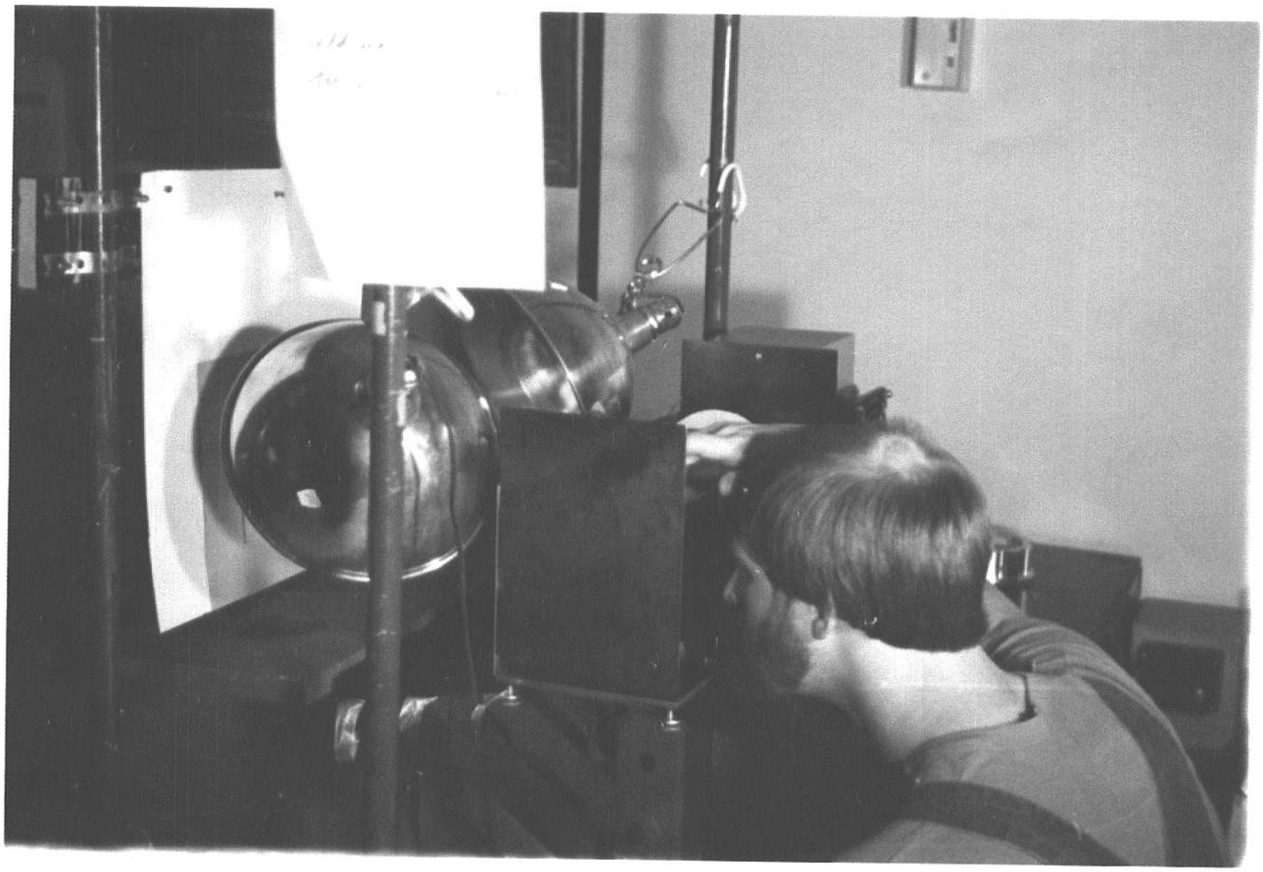


Figure 24. Experimental setup to test the pupillary response visibility meter: Side view of the setup showing observer adjusting the polarizer control.

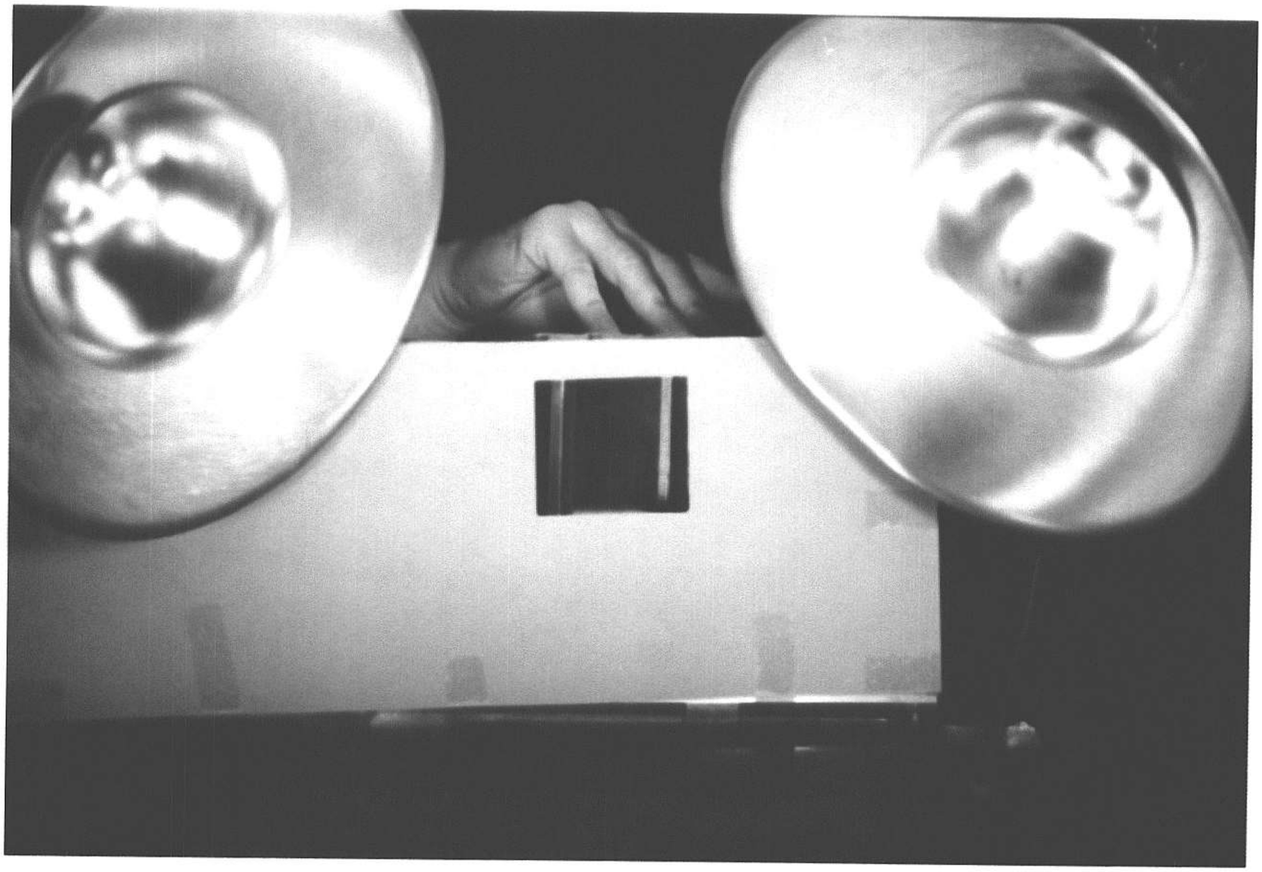


Figure 25. Experimental setup to test the pupillary response visibility meter: View from the front showing the viewing port and sources of light.

1. Select the task to be viewed.
2. Place your face in the position instructed and view the target through the beam splitter. Move your head from side to side until the two spots you see in your left eye lie superimposed on the target.
3. Adjust the pupil display control until the two spots are tangential.
4. Inform me after completing step 3. Wait to be told to proceed.
5. The task will be occluded. Now adjust the polarizer control till the light reaching your left eye from the veiling source produces the same tangency criterion as was produced by the task. For this procedure your eyes must be focussed at infinity. You may find this step a bit difficult at first. Take your time and repeat this step as often as you like till you feel confident of making a setting.
6. Inform me and wait to be told to proceed after making a setting.
7. The task will be once again brought into the field of view. Viewing the target adjust the polarizer control until the task reaches threshold. There are two threshold situations one could set for. Since visibility is expressed in terms of detection, recognition and identification of the object, either the detection-recognition or the recognition-identification threshold could be chosen. In the former the threshold would be reached when the task being viewed would become just invisible when sufficient veiling luminance is superimposed on it. In the latter the threshold would be at the point where the letter task being viewed would be recognized as an alphabet but cannot be identified as a particular letter.
8. Inform me when you have set for the threshold.
9. Repeat steps 1-8 for the three different targets under the three contrasts.

There should be no discomfort or risk to you in this procedure.

However, if you would rather not participate feel free to leave. Naturally, I would prefer that you complete the experiment so that I can gather all the required data."

