INFLUENCE OF BLUE/GREEN VERSUS RED AND WHITE LIGHT SOURCES ON HUMAN DARK ADAPTATION AND OTHER SELECTED VISUAL FUNCTIONS

BY

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ABSTRACT

Red interior lighting used to preserve dark-adaptation needs to be replaced in military applications by blue/green lighting which is not detectable by 3rd-generation image intensifiers. This study investigated the influence of blue/green as compared to red and white light of equal photopic intensity on subsequent visual acuity, contrast sensitivity and dark-adaptation.

Male subjects (n = 90) were assigned to one of 15 treatment conditions (n = 6) as determined by the colour (blue/green, red or white) and intensity (0.1; 0.4; 1.6; 6.4 and 25.6 cd/m^2) of the pre-adaptation stimuli. A modified Goldmann/Weekers adaptometer was used to present the pre-adaptation stimuli, test stimuli and record visual (luminance) thresholds of each subject. Blue/green lighting had the same affect on visual (photopic) acuity and contrast sensitivity as white and red lighting. Blue/green affected visual (absolute) threshold at the start and during the process of dark-adaptation in the same manner as white but not the same as red lighting. White and red lighting did not differ significantly ($p < 0.01$) at low intensities (mesopic range) but did at the higher intensities (photopic range).

After exposure to blue/green and white light, it will take longer to reach the same level of dark-adaptation than after exposure to red. These time differences increase with increased intensities. The brightness ratio between red and white lights to produce the same dark-adaptation increases with an increase in intensity. At the upper mesopic region the differences between the effects of white and red lighting on subsequent dark-adaptation become irregular due to the inability to accurately equate non-monochromatic lights in the mesopic range.

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1. INTRODUCTION

1.1 Background and Problem Statement

Red light has been used for many years to illuminate various compartments in submarines, ships or other military vehicles at night. Red light was used because dark adaptation for scotopic vision is then achieved more quickly when the ambient light is turned off. (Hecht and Hsia, 1945; Hulbert, 1951; Cavonius and Hilz, 1970). Hecht and Hsia (1945) found that dark adaptation is substantially faster following red light pre-adaptation and may even be 30 times as bright as a white light and still be followed by the same speed of dark adaptation.

This one advantage of red light is offset, however, by several disadvantages. The red light is fatiguing for hyperopes (far-sighted) according to Kinney et al. (1983). Red light also makes it virtually impossible to read colour-coded charts (Luria and Kobus,1986) and indeed, it makes it more difficult to read coloured Cathode Ray Tubes (CRT's).

These problems have led to the desire to substitute another ambient light for red lighting (Luria and Kobus, 1986). Studies by Luria and Kobus (1984; 1985) have shown that the problems associated with red light could be alleviated, if not eliminated, by substituting red with white light of generally comparable brightness. Briefly, laboratory studies have demonstrated that, compared to red light, low level white light does not degrade either contrast sensitivity (Neri and Kinney, 1982), visibility through the periscope of a submarine (Luria and Kobus, 1985) or the detection of targets on sonar CRT's (Neri et al., 1984; Neri et al., 1986). Nor according to Kinney et al.(1983) is white light as fatiguing as red.

The use of blue light in submarines has also been studied. Although blue light was subjectively preferred when compared with red and white light, studies conducted by Neri and Kinney (1982) revealed no significant differences in contrast sensitivity as a function of the colour of the illumination under conditions identical to those found in submarine sonar shacks.

In order to enhance vision at night the military introduced electro-optical devices which provide an image that is many times brighter than the scene as viewed by the unaided eye. One such passive electro-optical surveillance device is the image intensifier which uses the ambient visual light plus some of the night sky radiation reflected from the scene. Image intensifiers utilise the significant amounts of ambient near infra-red illumination. The latest version of image intensifiers, 3rd-generation instruments, use wavelengths longer than 600 nm which therefore include part of the visable spectrum; viz. yellow, orange and red. These latter lead to a problem in the sense that any light source emitting wavelengths above 600 nm falls within the sensitivity range of the image intensifiers and is therefore intensified and thus easily detected by the human observer. On the other hand the use of 3rd-generation image intensifiers precludes the use of any light source emitting light with wavelengths longer than 600 nm anywhere near the observer using such a device. This is because they generate internal noise within the tube of the image intensifier and therefore degrade any contrast. Consequently the traditional red and white lights used in military vehicles are now unacceptable.

In order to overcome the previous problem of providing a light source to be used where people operate with image intensifiers and also which can be used in military vehicles and not be detected by enemy image intensifiers, the author is presently involved in the development of a specially designed filter which has a cut-off at 570 nm. When the filter is used it results in a blue/green coloured light which is not detectable when using 3rd-generation image intensifiers.

The introduction of the blue/green light raises a number of important questions such as the following:

1. To what degree will low level blue/green ambient illuminance/luminance affect visual acuity when compared with white and red light?

2. To what degree will low level blue/green ambient illuminance/luminance affect contrast sensitivity when compared with white and red light?

3. To what degree will low level blue/green ambient illuminance/luminance affect visual threshold levels compared with white and red light?

4. To what degree will pre-adaptation to low level blue/green ambient illuminance/luminance affect subsequent dark adaptation when compared with white and red light?

The aim of the present study was to resolve the above-mentioned issues and to provide design guidelines as to which colour of lighting should be used depending on the type of application as well as the illuminance/luminance levels required.

1.2 Research Hypotheses

A number of hypotheses were generated to enable a broad examination of the relationship between the colour and intensity of pre-adaptation stimuli and certain human visual functions.