Subjects who read the instructions and consented to participate in the experiment signed an informed consent and were told to proceed with the experiment.

Visual Display Terminal Tests

After the first two experiments the PRVM was set up in the computing room and measurements were made on three CRT units. Initial luminance levels were determined and then visibility measurements were made using the PRVM. All measurements were cross checked with the EB meter.

The three displays were called CRT-I, CRT-II AND CRT-III for reasons of convenience. CRT-I was a model 4054 Tetronix Graphic Systems terminal with a 19" DVST screen using P1 storage phosphor. The luminance reading on this terminal was 1.25 ft-L.

CRT-II and CRT-III were made by SOROC Technology. Both the units had a 12" diagonal rectangular screen with P4 phosphor displays. The luminance readings on these displays with and without the room lights were 5.25 ft-L and 1.50 ft-L for CRT-II respectively and 2.5 ft-L and 0.75 ft-L for CRT-III respectively. The room was illuminated by a group of four cool white flourescent lamps mounted in an enclosed panel in the ceiling, the light being diffused by a serrated plastic material.

The same two observers made these measurements.

Verification. All measurements made with the PRVM were repeated with the EB meter.

Subjects. Two observers performed the experiment with the PRVM and EB meters. Both of them were male and both were students at the Kansas State University. They wore no form of visual aids and they both had better than 20/20 vision. The subjects will be referred to as BR and GG.

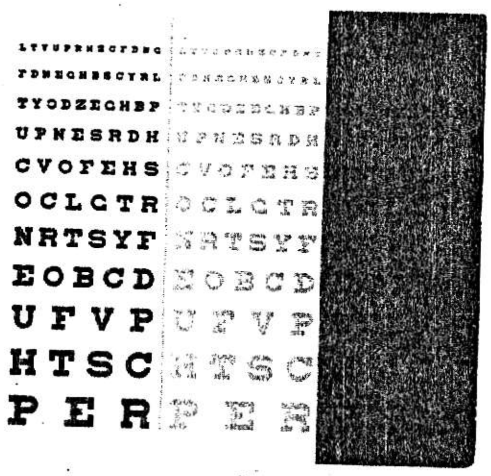


Figure 26. Photocopy of the target used in the experiment to test the PRVM.

Target. Figure 26 illustrates the target used in the experiment to test the pupillary response visibility meter. The figure is a photocopy of the original supplied by General Electric. The target consists of a group of randomly arranged letters of the English alhabet. Each group is arranged in columns with the letter sizes decreasing from bottom to top. Each column has a different contrast between object (task) and background with the contrast decreasing from left to right. For purposes of convenience the extreme left column was called the maximum contrast column, the middle column was called the medium contrast column and the extreme right column was called the minimum contrast column.

The two subjets BR and GG viewed a particular combination of these alphabets. BR measured the visibilities of letters P, U, N, C and T for all the contrasts. GG measured the visibilities of letters P, N and T, each for all the luminances. For ease of identification the targets were identified by numbers from 1-5 with the P referred by the number 1. Thus BR viewed targets 1-5 while GG measured only targets 1, 3 and 5.

Measurements of Luminances. All luminances were measured with a photometer. The photometer requires a field of uniform luminance for accurate measurements. This situation was difficult to obtain in this experimental setup with the type of targets employed. Hence an average field of luminance of both the target and the background was measured, this measurement being maintained consistently over the entire experiment.

RESULTS

Pupillary Calibration

Table 5 shows the mean, median, lowest and highest values of pupil diameters, measured for the given levels of luminances, of twenty four subjects.

Regression analyses with the natural logarithm of luminance as the independent variable and the mean, median, lowest and highest values as dependent variables produced the following results.

For the mean pupil diameters the analysis gave the relation between pupil diameter and the natural logarithm of luminance as

$$\text{Mean diameter (mm)} = 4.814 - 0.329 \text{Log}_e(\text{luminance})$$

with an R^2 value of 0.94

For the median values the relation obtained from the analysis was

$$\text{Median diameter} = 4.885 - 0.359 \text{ Log}_e(\text{luminance})$$

with a R^2 value of 0.92. For the lowest values of pupil diameter the relation linking pupil diameter to luminance was found through analysis to be

$$\text{Lowest diameter} = 3.35 - 0.168 \text{ Log}_e(\text{luminance})$$

with a R^2 value of 0.96. The equation linking highest value to luminance was

$$\text{Highest diameter} = 6.17 - 0.426 \text{ Log}_e(\text{luminance})$$

with an R^2 value of 0.83.

Table 6 lists the predicted values of pupil diameters for the given levels of luminances.

Figures 27, 28 and 29 show the observed values of pupil diameter (mean values) with the regression line drawn through the data points.

For the general tests on the PRVM the luminance of the target was 1.25 ft-L. For this level of luminance the pupil diameter as measured by the pupil spot display was 5.71mm for subject BR and 5.29 mm

Table 5

Pupil Diameter Measurements of Twenty Four Subjects

Luminance in foot-lamberts	Pupil diameter in millimeters			
	Mean	Median	Lowest	Highest
0.1	5.142	5.2	3.72	6.30
1.0	4.911	5.0	3.2	6.15
10.0	4.478	4.6	3.15	5.9
25.0	4.085	4.2	3.00	5.6
50.0	3.651	3.6	2.7	5.25
100.0	3.365	3.3	2.5	4.6
150.0	3.132	3.0	2.45	4.0
200.0	2.943	2.80	2.4	3.8
300.0	2.821	2.75	2.38	3.50
400.0	2.718	2.65	2.35	3.3
500.0	2.649	2.60	2.3	3.2
600.0	2.591	2.45	2.28	3.1
650.0	2.541	2.40	2.25	3.00
Means	3.478	3.427	2.668	4.439
Std. Deviation	0.237	0.288	0.099	0.535

Table 6

Predicted Pupil Diameters for the Given Levels of Luminance

Luminance in foot-lamberts	Predicted pupil diameters			
	Mean	Median	Lowest	Highest
0.1	5.57	5.71	3.73	7.16
1.0	4.81	4.89	3.35	6.17
10.0	4.06	4.06	2.96	5.19
25.0	3.75	3.73	2.81	4.80
50.0	3.53	3.48	2.7	4.5
100.0	3.3	3.23	2.58	4.21
150.0	3.17	3.09	2.51	4.04
200.0	3.07	2.98	2.46	3.91
300.0	2.94	2.84	2.39	3.73
400.0	2.84	2.73	2.34	3.62
500.0	2.77	2.65	2.31	3.52
600.0	2.71	2.59	2.28	3.44
650.0	2.65	2.56	2.26	3.41