1.2.1 Low level blue/green illuminance/luminance will affect human visual acuity in the same manner as white and red lighting of equal photopic efficiency.

Stated statistically, the null hypothesis was:

Ho : μ (blue/green) = μ (white) = μ (red)

Where μ is the populational mean luminance of the visual field necessary to obtain a certain visual acuity after a specific pre-adaptation period.

The alternative hypothesis was:

Ha : μ (blue/green) $\neq$ μ (white) $\neq$ μ (red)

1.2.2 Low level blue/green illuminance/luminance will affect human contrast sensitivity in the same manner as white and red lighting of equal photopic efficiency.

Stated statistically, the null hypothesis was:

Ho : μ (blue/green) = μ (white) = μ (red)

Where μ is the populational mean luminance of the visual field necessary to obtain a certain contrast sensitivity after a specific pre-adaptation period.

The alternative hypothesis was:

Ha : μ (blue/green) $\neq$ μ (white) $\neq$ μ (red)

1.2.3 Low level blue/green illuminance/luminance will affect the human visual (absolute) threshold in the same manner as white and red lighting of equal photopic efficiency.

Stated statistically, the null hypothesis was:

Ho : μ (blue/green) = μ (white) = μ (red)

Where μ is the populational mean absolute threshold of light perception of the whole retina (integral dark adaptation).

The alternative hypothesis was:

Ha : μ (blue/green) $\neq$ μ (white) $\neq$ μ (red)

1.2.4 Pre-adaptation to low level blue/green illuminance/luminance will affect human dark adaptation in the same manner as white and red lighting of equal photopic efficiency.

Stated statistically, the null hypothesis was:

Ho : μ (blue/green) = μ (white) = μ (red)

Where μ is the populational mean absolute threshold of light perception in the course of dark adaptation of the whole retina (integral dark adaptation).

The alternative hypothesis was:

Ha : μ (blue/green) $\neq$ μ (white) $\neq$ μ (red)

1.3 Delimitations

Ninety adult male subjects between the age of 20 and 40 years acted as subjects for this study. Each subject received a preliminary ophthalmologic examination. All subjects had at least 6/6 visual acuity (corrected), normal contrast sensitivity as well as colour discrimination. Each subject was randomly assigned to one treatment condition, (there were 15 treatments in total) determined by the intensity of the pre-adaptation light stimuli and the colour of pre-adaptation stimuli. There were 5 different intensities of the pre-adaptation stimuli (0.1, 0.4, 1.6, 6.4 and 25.6 cd/m^2) and 3 colours of pre-adaptation stimuli (blue/green, red and white).

For the first 20 min. each subject was required to remain in complete darkness in order to dark adapt. For the next 20 min. each subject was light pre-adapted to the selected intensity and colour as defined by the treatment condition. During the last 10 of the 20 min. of light pre-adaptation visual acuity (5 min. of arc) and contrast sensitivity 20% tests were conducted with each subject using the Goldmann/Weekers Adaptometer.

After the 20 min. of light pre-adaptation the lights were turned off and for each subject the threshold of light perception in the course of dark adaptation of the whole retina was determined with the Goldmann/Weekers Adaptometer using a 100% contrast target in the centre of 11° test field.

1.4 Limitations

Several logistical limitations must be borne in mind when examining the implications of these experimental results and subsequent conclusions.

1.4.1 The subjects could not be randomly selected. The size of sample, the substantial time commitment and the nature of the tests meant that potential subjects were approached with an explanation of experimental procedures and a request for voluntary participation. Every attempt was made, however, to approach as broad a spectrum of potential subjects as possible.

1.4.2 Subjects were not all tested at the same time of day. Thus visuo-perceptual fatigue might have influenced the experimental results.

1.4.3 The pre-adaptation light stimuli were photopically equated. The photopically measured levels under estimates the relative visual effectiveness of the blue/green light and over estimates that of the red due to the Purkinje shift. The reasons for using photopic measurements were two-fold. Firstly this is the accepted method for determining the amount of light stimulating the visual system and would be the method used by lighting engineers in making measurements at low intensities. Secondly, no standard has yet been specified by the International Commission on Illumination for measuring light quantities in the mesopic range.

1.4.4 The final thresholds for the adaptation tests in this study were higher than thresholds determined by the conventional technique because of the following reasons:

1.4.4.1 Morphoscopic identification (orientation of 100% contrast grating) rather than a simple light perception.

1.4.4.2 Change of adaptation state due to the effect of the test stimulus.

1.4.4.3 Mental fatigue due to sustained attention required in the continuous recording.

Limitations of this nature are typical of the problems facing research into human dark adaptation. They were considered to be noteworthy but not stultifying.

2. REVIEW OF THE LITERATURE

2.1 General Overview

Before conducting a critical appraisal of the related literature it is deemed necessary to provide a brief overview of the structure of the eye and to define some of the relevant terminology. Furthermore, factors affecting dark adaptation, as well as important criteria for the measurement thereof, are required as a basis for the critical review of the literature.

2.1.1 The Structure of the Visual System

The basic structure of the human eye is shown in Figure 1. Light enters the eye by first passing through the transparent protective covering called the cornea. The curved surface of the cornea produces most of the focusing of the image that falls on the retina (Kantowitz and Sorkin, 1983). Behind the cornea the light passes through a chamber of transparent fluid, the aqueous humor, and then through the pupil, an opening in the iris which can change in diameter.