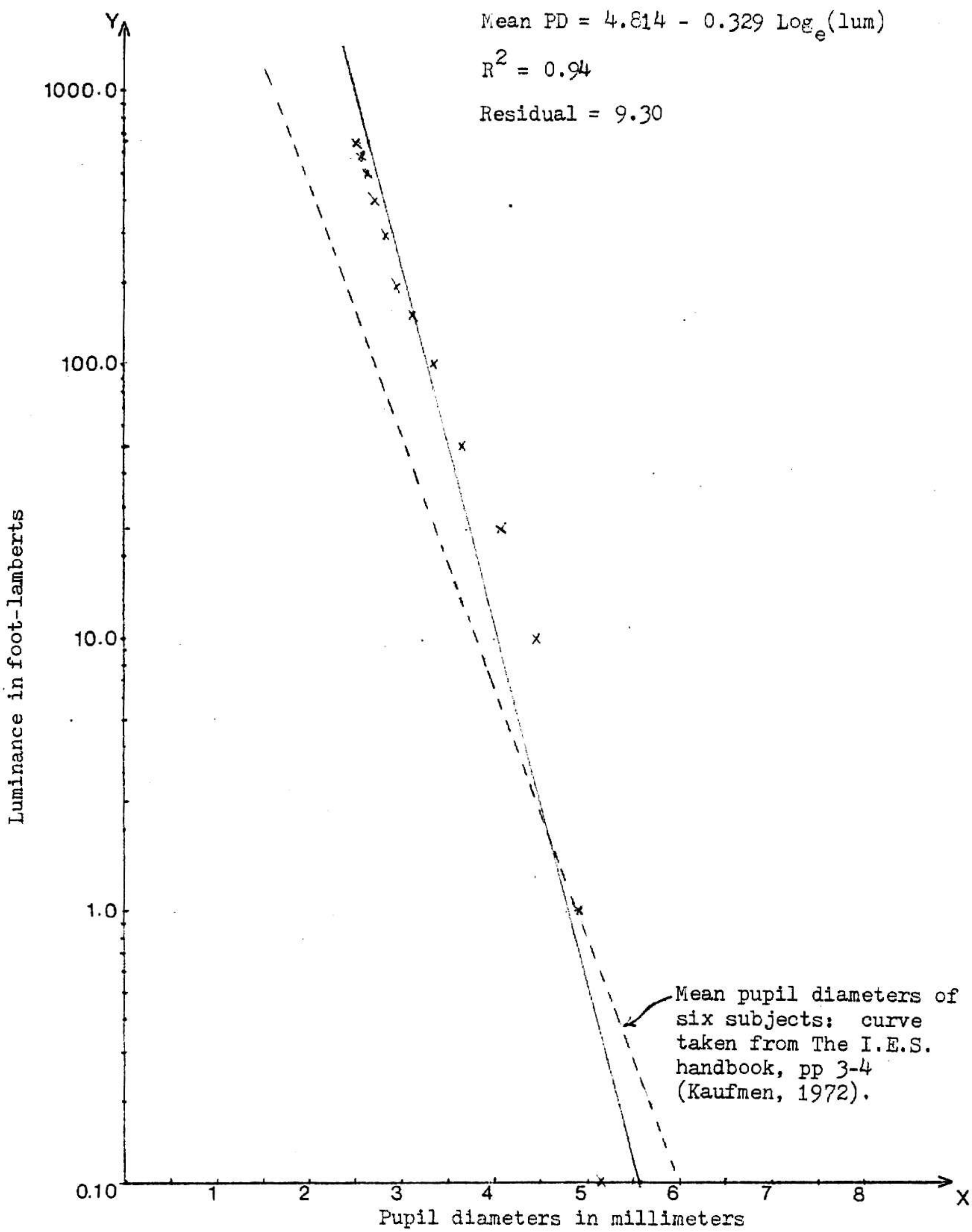


Figure 27. Mean pupil diameters of twenty four subjects for thirteen levels of luminance and the regression line.

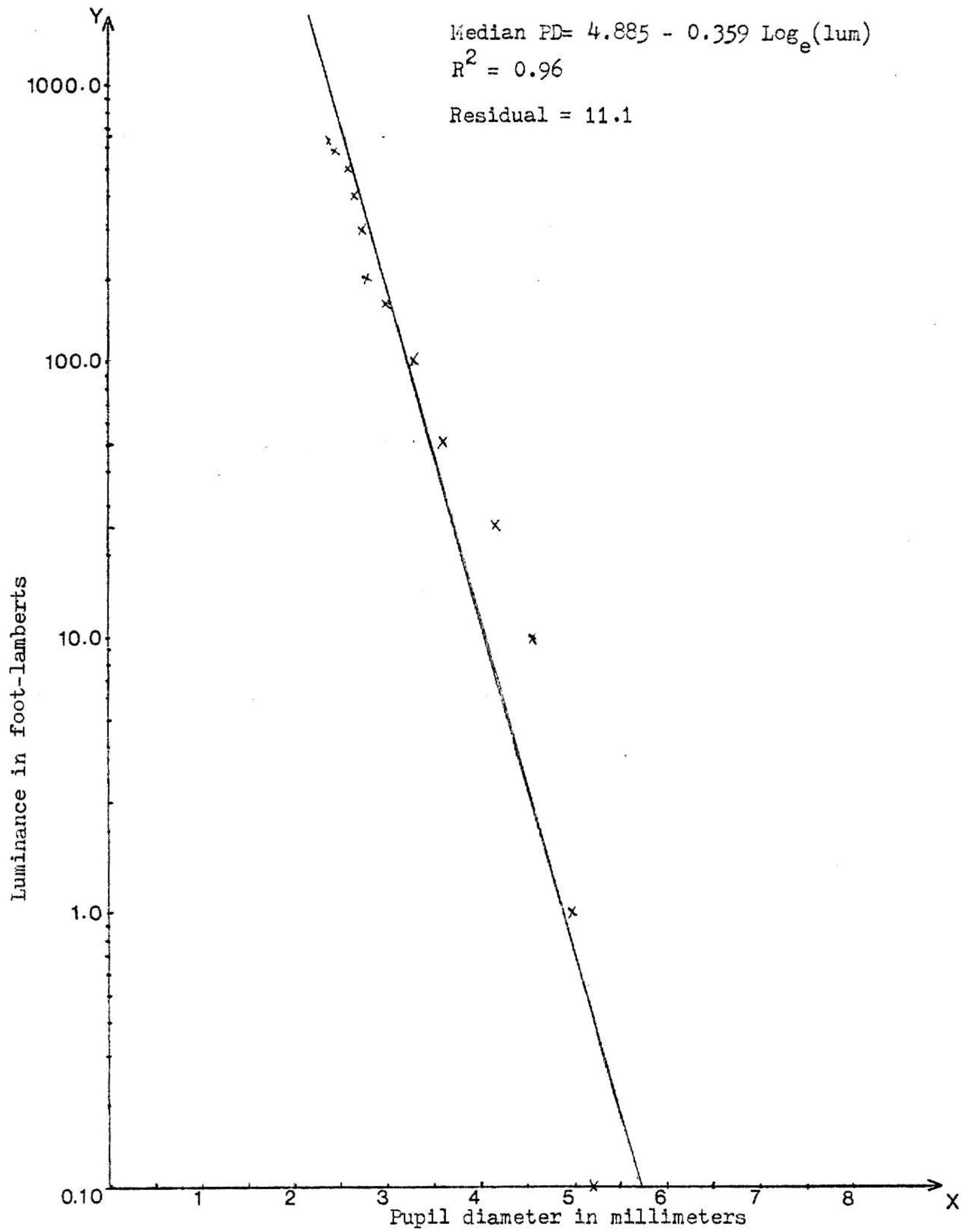


Figure 28. Median pupil diameters of twenty four subjects for thirteen levels of luminance and the regression line.

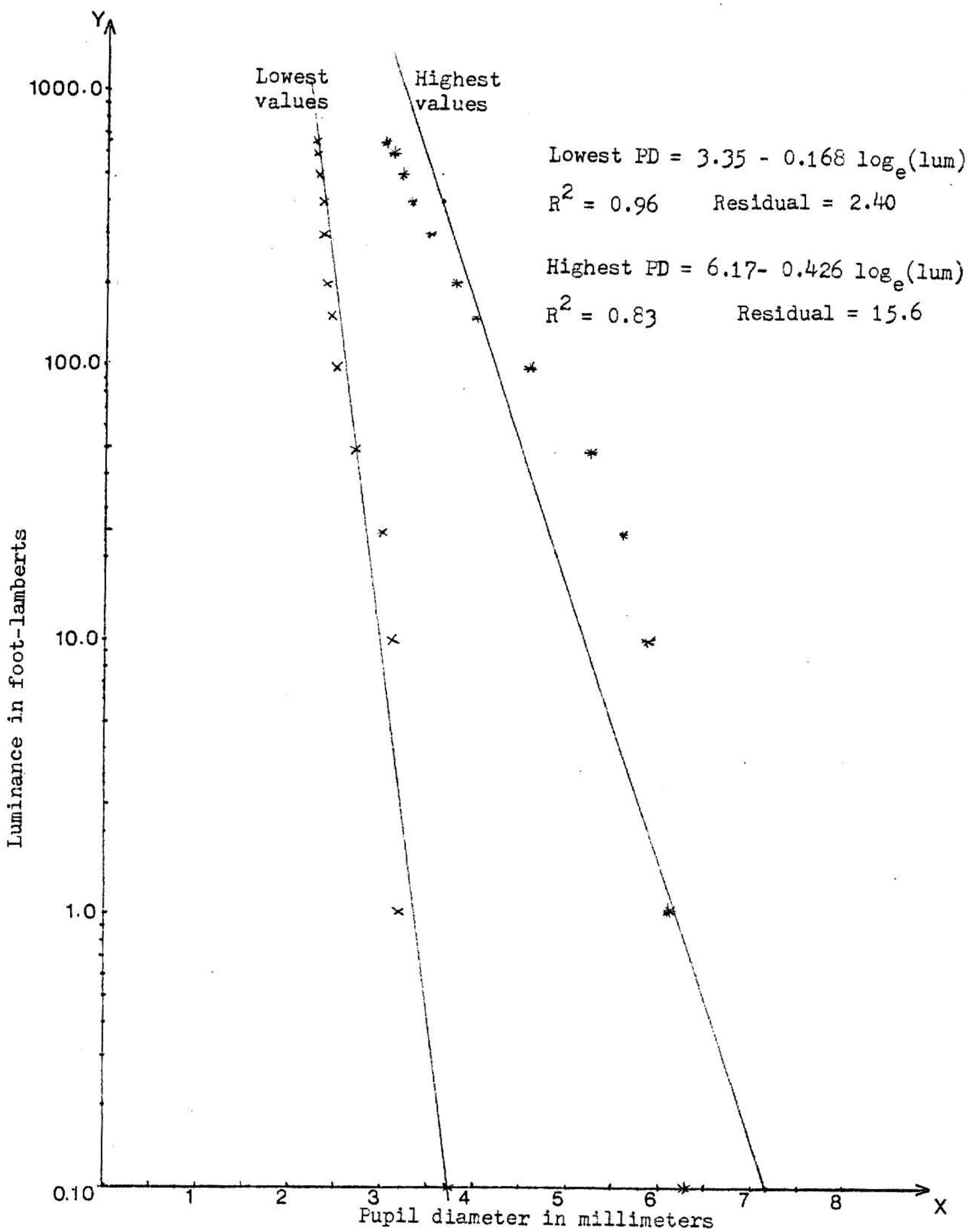


Figure 29. Lowest and highest values of pupil diameters of twenty four subjects and the regression lines.

for the subject GG. For this luminance level the estimated pupil diameters had a mean of 4.74 mm, a median of 4.81 mm and a range of 3.31-6.08 mm. For the CRT-I BR had a measured pupil diameter of 4.95mm and GG had one of 4.13mm in size. Corresponding to these pupil sizes the luminance level was measured to be 1.25 ft-L. The predicted pupil diameters would be the same as for the target, as both displays had a luminance level of 1.25 ft-L.

For CRT-II the measured luminance was 5.25ft-L with the room lights and 1.50 ft-L without the room lights. The measured pupil size was 3.6mm with the room lights and 5.45mm without the room lights. The predicted pupil diameter for these levels of luminance is :

for 5.25 ft-L the mean is 4.27mm and median is 4.78mm.

For 1.50 ft-L the mean is 4.32mm and the median is 4.45mm.

For CRT-III the luminances with and without room lights were 2.5 ft-L and 0.75 ft-L respectively. The mean pupil diameter for these luminances were predicted to be 3.99mm and 4.57mm. The median pupil diamters were 3.99 and 4.62mm and the measured pupil diameters were 4.23mm and 5.5 mm.

General tests. Table 7 contains the means and standard deviations of the visibility indexes for each of the five targets viewed by the two subjects BR and GG under three levels of contrast and under 1.25 ft-L illumination. The mean values were obtained by averaging the values of eighteen settings obtained in three trials of six settings each. Table 8 shows the visibility readings measured by the EB meter. Figure 30 illustrates the visibility index vs targets viewed curves. The curves connect the overall mean of the eighteen readings and the three points plotted are the means of each trial. The contrast between the object viewed and the background in this case was maximum.

Figure 31 is similar to figure 30 except that the contrast used was

Table 7

Mean and Standard Deviations of the Visibility Indexes for the Tasks

Experimental sequence	Letter viewed	Maximum contrast				Medium contrast				Minimum contrast			
		BR		GG		BR		GG		BR		GG	
		Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.
1	P	4.03	0.25	3.36	0.15	2.33	0.16	1.93	0.12	0.39	0.05	--	----
2	U	3.95	0.30	---	---	2.28	0.21	---	---	0.32	0.04	---	---
3	N	2.97	0.20	2.19	0.15	1.56	0.11	1.29	0.09	---	---	---	---
4	C	2.39	0.19	---	---	1.11	0.06	---	---	---	---	---	---
5	T	1.66	0.11	0.88	0.12	0.79	0.07	0.36	0.14	---	---	---	---

Table 8

Visibility Indexes for the Targets Viewed Through the EB Meter

Experimental sequence	Letter viewed	Maximum contrast				Medium contrast			
		BR		GG		BR		GG	
		Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.
1	P	6.55	0.27	3.84	0.54	4.58	0.28	3.46	0.27
2	U	6.78	0.36	--	--	4.18	0.31	--	--
3	N	5.00	0.24	4.47	0.51	2.65	0.05	2.83	0.30
4	C	3.53	0.14	--	--	1.90	0.06	--	--
5	T	2.37	0.05	2.43	0.16	1.55	0.05	2.08	0.56

medium.

Figures 30 and 31 show the plots for both the PRVM and the EB meter. The plots are for both the subjects BR and GG.

Figure 32 is a plot of the visibility indexes of the EB meter vs the PRVM. The correlations between the readings obtained from both these instruments is 0.996 for the observer BR and 0.70 for the observer GG. For this condition the background and the objects were under maximum contrast.

Figure 33 is identical to figure 32 except that the contrast of the object against its background was medium. The correlations between these two instruments for this medium contrast task are 0.99 for BR and 0.994 for GG.

Figure 34 shows the plot for the measurements made with the low contrast job. Only two points could be obtained by BR due to the low luminance on the low contrast. Observer GG could not see any of the letters. The EB meter was not useable for this task.

Visual Display Terminals

Table 9 contains information on the CRT units whose visibilities were measured. Table 10 shows the visibility indexes for each of the three CRT units under a particular lighting condition and when measured by each of the two observers with the PRVM.

CRT-I was measured with the EB meter and the indexes obtained were the same for both the lower and upper case letters. When measured by the observer BR with the EB meter, a mean visibility value of 18.8 with a standard deviation of 3.52 was obtained. GG measured the CRT with the EB meter and obtained a mean value of 19.96 with a standard deviation of 2.01. The range of visibility indexes for the two observers were 10.7-21.2 for BR and 15.9-22.0 for GG.

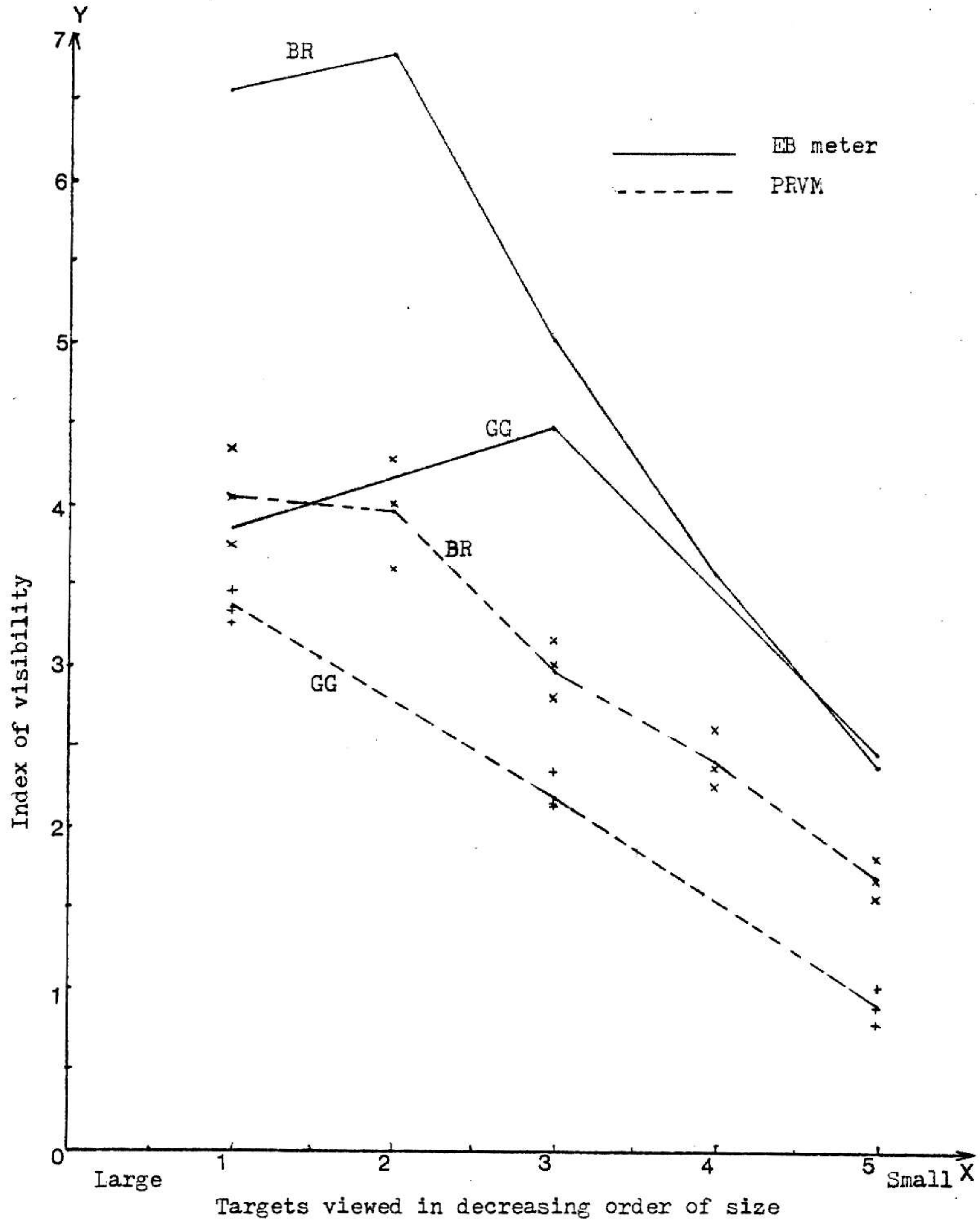


Figure 30. Target viewed vs visibility index for the pupillary response visibility meter and Levy's EB meter for two observers, BR and GG. Targets viewed under a maximum contrast between object and background.