The size (diameter) of the pupil, which can vary from 2 mm to 8 mm, is determined by several different interacting factors. It is primarily controlled by feedback from the photoreceptor surface, the retina. If the amount of light reaching the retina is too great for the state of adaptation prevailing then the pupil size is reduced. If the amount of light is too small then the pupil size is increased. Feedback from the retina is not the only factor that influences pupil size, for according to Boyce (1981) and Kantowitz and Sorkin (1983) emotional state of the individual will affect it, as will the distance at which the eye is focused.

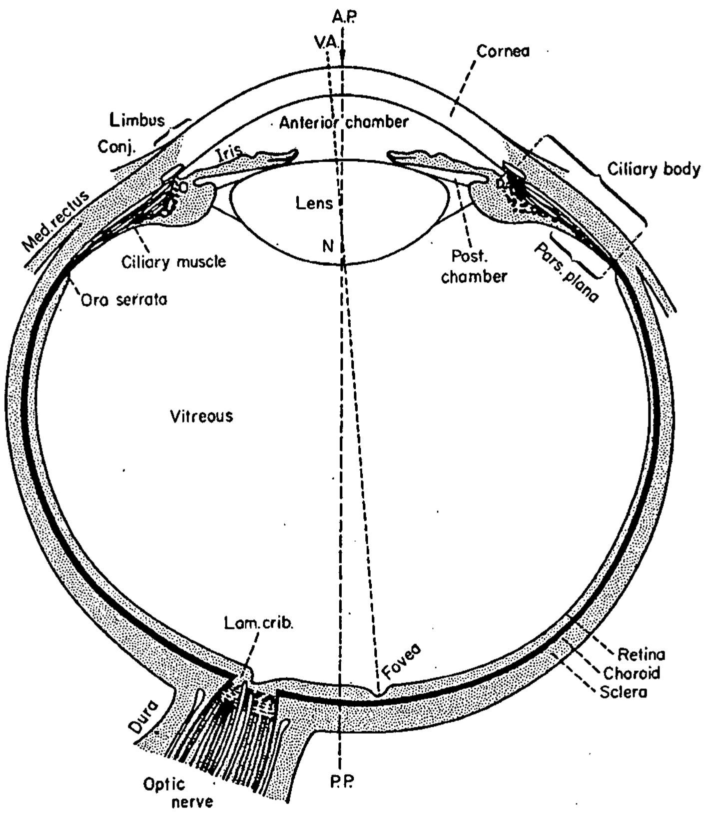

Figure 1 : Horizontal section of the human eye. (From <u>The Ergonomics of Lighting</u>, 1970 by Hopkinson, R G and Collins, J B, Mac Donald Technical and Scientific, London).

After passing through the pupil, the light passes through the lens. Focusing of the image on the retina is accomplished by changing the refractive power of the lens which is dependent on the shape of the lens. This process, called accommodation, is accomplished by increasing or decreasing the lens thickness. The process is relatively slow, taking almost 400 msec for a complete change from near vision to far vision (Kantowitz and Sorkin, 1983). After passing through the lens, light then travels through a jelly-like fluid called the "vitreous body" before reaching the light-sensitive region, the retina, at which location it undergoes a photochemical transformation (Boyce, 1981).

The structure of the eye is often likened to a camera and it is easy to see why this should be so. The eye produces an image on a photo-chemically sensitive surface by means of a lens, and the amount of light admitted is controlled by an aperture. However, as soon as the retina is considered, the analogy breaks down. The retina is a very complicated structure, as can be seen from the section shown in Figure 2. Basically it can be considered as having three layers : a layer of photo-receptors which are conventionally divided into two functional types, named rods and cones, because of their characteristic shapes; and a layer of bipolar cells which provide interconnections amongst themselves and from the photoreceptors (rods and cones) to the third layer, the ganglion cells. Each ganglion cell links to one nerve fibre which extends from the eye along the optic nerve to the brain (Boyce, 1981).

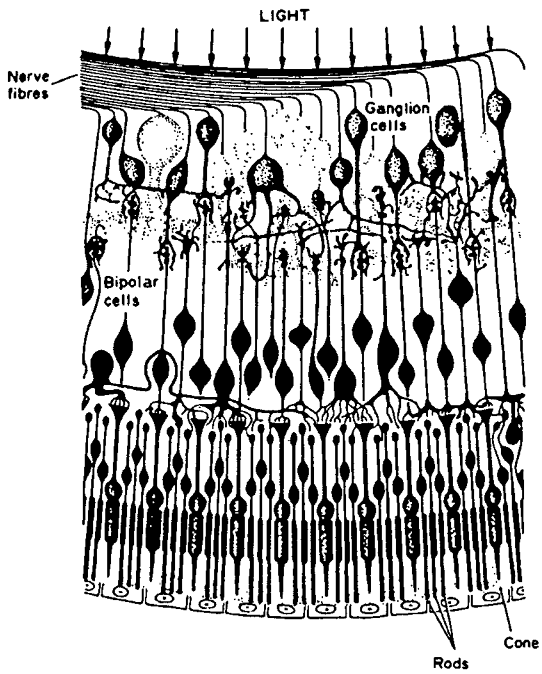

Figure 2 : Schematic illustration of the retinal structure. (From Human Factors in Lighting, 1981 by Boyce, P R, Applied Science Publishers, London)

It should be realised that response to light is not the same for the entire surface of the retina. This is partly because the rods and cones have different spectral sensitivities and different absolute sensitivities to light and are not evenly distributed across the retina (Boyce, 1981). Figure 3 illustrates how the rods and cones are distributed throughout the retina on a horizontal meridian. The cones are concentrated on the visual axis in an area called the fovea. Outside the fovea there is initially a rapid increase in the number of rods and then a steady decline until, by the far periphery, there are almost the same number of rods and cones. The distribution is symmetrical about the visual axis except for the "blind spot" where the nerve fibres from the ganglion cells leave the retina so that there are no photoreceptors in this area (Figure 3). In the fovea there is more of a direct one-to-one connection of receptor cells (cones) to the fibres of the optic nerve.