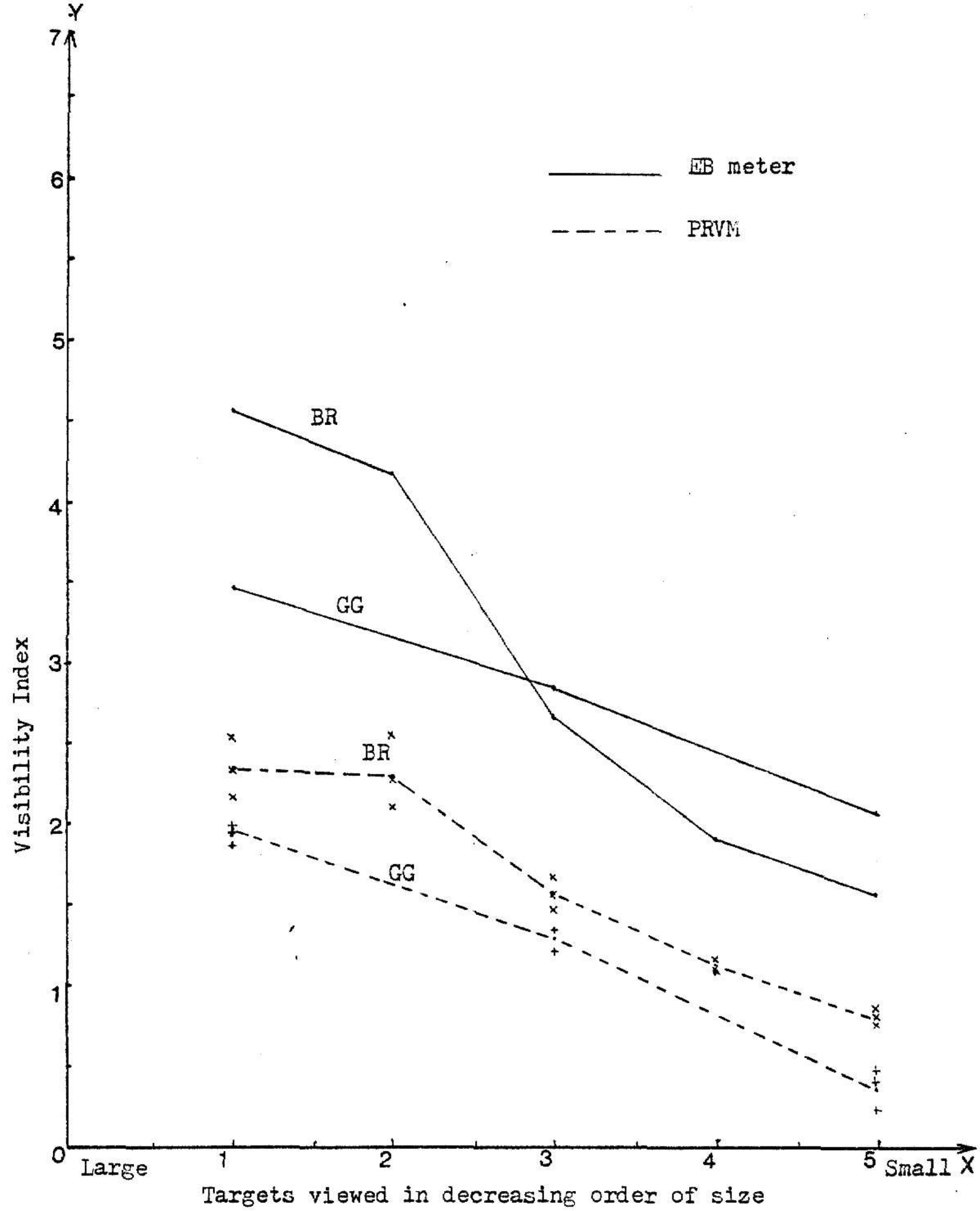


Figure 31. Target viewed vs visibility index for the pupillary response visibility meter and Levy s EB meter for two observers, BR and GG. Targets viewed under a medium contrast between object and background,

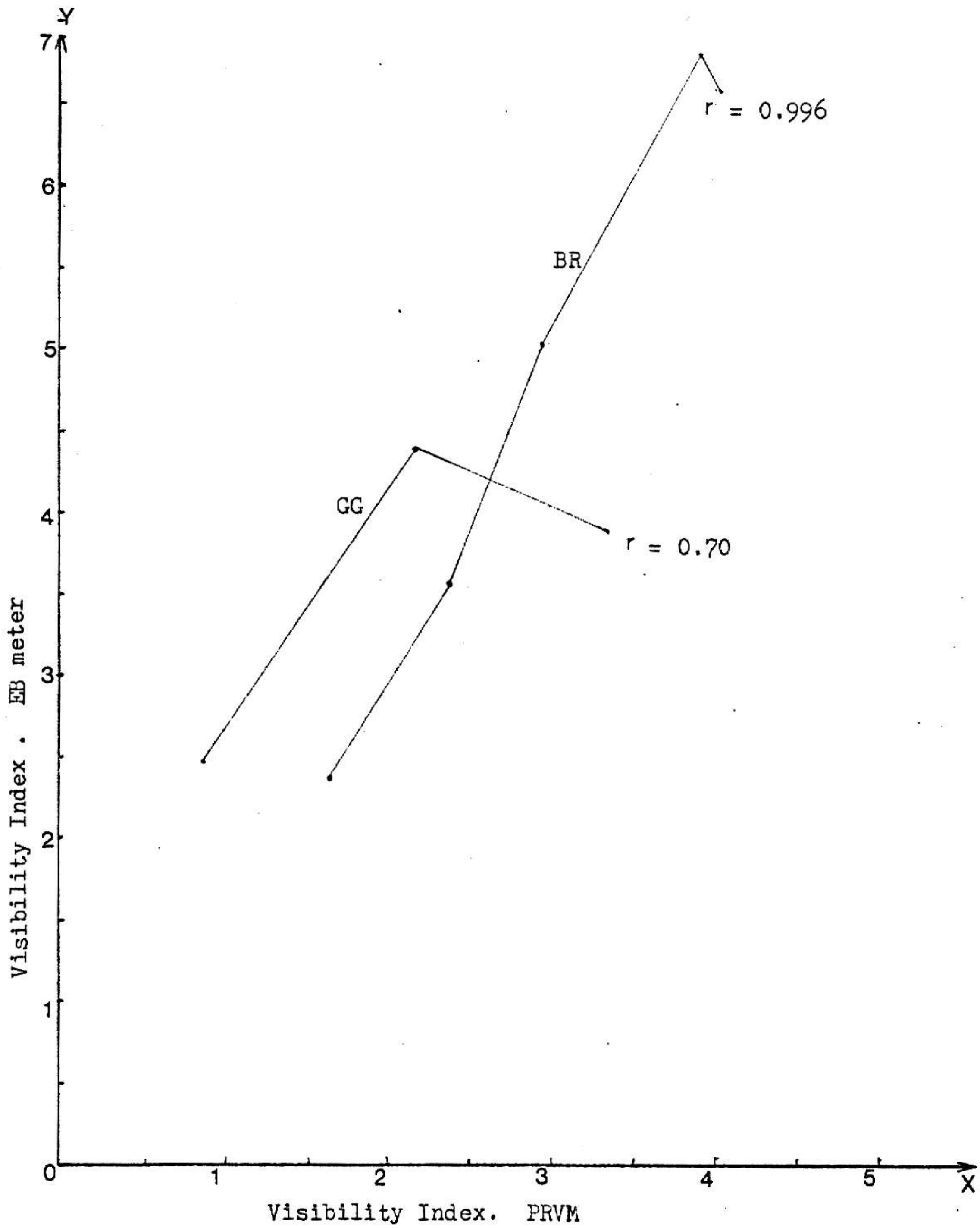


Figure 32. Visibility indexes: EB meter vs PRVM. Maximum contrast between object and background.

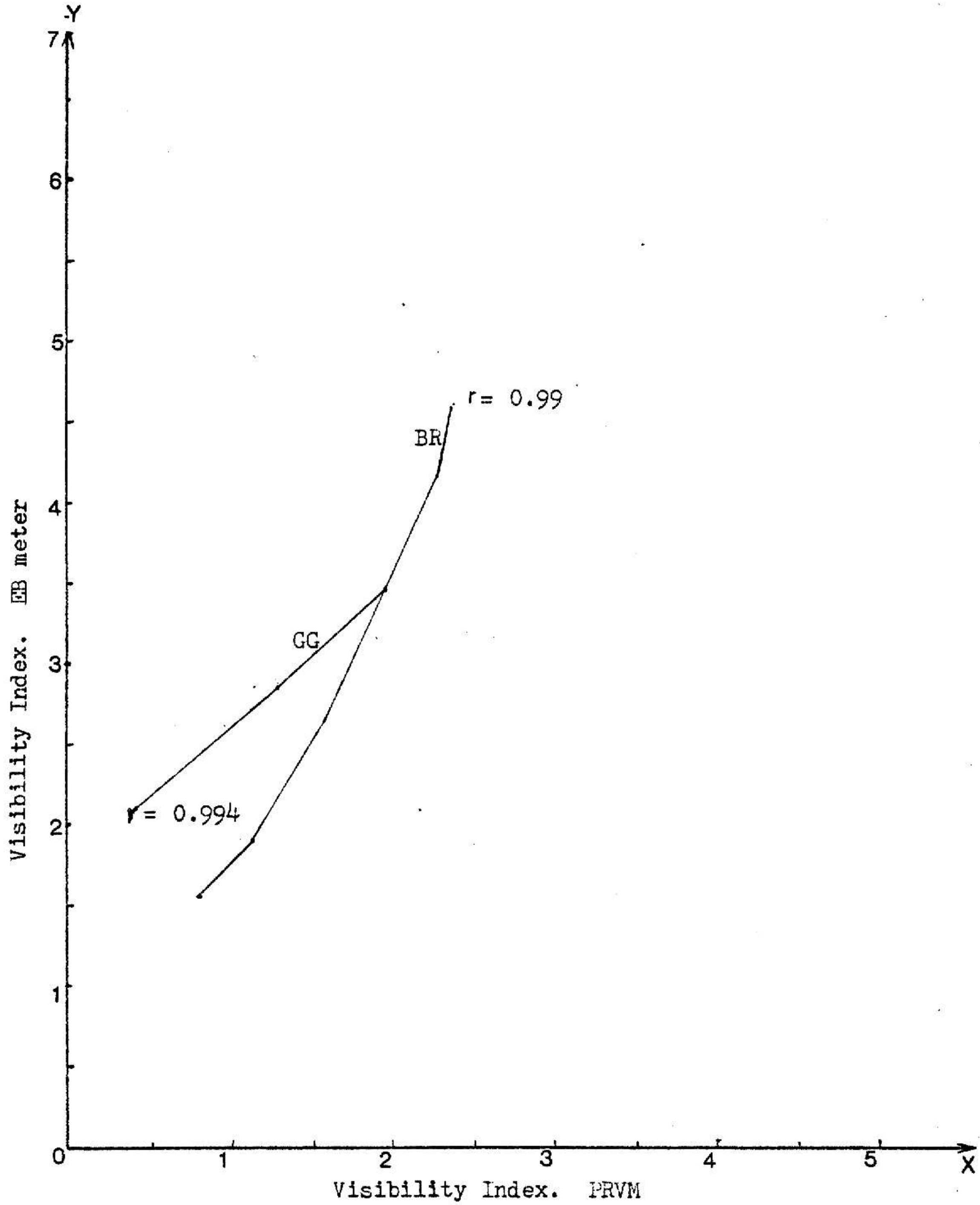


Figure 33. Visibility indexes: EB meter vs PRVM. Medium contrast between object and background.

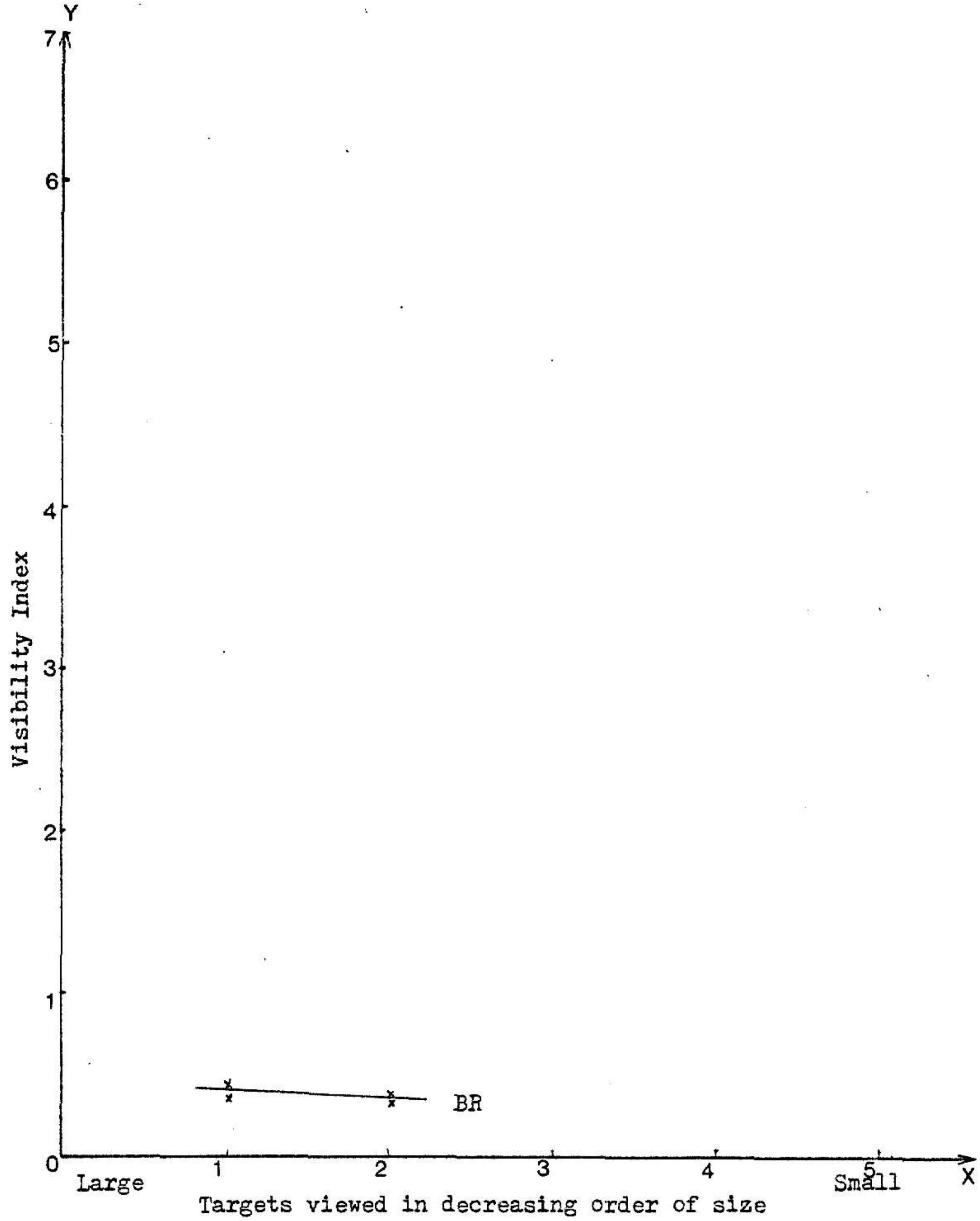


Figure 31. Target viewed vs visibility index for the pupillary response visibility meter for observer BR. Targets viewed under a minimum contrast between object and background.

Table 9

Information on the CRT Terminals used to Measure Visibility

Make	Luminance of the display with light	Luminance of the display without light	Type of phosphor	Screen size
Tetronix	---	1.25	P 1	19" DVST
Soroc Tech.	5.25	1.50	P 4	12" diag.
Soroc Tech.	2.5	0.75	P 4	12" diag

Table 10

Visibility Indexes for the CRTs' Measured by the PRVM

Type of CRT	Room lights	Luminance of CRT (ft-L)	Subject	Pupil diameter	Type of letter	Visibility Indexes		
						Mean	sd	Range
Tetronix (CRT-I)	Without lights	1.25	BR	4.95	upper case	4.68	0.38	4.6-5.2
					lower case	3.97	0.48	3.4-4.7
			GG	4.13	upper case	4.48	0.55	3.8-5.0
					lower case	3.76	0.39	3.0-4.3
Soroc (CRT-II)	With lights	5.25	BR	3.6	upper case	1.6	0.06	1.5-1.7
	Without lights	1.50	BR	5.45	upper case	3.11	0.11	2.9-3.2
Soroc (CRT-III)	With lights	2.5	BR	4.23	upper case	1.36	0.09	1.2-1.5
	Without lights	0.75	BR	5.50	upper case	4.93	0.44	4.4-5.0

Although these values seem very different from the ones obtained with the PRVM the normalized visibility indexes were in the same range. The normalized means for the two meters for the observer BR were 0.85 (PRVM) and 0.89 (EB) for the upper case letter and 0.9 (PRVM) and 0.89 (EB) for the lower case letter. For the observer GG the normalized means were 0.87 (PRVM) and 0.89 (EB) for the upper case letter and 0.9 (PRVM) and 0.9 (EB) for the lower case letter.

The observer GG did not measure the other two CRTs'.

DISCUSSION

Pupillary Calibration

This calibration procedure was carried out with no direct use in the operation of the pupillary response visibility meter. The pupil spot display is used to establish equivalence of luminance between the display and veiling luminances. However, with the pupil spot display scale and the capability to measure pupil diameter (separation of the two spots) as explained on page 36, the calibration curves (figures 27, 28 and 29) could be used to obtain a direct measure of luminance with a given pupillary response or vice versa. The calibration curves exhibit certain trends with straight line fits not the best of them. However, with a wider range of beam splitters and better control of the veiling luminance the pupil diameter could be restricted to a more sensitive range so as to guarantee better results.