This central region is optimally located for the area of the optical image that the eye is directly fixating, and it has the best capacity for resolving fine details of the image. It is also the region responsible for human sensitivity to colour (Kantowitz and Sorkin, 1983). The rods, on the other hand, distributed more widely around the periphery of the eye, are not colour-sensitive but have an extremely high sensitivity, so that their function is to permit seeing at very low levels of light. The rods are far less closely packed than the cones, and so the resolution of detail by rod vision is very much less precise than with cone vision. In other words, the eye sees best centrally in bright light, its resolution is very high and it is capable of detecting colour; whereas in near-dark situations, resolution is poor, colour vision is absent and vision, though nowhere good, is better away from the centre (Hopkinson, 1970).

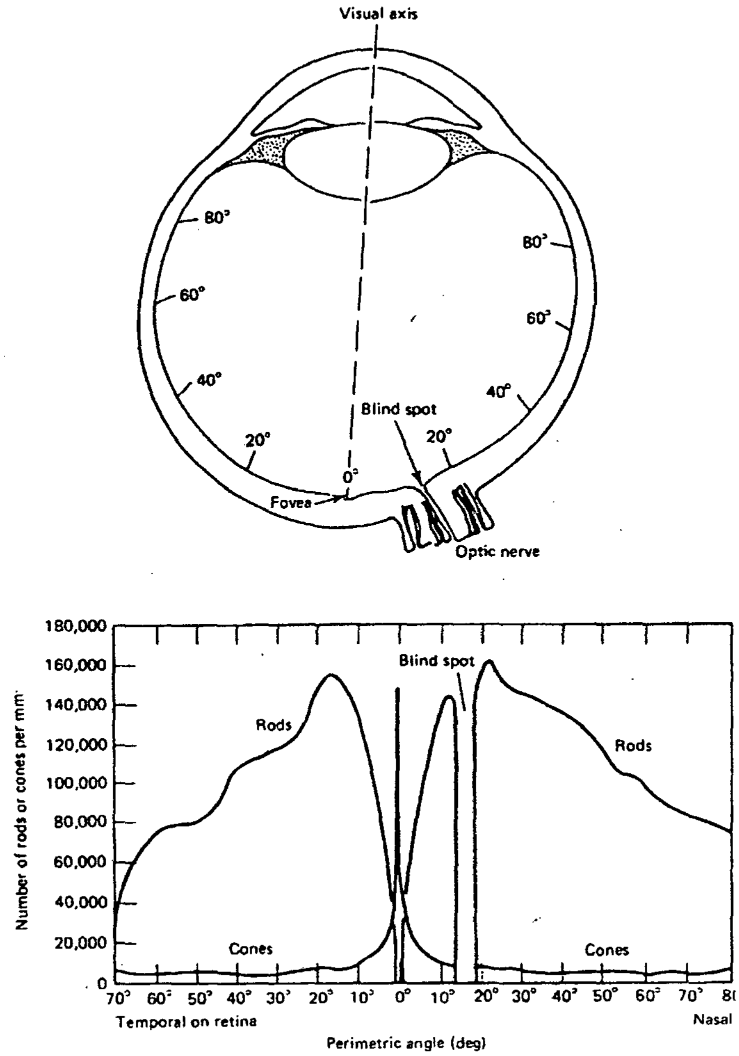

Figure 3 : Top view of the eye, and the distribution of rods and cones across the retina. (From Vision and the Eye, 1967 by Pirenne, M H, Chapman & Hall Ltd, London)

The cones are connected to the visual centres of the brain by a direct one-to-one link. The rods, on the other hand, are linked in groups to a single nerve path, so that these two factors, taken together with the closer packing of the cones, exaggerate even more the disparity between the resolution of the eye by cone vision and by rod vision (Hopkinson, 1970). There are also other differences between rods and cones. In Figure 4 the spectral sensitivity of rods, foveal cones and peripheral cones are shown. It can be seen that the spectral responses of the two cone types are similar and both are different from that of the rods. The rods are much more sensitive than the cones and differ in the wavelength to which they are sensitive. The peak sensitivity for cones is about 555 nm but that for rods is about 505 nm.

Since both rods and cones respond to incident light in the same way, i.e. by using the quanta to initiate a photo-chemical reaction, differences in spectral sensitivity suggest that rods and cones contain different photo pigments. This view is supported by another distinct difference between rods and cones mentioned briefly previously. It can be broadly said that cones operate during the daytime, at which level of radiant flux nearly all the photo pigment in the rods will be "bleached", so that the rods emit few if any signals (Boyce, 1981). However, at night-time there is insufficient radiant flux (the power received as radiation) to cause the cones to operate, so vision is mediated by the rods alone (Boyce, 1981).