The results presented on pages 65 and 71 show that the pupil spot display can be used to obtain either a luminance for a given pupil diameter or a pupil diameter for a given luminance. Although the results are not very accurate due to errors imposed by equipment limitations, it is safe to conclude that the pupil spot display is a valid measure of pupillary responses for suprathreshold information displays.

General Tests

The luminance level of 1.25 ft-L was not chosen arbitrarily. This is the highest luminance that can be used so as to enable one to make measurements on the maximum contrast column of the target. The reason for this limitation was that a beam splitter of 55% transmittance was used. A denser beam splitter would have increased the sensitivity of the instrument and a range of beam splitters varying from 10% to 90%

transmittance could make the illumination range that could be measured much broader.

The luminance measure of 1.25 ft-L on the cathode ray terminal (CRT-I) produced a smaller pupillary response than that of the target used in the experiment. This measure is only approximate as the photometer that was used to measure the luminance of the target and CRTs' requires a field of uniform luminance which was very difficult to obtain in displays of this nature. Therefore, wherein the measured' luminance was 1.25 ft-L the actual luminance may have been higher. The same is true for all the displays .

In the pupil spot display the two spots (tips of fiber optics) and the pointer move on a fulcrum. For the particular adjustment in this experiment the separation of the two spots was calculated , by geometry, to be 0.423 x scale reading in millimeters. This separation is the pupil diameter.

Measurements of the visibility indexes entailed two settings of the polarizer, one giving the equivalent luminance angle "θ" and the other giving the veiling angle "ø". Visibility was expressed by the relation $\sin^2 \theta / \sin^2 \phi$. The first angle theta was not reset for a given luminance and for a fixed viewing distance as changes in the pupillary response will not be affected if these two parameters are kept constant. However, from trial to trial the angle theta varied within narrow limits while the angle phi was relatively unaffected. This is a difficulty in using the instrument and the user will have to gain sufficient experience before making measurements.

The equivalent luminance is obtained by obscuring the task from the field of vision and adjusting the polarizer to produce a level of luminance that would move the two spots at the left eye to tangency. This setting entails maintaining focus of the eye at a distance at which the task is, superimposing the spots on the field of vision and adjusting the polarizer till the tangency criterion is reached.

Two earlier observers who made observations with this device experienced difficulty in obtaining this setting because of the inherent difficulty of maintaining focus at the task distance while viewing the veiling glare field which is closer than the task. To overcome this difficulty the following procedure was followed.

The spots were moved away from the field of view by moving the head to the right. The task was viewed and then obscured with the left hand. The polarizer was then adjusted with the right hand while still maintaining focus on the task. By moving the head, the spots were brought over the field of view and tested for tangency. The procedure was repeated until the criterion of tangency was reached. Several repititions of this procedure coupled with experience produced a more or less constant equivalent luminance angle. Even though slight changes could cause variations in the visibility, repeated observations over a period of time will produce a reasonably consistent "θ".

Another criterion which should be maintained constant over the entire period of the experiment is the threshold criterion. Visibility was defined in terms of detection, recognition and identification of an object. Two possible thresholds could be chosen, one between detection and recognition and the other between recognition and identification. Changes in threshold chosen could cause variations in the measure of visibility. Therfore, it is very important to select a suitable threshold and use it over the entire period. In this research the recognition-identification threshold was chosen.

Figures 30 and 31 illustrate the change in visibility with size of the task. On the abscissa the scale from 0-5 indicates the letter sizes in decreasing order. The number 1 corresponded to a letter size of 5/32" and every other number correponded to a decrease by 1/32". For the PRVM the trend indicates that decreasing task sizes produce decreasing visibility indexes. However, letter or display sizes cannot be increased indefinitely. Over a particular size they will not produce noticeable changes in visibility. Visibility drops with decreasing letter sizes and with reducing contrasts. Figure 30 had visibility curves which were higher than those in figure 31. This is due to the contrast in the former being higher than that in the latter.

It is very important to remenber that visibility values will not be the same for all observers. Individual differences will cause variations in visibility between observers. To develop visibility standards it may be necessary to establish a minimum visibility level for a large population of the observers.

Levy's EB meter. The measurements of visibility using the EB meter were a little more erratic than the PRVM. In figure 30 subject GG exhibited an upward trend in visibility even though the size of the object was decreasing. This is entirely contradictory to theory. However, the trend is more conclusive in figure 31 which indicates a decreasing visibility index with decreasing size.

The curves for the two meters are separated because of the differences in the principles of operation and measurement. However the strong positive correlation between the visibility values indicates that the two devices are producing equivalent results. The reason for the steadier results obtained by the observer BR may have been due to the fact that BR was more experienced and familiar with the instrument.

Of the four observers who used the two visibility meters all of them unanimously agreed that the PRVM was a easier to use instrument and less tedious. One of the reasons for this may have been due to the difference in viewing the target. Whereas the PRVM allows binocular vision the EB meter requires monocular vision. Another factor is that the variable disc chopper is very tedious to keep turning in order to adjust the transmittance of the task.path. The adjustment requires the right arm to be raised and causes cramps in the upper arm. A third reason is that the EB meter produces an inverted image of the task, whereas the image is erect when viewed through the PRVM. However, there are certain advantages in the EB meter. The timer to control the shutter is an important addition as this guarantees a high degree in repeatability..

The PRVM is intended to be used to measure quality of information displays.

Visual Display tests. Measurements on CRT terminals produced conclusive results that the PRVM can in fact be used in its intended application. The range of CRT visibilites were within limits for a particular display type. Further, normalized visibility values were within very close distances from each other.

CONCLUSIONS

The pupillary response visibility meter proves to be a useful device for obtaining measures of visibility of suprathreshold display information. Although more extensive testing procedures need to be carried out, the results presented here provide a degree of merit on the instrument.

The results have proven that consistency in measurements increase with familiarity of the instrument and experience. Repeated use of the instrument is mandatory for consistent and reliable results.

A wider range of beam splitters is essential for better results and for restricting the response of the pupil to a sensitive region. Figures 27,28 and 29 provide information on the behavior of the pupil to changes in luminances. A region on the curves which is flatter than the other regions is a sensitive region for the pupil. A wider range of beam splitters and a variable veiling source (to enable usage of the entire scale of the polarizers) would enable users to restrict the luminances entering the right eye to this sensitive range.

The visibility numbers may not mean much from a design point of view. It is essential to establish a minimum visibility level for a large population of users. This minimum level can be established through more extensive studies and feedback from the consumer.

The concept of pupillary response is an important factor in design of imaging type displays as it increases user input. More sophisticated techniques could be used to measure the luminances but all these would defeat the purpose of designing for use by humans.

REFERENCES

Bennett, M.G. A visibility meter. Journal of Scientific Instruments, 1931, 8, 122-126.

Blackwell, H.R. Specification of interior illumination levels. Illuminating Engineering, 1959, 54, 317-353.

Blackwell, H.R. Development of procedures and instruments for visual task evaluation. Illuminating Engineering, 1970, 65, 267-291.

Clauer, C.K. and Bates, A.D. Measuring the discernibility of visual information. Laboratory Report, IBM Corp., 1970.

Cottrell, C.L. Measurement of visibility. Illuminating Engineering, 1951, 46, 95-104.

Davson, H. (Ed.) The eye. Vol.3. Muscular mechanisms . New York and London: Academic Press, 1962.

Duntley, S.Q., Gordon, J.I., Taylor, J.H., White, C.T., Boileau, A.R., Tyler, J.E., Austin, R.W. and Harris, J.L. Visibility. Applied Optics, 1964, 3-5, 549

Eastman, A.A. A new contrast threshold visibility meter. Illuminating Engineering, January 1968, 37-41.

Feree,C.E. and Rand,G. Size of object, visibility and vision. Illuminating Engineering, 1931, 26, 820.

Finch, D.M. and Simmons, A,E, An instrument for the evaluation of night visibility on highways. Illuminating Engineering, Oct. 1953, 517-523.

Finch, D.M. Some factors influencing the night visibility of roadway obstacles. Illuminating Engineering, 1957, 52, 120-130.

Finch, D.M. and Palmer, J.D. Assessment of nightime roadway visibility. Highway Research Board Bullettin, 1957, 163, 1-16.

Hecht, S. Rods, cones and the chemical basis of vision. Physiological Reviews, 1937, 125, 239-290.

Janisse, M.P. (Ed.) Pupillary dynamics and behavior. New York and London: Plenum Press, 1974.

Jones, L.A. A mehtod and instrument for the measurement of the visibility of objects. Philosophical Magazine and Journal of Science, Jan. 1920, 39, 96-134.

Kaufman, J.E. (Ed.) I.E.S. lighting handbook, Fifth Edition. New york: I.E.S. , 1972.

Luckiesh, M. and Moss, F.K., Visibility-its measurement and significance in seeing. Journal of the Franklin Institute, 1935, 220, 431.

APPENDIX

Model 1992S Eye View Monitor and TV Pupillometer System with Free Head Movement

Description. The series 1900 Eye View Monitor is a complete system for measuring a subject's eye position and pupil diameter while allowing relatively free head movement. The output is provided in a number of convenient formats and allows easy correlation of pupil diameter with fixation points.

The output is available in digital, analog and visual forms for recording on strip chart recorders, x-y recorders, storage oscilloscopes, digital tape or directly into a digital computer. This data can be processed at the time of the experiment or recorded for later analysis by a computer. Also provided, is a monitor showing the scene being viewed by the subject, and superimposed on this is a spot or crosshairs indicating the point of view of the subject in real time. This is available to the operator both for adjusting and calibrating the experiment and as an output for study or video tape recording if desired. The configuration of the system is schematically shown in Figure 18. The television camera views the left eye of the subject which is illuminated by a near infrared completely invisible illuminator. The resulting picture of the eye is displayed on a five inch TV Pupil Monitor.

A special recognition circuit detects the pupil and the corneal reflection from the video signal. The horizontal scan lines which intersect them are selected to the exclusion of the scan lines which intersect the eyelids, eyelashes or other noise. This recognition circuit allows operation for a broad range of subjects and under varying conditions with minimum operator adjustments. It superimposes delimeters and other indicators on the TV pupil image to show the operator that the measurements are correct without any possible doubt.

The subjects eye rotation (as opposed to translation resulting from head motion) and consequently his point of fixation is determined by the measurement of the center of the pupil with respect to the center of the corneal reflection. The two features of the eye move together with head motion, but move differentially with eye rotation, hence the difference in their positions is indicative of the eye's point of fixation. In this way eye position is independent of head position so long as the pupil image is contained within the field of view of the camera. This allows the system to tolerate small head motion, talking, etc., and continuing the measurement without the necessity of recalibration. Without such a capability, an eyeball translation of 0.1 mm, resulting from head motion or eyeball motion within the socket, would falsely indicate eye rotation of about 1°.

The position information is presented to the operator as a spot superimposed on a 9"television monitor image of the scene being viewed by the subject. The operator can control the spot on the monitor. By asking the subject to move his eye horizontally and vertically, the operator can also adjust the gain by viewing the motion of the spot on the scene monitor. Once this is done the computed eye position is calibrated and may be recorded.

The system uses a sensitive Silicon Matrix Tube television camera, which functions at very low illumination, to view the eye. The illuminator is a low level near infrared completely invisible light source which does not annoy or distract the subject.

Options which are available with this system include:

1) Remote Measurement with no chin rest required

2) Digital Output Calibration and Presentation Unit

3) Zoom Lens for Scene Camera to vary field of view

4) Digital Tape Recorder for data recording
5) Interface and controller for Digital Tape Recorder, Slide Projector, etc.
6) Rear Projection Screen and Integrated Slide Projector
7) Large external Pupil Monitor
8) Binocular Measurement
9) Video Tape Recorder
10) Adjustable Subject Stool
11) Travelling Cases
12) 19" Rack Mounting Brackets

Applications. There has been great interest for a long time in measuring eye position for various clinical, research, and commercial applications. The Series 1900 Eye View Monitor Provides a convenient way for quantitative analysis of eye movement, especially where this information must be directly related to the point of gaze of the subject. The output is particularly suitable for computer processing eliminating the necessity of tedious measurement of photographs frame by frame.

Changes in pupil diameter which indicate arousal or interest may be recorded along with eye position to correlate such a psychological response with exactly what the subject is viewing. Pupil diameter appears to be a more sensitive, reliable, and practical method than traditional techniques such as measurement of galvanic skin response or heart rate.

Clinical and psychological applications include measurement of pursuit and saccadic eye movements, nystagmus, measurement of vergence and muscular imbalance (if positions of both eyes are recorded) reading studies, testing effects of training, stress and fatigue, workload, etc.

Commercial applications include human factors design of control panels or other equipment, preparation of advertisements and presentation material. Measurement of eye position and especially pupil diameter can indicate the amount of interest the subject shows in a particular picture, what he is fixating and for how long.

Specifications.

Allowable eye movement:	Horizontal 30°; 40° or higher with-reduced accuracy. Vertical 25°; 30° or higher with reduced accuracy. Eyelids may limit this range with some subjects.
Measurement resolution:	Better than one part in 100 horizontally and vertically.
Precision:	Better than 1/2°
Linearity:	Worst case spatial error between true eye position and obtained eye position measurement is 1°. This is generally due to non-uniformities in the surface of the cornea. The spatial error is time invariant and may be calibrated out if desired. Errors are smaller if only a small central field, e.g. TV monitor or rear projection screen, is needed.

	Error may increase to 2° in peripheral corners.
Sampling rate:	60 per second. Output is averaged every two fields; i.e., each 1/30 of a second. Non-averaged output is also available.
Eye Position Measurement: Analog	± 5 volts linearly related to horizontal eye position, gain and zero adjustable. ± 5 volts linearly related to vertical eye position, gain and zero adjustable. Output impedance: 75 ohms.
Digital	8 bits, TTL compatible, representing horizontal eye position in offset binary. 8 bits, TTL compatible, representing vertical eye position in offset binary. Output drives up to 4 TTL loads. Logical "1" greater than 2.5 volts Logical "0" less than 0.5 volts
Pupil Diameter Measurement: Analog	Pupil measurement and display range: 2.0 to 10 mm (normal pupil diameter: 2.9 mm to 6.5 mm).

	Lower pupil diameter is also measurable. Analog output signal accuracy: better than 1%. Meter accuracy: 2% of full scale. Frequency response: smoothing filter, flat from 0 to 6 Hz; may be switched out. External analog signal output: 0 to 10 volts DC. Scaling: 1.0 volt/mm of pupil diameter.
Digital	9 bits TTL compatible, representing pupil diameter in straight binary. LSB is zero in non-averaged sampling rate. Logical "1" greater than 2.5 volts Logical "0" less than 0.5 volts Output drives up to 4 TTL loads.
Timing Outputs:	Positive strobe and busy signal are output every 1/60th of a second for transferring of data. Data is constant during strobe pulse and changing during busy signal. Strobe pulse is 1-2 microseconds; busy pulse is 0.5-0.8 milliseconds. Output drives up to 4 TTL loads.

TV Camera:	Output impedance: 75 ohms, 1 inch Silicon Matrix Vidicon tube with 2:1 sync, 525 lines (625 lines at 50 Hz)
Illumination:	Invisible near infra-red filtered incandescent lamp illumination centered at 8500 Angstroms.
Operator setting indicators:	Discriminator Crescents appears on monitor at edge of pupil and the corneal reflection, along with a white line through the vertical center of the pupil and a black line through the vertical center of the corneal reflection as determined by the Recognition Circuit. The proper position of those lines indicates to the operator that no adjustment has to be made and that the measurement is being performed correctly. Delimiters are placed on top and bottom of the pupil to indicate to the operator just what is discriminated.
Mechanical:	Contol Unit Weight: 37 lbs.

	Dimensions: 17"x 7.5"x17" (WHD)
	Camera Unit Weight: 42 lbs
	Dimensions: 15"x 20"x 13" (WHD)
	Scene Monitor Weight: 9 lbs
	Dimensions: 8.6" x 9.2" x 8.7" (WHD)
Power Souce:	105-125 volts AC, 60 Hz
	220 volts AC, 50 Hz available

PUPILLARY RESPONSE VISIBILITY METER: FUNCTION, OPERATION AND APPLICATION

by

BALAJI RAMARAO

B.E.(Honors), Madras University, India, 1979

AN ABSTRACT OF

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1981

Visibility meters are devices used to determine the extent to which a visual task or display is above threshold -- as a measure of its visibility. A wide variety of visibility meters have been developed and are described. The only visibility meter that is currently available on the market is Levy's EB meter.

A newly developed meter is the "pupillary response visibility meter" (PRVM) invented by Rupp and Clauer of IBM. This instrument is based on adding masking luminance to the scene (task, display) to degrade it to threshold. It utilizes the consensual pupillary response, the fact that the pupil size of both eyes depends on the greater luminance deliveres to one eye. The device was modified and developed at the Kansas State University and is a very simple instrument.

Three sets of tests were carried out relating to the PRVM. Pupil calibration tests enable determination of the actual pupil size from the PRVM's fiber optics' scale. General tests showed the optical-mechanical workability, and demonstrated the general validity of the insrument. These tests showed the expected correlations of the visibility index with changes in letter size ans contrast and with visibility measures obtained with the EB meter. The visual display terminal (VDT) tests extended the general tests to show the feasibility of use with several VDT displays.

While further testing and development are desirable, the results of this research show the suitability of the PRVM as a low cost visibility meter for VDTs, in the hands of experienced operators.