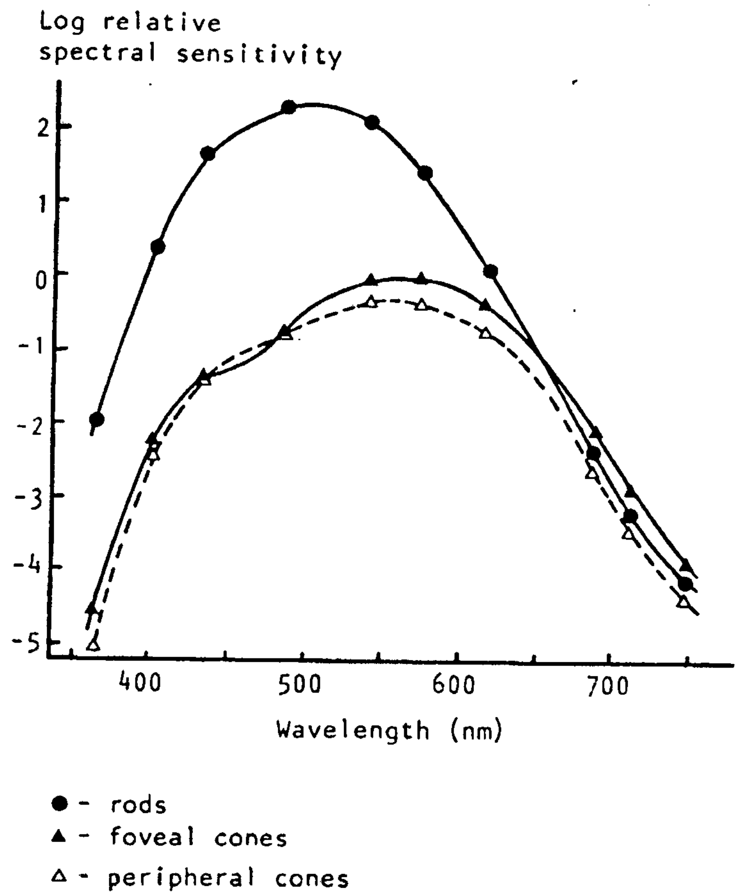

Figure 4 : Log relative spectral sensitivity of rods, foveal cones and peripheral cones plotted against wavelength. (From Human Factors in Lighting, 1981 by Boyce, P R, Applied Science Publishers, London)

Fundamentally, the human can be considered to have two separate retinas : a night retina consisting of rods only and a day retina which uses only cones. For field luminances below about $10^{-6}cd/m^2$ there is insufficient light for the visual system to operate at all. Between 10^{-6} and 10^{-3} cd/m^2 only the rods are operating, a condition conventionally referred to as scotopic. For fields of luminance above about 3 cd/m^2 the rods are saturated and only cones are important, this condition being called photopic. As is evident in Figure 4 the spectral response of the eye changes on moving from scotopic to photopic conditions, a change called the Purkinje shift. For visual field luminances between 10^{-3} and 3 cd/m^2 an intermediate state exists called mesopic, in which both cones and rods operate. Spectral sensitivity is intermediate between the scotopic and photopic extremes (Boyce, 1981). This classification of conditions may seem rather academic but it does relate to some major changes in visual capabilities. In scotopic conditions colours are not visible. As the mesopic condition is reached, colour vision starts to appear and strengthens until, when photopic conditions are reached, complete colour vision is available. In scotopic conditions only the rods are operating so the fovea is blind, in other words the retinal area used for fine discrimination of detail is not functioning. The best discrimination that can be achieved is in the near periphery where the size of receptive fields is greater than in the fovea. This means that discrimination of detail is reduced in scotopic conditions. Again there is no abrupt transition. In the mesopic state, discrimination of detail in the fovea improves above that for the scotopic condition, but is not as good as in photopic conditions (Boyce, 1981).

It will be apparent from the foregoing discussion that the human visual system can operate over a very large range of luminances. According to Kantowitz and Sorkin (1983) the human eye is sensitive to light over almost a 10^{13} span of intensity, or 13 log units, but at any given moment the human eye can accurately discriminate among different light intensities only over a much smaller range of about 2 log units.

Within this smaller range of intensities humans can make very accurate intensity discriminations of less than 1% (Kantowitz and Sorkin, 1983). This 2 log unit range of discriminable intensities is called the operating range of the system. Its location within the larger 13 log unit span of sensitivity depends on the state of adaptation of the eye. If the eye is exposed to a suddenly dimmer or much more intense light, it will be unable to respond accurately to small intensity changes. When the average level of illumination is changed, the visual system adapts to the new level, and the operating range shifts to a new position. This whole process of adjustment of the visual system to the prevailing conditions is called adaptation.

Putting a person in the dark for 40 min. will push his operating range to its lowest and most sensitive position. The curves in Figure 5 illustrate the time course of this adaptation as a function of the amount of time the person is in the dark after initial stimulation to an intense source of light. As can be seen from Figure 5 the threshold decreases (sensitivity increases) as a function of time in the dark. There is an initial rapid threshold-decrease of about one log unit that flattens out after about 10 min. This corresponds to the recovery of the cone system in the fovea of the eye. During this period the rod system will slowly increase in sensitivity until after 30 or more min. an additional decrease of several more log units of threshold will occur (Kantowitz and Sorkin, 1983). This whole process of adjustment of the visual system to darker conditions is called dark adaptation.

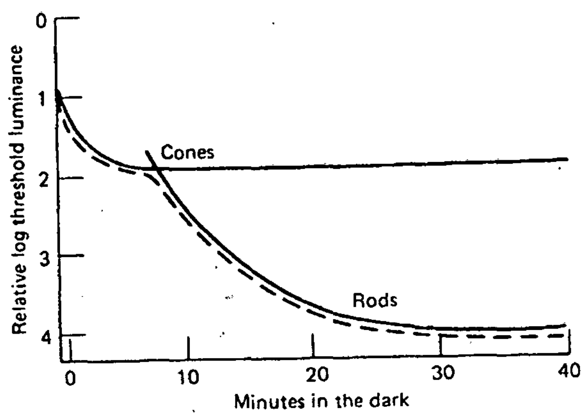

Figure 5 : Decreases in threshold of the rod and cone systems as a function of time in the dark; the dotted curve is a composite of the rod and cone function. (From Human Factors - Understanding People System Relationships, 1983, by Kantowitz, B H and Sorkin, R D. John Wiley & Sons, New York)

2.1.2 Factors affecting dark adaptation

Since Aubert first described the phenomenon of dark adaptation (Donaldson, 1983), a large number of factors have been investigated whose influence on the course or end point of adaptation had been suspected. These factors, apart from disease and unusual conditions, may be considered in two categories: endogenous factors which have an individual physiological and anatomical basis and account for biological variability, and exogenous factors in the environment which are subject to experimental control.

2.1.2.1 Hypoxia

Hypoxia seems to produce a general darkening of the visual field subjectively. A clear demonstration of the effects on night vision threshold was given by McFarland and Evans in 1939. They showed significant changes in the visual threshold values in 15 of their 20 subjects breathing an oxygen mixture such that the oxygen concentration was 15.7% (equivalent to an altitude of 2 256 m). At an equivalent altitude of 4 572 m (11.7% oxygen) the threshold returned to the sea level value in two or three minutes after inhaling oxygen. Upon further deprivation in four subjects, the threshold rose again to the 4 572 m level within two minutes.

The curves for dark adaptation obtained while breathing diminished partial pressures of oxygen were approximately parallel to the curves at sea level. Hecht et al. (1946) showed that both rod and cone portions of the curve are affected by low oxygen concentrations. Since threshold could be varied in the dark adapted subject by increasing or decreasing the partial pressure of oxygen, it suggests that the effect is mediated through nervous tissue. Mc Farland et al. (1945) found that for a given subject, the effect of hypoxia on the threshold values varied from day to day.

Sheard (1944), using a different procedure, was able to detect a difference in sensitivity with the subject breathing a mixture which gave a simulated altitude of 1 524 m. Wald et al. (1942) in his experiments showed a lowering of the average threshold at a simulated altitude of 1 219 m, although he pointed out that at 3 048 m there was an overlap with the ground level values. Response time to peripheral retinal stimulation is, in part, a measure of rod function and according to Kobrick (1970; 1974) hypoxia has been shown to have a detrimental effect on response time.

2.1.2.2 Carbon Monoxide

Halperin and co-workers (1959) reported a series of experiments in which they used four well-trained subjects breathing gas mixtures while dark adapted. Their visual threshold levels were tested at 10 min. intervals with a

Crosier Holway discriminometer and thus only cone vision was involved according to Donaldson (1983). Carbon monoxide (CO) was introduced into the system and the amount of CO in the blood was estimated using finger prick samples taken at 10 to 15 min. intervals. A rise in visual threshold was demonstrated following successive doses of CO. An effect was noticeable when the carboxy haemoglobin percentage in the blood rose from a pre-set 0.5% to 4.5%. The immediate effect was approximately the same as that produced by an equivalent amount of oxygen desaturation in the arterial blood. According to Halperin (1959) the recovery from the effects of carbon monoxide will lag behind the elimination of the gas from the blood, so the effects are related to the duration of the presence of carbon monoxide in the blood as well as to its concentration. In 1973 Mc Farland published the results of experiments wherein the subjects had carboxy haemoglobin levels in the order of 4%, 11% and 17%. Their dark adaptation levels were measured with a visual discriminometer. He was unable to demonstrate statistically significant differences in the test - retest results at carboxy haemoglobin levels less than 17%.

Luria and McKay (1979), using a night vision sensitivity test developed at the American Naval Research Laboratory, to sample the subjects' scotopic sensitivity at a number of retinal positions, could not demonstrate that breathing 195 ppm CO in air for three hours (enough to raise the carboxy haemoglobin level in the blood by approximately 10%) had any effect on night vision.

2.1.2.3 Smoking

The inhalation of tobacco smoke from three cigarettes was reported to increase the visual threshold to that obtained at an equivalent altitude of 2 286 m, and this was attributed to the influence of CO (Donaldson, 1983). In view of the evidence sited previously this, however, seems unlikely. Constriction of the retinal vessels by nicotine may be a factor according to Donaldson (1983) but Troemel (1951) showed a facilitation of dark adaptation with nicotine. Using an automatic adaptometer and 12 subjects Calissendorf (1977) was able to demonstrate only a minor impairment in dark adaptation, primarily in the mesopic range. The inconsistency in these results can most probably be attributed to different measuring devices, techniques used and individual variations.

2.1.2.4 Glucose

The ingestion of glucose (1 g per kg body mass) has been shown to counteract, to some extent, the raised threshold levels due to hypoxia at a simulated altitude of 5 486 m (Mc Farland et al.; 1940) and 50 g of glucose to counteract the effects at 3 871 m within six to eight minutes (Mc Farland et al., 1945). Following intra-muscular injection of insulin the dark adaptation thresholds were raised and the inhalation of oxygen lowered the threshold levels (Mc Farland et al., 1940; 1941).

According to Donaldson (1983) there is conflicting evidence on the effect of blood sugar when the subject is breathing air at sea level. In a glucose tolerance test, the dark adaptation thresholds were raised during the second hour when the blood sugar levels were falling and, in nine of ten fasting subjects, a normal breakfast was found to lower the thresholds (Mc Farland et al., 1940). Mc Farland et al. (1945) later reported the results of an experiment in which the dark adaptation thresholds were monitored following the ingestion of 50 g of glucose by fasting subjects and he found no change in visual sensitivity. Sheard (1944) reported that for his subjects, fasting for 15 or 16 hours, breathing oxygen at ground level not only increased the speed of dark adaptation but also produced lower thresholds than those obtained when the subjects were breathing air. After the ingestion of food, the threshold levels were approximately the same or better irrespective of whether the subjects were breathing air or oxygen.

2.1.2.5 Vitamin A

Following the work of Hecht and Mandelbaum (1939) it was held that a rise in the threshold of dark adaptation was a very sensitive index of dietary avitaminosis. In their study, using a Hecht-Shlaer Adaptometer, and two subjects on a diet almost free from Vitamin A, a trend was noticeable in their data after the first day of absence of Vitamin A from the diet. After 15 days, the rod threshold had risen to an extreme found only in 3 percent of the normal population examined. With a return to a balanced diet and Vitamin A supplements, the threshold remained elevated for two months.

According to Donaldson (1983) three facts are beyond dispute - Vitamin A is found in mammalian retinas (Wald, 1934); in some persons whose dark adaptation thresholds are high the administration of Vitamin A reduces the threshold; the threshold of dark adaptation can be raised by restricting Vitamin A in the diet. Sheard (1944) reported that three normal subjects on a diet containing only 100 to 300 international units of Vitamin A for periods of 42, 160 and 190 days respectively, maintained less than a 0.4 log unit rise in threshold for rods and cones.

Donaldson (1983) states that there is evidence to suggest that the skin and fatty tissues are depleted slowly of their stores of Vitamin A. Both the above experiments were well controlled according to Donaldson and used suitable apparatus, but the number of subjects was small and the effects of individual variations cannot be discounted. Donaldson furthermore states that the biophotometer was used in many studies in the late 1930's, which perhaps accounts for the reported varied effects of Vitamin A on dark adaptation, for this instrument does not incorporate some of the critical specifications for measuring dark adaptation.

Case reports of patients with coeliac disease (Norden and Stigmar, 1969) defective diets, follicular hyperkeratosis, and cirrhosis of the liver (Sheard, 1944), have shown marked rises in dark adaptation thresholds which were lowered to normal levels after therapy with Vitamin A. Sloan (1947) studied nine patients with elevated thresholds which were restored to normal levels following Vitamin A administration, sometimes with the addition of Riboflavin.

It may be concluded that severe Vitamin A deficiency causes an elevation of dark adaptation threshold throughout the dark adaptation process, but this is a late manifestation of Vitamin A deficiency. Recovery is variable.

Since it has been found that the reduction in Rhodopsin concentration from Vitamin A deficiency is related to the threshold in the same manner as the photopic "bleaching" of Rhodopsin (Dowling, 1960), there is little doubt of the mechanism of action of the deficiency according to Donaldson (1983).

2.1.2.6 Acid-Base Balance

Wald et al. (1942) investigating the effects of respiratory acid-base imbalance on dark adaptation threshold found that an increase in the rate of breathing room air could decrease the threshold by 0.12 log units in 5 to 10 min. On return to the normal rate of breathing, the threshold rose again in 2 or 3 min. The increases in sensitivity were abolished by adding 2% Carbon dioxide to the inspired gas. When acidosis was induced by gas mixtures containing 5% carbon dioxide, the threshold levels rose 0.2 to 0.5 log units both for normal and rapid ventilation. Donaldson (1983) showed that a subjects' threshold levels can improve as a result of hyperventilation accompanying anxiety.

2.1.2.7 Drugs

According to Donaldson (1983) very few of the drugs known to affect night vision will lower the dark adaptation threshold. Thyroid extract or Alpha dinitrophenal, given to three patients with cirrhosis of the liver or rheumatoid arthritis, apparently lowered the dark adaptation threshold (Patek & Haig; 1941). In a similar manner, Vitamin A administration has been observed to lower the threshold in cases of Vitamin A deficiency. There are no available reports which show a prolonged lowering of the threshold in healthy males after drug administration.

Individual metabolic differences account for a number of drug toxic effects on the visual apparatus. Drugs which interfere with oxygen transport or utilization adversely affect visual sensitivity. The phenothiazines can block Rhodopson synthesis and Halothane interferes with pigment regeneration (Donaldson, 1983).

Alcohol has been shown to have a detrimental effect on threshold values (Feldman, 1941), Dimenhydinate significantly degrades night vision (Luria et al., 1979) and Acetylsalicylic acid appears to have no significant practical affect on dark adaptation.

2.1.2.8 Exercise

In a study of four long distance runners under controlled laboratory conditions using the Hecht-Schlaer adaptometer, Jones and Wilcott (1977) reported elevation of the dark adaptation threshold during moderate exercise (pulse rate 100-120 b/min). The elevation of two or more log units occurred during the first 20 min. and was sustained throughout the period of exercise. They hypothesized that the decrement may have been due to the lack of increased ophthalmic artery pressure during exercise and changes due to cerebral auto-regulation reducing the blood flow to the retina.

2.1.2.9 Age

There is a general agreement on the detrimental effect of aging on night vision (Donaldson, 1983). Hecht and Mandelbaum (1939) found that the greatest effect of aging on dark adaptation was on the cone threshold, but they also describe a subtle shift in rod thresholds as age increased. Robertson and Yudkin (1944), using different apparatus, reported a significant correlation co-efficient between age and final rod threshold of 0.56 and that the range of variation in rod threshold increased with age, e.g. between 20 and 30 years it was 1.1 log units and between 50 to 60 it was 1.45 log units.

Mc Farland and Fisher (1955) studied 201 subjects using the Hecht-Shlaer adaptometer and described a consistent decline in ability to see at low levels of illumination with increasing age. They were able to predict the final threshold using age and a correlation co-efficient of 0.89. In their series, an increase of 13 years in age correspond to a multiple of 2 in the intensity of illumination necessary at threshold. As the Hecht-Schlaer adaptometer uses an artificial pupil, it seems unlikely that the deviation of the pupil size with age can account for the deterioration noted as was suggested by Robertson and Yudkin (1944). It seems more likely that the effect is neurological (Donaldson, 1983).

Zuege and Drance (1967) reported that thresholds increased with age particularly after 40 years of age, and their measurements were corrected for a 7 mm standard pupil. They also stated that most rod adaptation occurred within 20 min. in the under 50 age group and that the process was almost complete in 25 min. whereas, in the older group, it continued through 30 min.

2.1.2.10 Ethnicity

There is conflicting evidence regarding differences in dark adaptation between ethnic groups. Wyndham (1975) reports on a study of sixty Black South African male recruits to the gold mines. Their mean dark adaptation time was 33 min., with the majority of the sample being dark-adapted between 26 and 31 min. Caucasian military personnel of the same age-range as the Black mine workers took 29 min. on average to dark adapt, with a range of 18 to 26 min. A study conducted by Prestrude and Larson (1978), comparing the dark adaptation of 16 white and 12 black subjects, found no significant differences between the two groups.

2.1.2.11 Sex

Sex differences in the rate of threshold of dark adaptation have not been found in any large series (Donaldson, 1983) but in some experiments with few subjects differences have been noted (Riopelle & Bevan, 1953). Feldman (1941) had earlier reported that in his experience the threshold is higher in women. In a series designed to demonstrate any sex-related differences in the visual modality, Mc Guiness (1976) was unable to show any significant difference in threshold measurements.

Donaldson (1983) reported a significant increase in scotopic threshold in six women on the day of ovulation. It was suggested that the peak values of oestriol, luteinising hormone and vitamin A, which coincide with ovulation, may be related to the observed increase in sensitivity.

2.1.2.12 Ambient Light Levels and Day-to-Day Variation

Investigating the variability of dark adaptation Wolf (1960) reported that the variability in the final thresholds for rods and cones could be reduced by a factor of two if the subject was seated in the dark for 30 min. before the pre-adaptation light exposure. The tungsten filament lamp and lens system used for the pre-exposure gave a luminance of 4 775 cd/m^2 for 10 min. Elevated final thresholds for his subjects were found to be associated with prolonged periods outdoors or driving on a clear day without sunglasses. Seasonal sunlight changes may have an effect as Kinney et al. (1960), using a stimulus recognition technique, found a higher average percentage of stimuli identified in the winter months.

Mote et al. (1954) could not find any diurnal or seasonal factors which were a significant source of variation in the final threshold values obtained on their two subjects after a pre-adaptation exposure intensity of 3 960 cd/m^2 for 2 min. The examinations were repeated over a period of 11 months. In particular, there was no association between forenoon and afternoon recordings but the influence of factors in the early phase of rod adaptation could not be determined because of day-to-day variability. No seasonal changes were evident over the eleven month period. Craik and Vernon (1941) found that daily variations in the dark adaptation curve could be reduced to a range of 0.2 log units by a pre-adaptation exposure to 2.4 Lux viewed for 3 min. Hecht and Mendelbaum (1939) found a maximum day-to-day variation in threshold of 0.3 log units following pre-adaptation exposure to 4 775 cd/m^2 for 3 min. Sheard (1944) also found a 0.3 log unit variation in threshold from day to day. There is little change in the threshold levels over a period of minutes after adaptation (Donaldson, 1983).

Pre-adaptation exposure to ultra-violet light is followed by a later onset of rod-adaptation and a higher final threshold (Wolf, 1946).

2.1.2.13 Psychological Factors

Well motivated subjects perform well and confidence is engendered by training programs and practice, although there is little positive evidence to vouch for the improvement in night vision following training (Donaldson, 1983). Scano et al. (1970) found significantly better adaptation in a group of 35 military aircraft pilots than in a control group of 30 non-pilots. Training, motivation or both, may account for this apparent occupational difference.

Kinney et al. (1982) conducted an experiment to measure the subjective responses of sonar technicians to the colour of the ambient illuminance in a sonar control room. Three colours of ambient illuminance (red, white and blue) were used for this assessment. At the end of each session the subjects were asked to fill out a mood scale and to answer certain questions about the lights. The results indicated a general preference for blue lighting. Despite the overall preponderance of preference for blue illuminance the testing, conducted in submarines, revealed a distinct difference among submarine crews. Men on the first two submarines almost unanimously preferred blue, while the men from the third unanimously disliked blue.

The results of the mood questionnaire were in agreement with the answers to the general questions about the lights. The majority reported feeling good (active, alert, cheerful, efficient, etc.) in blue light; at the same time that they reported less negative feelings (annoyance, defiance, drowsiness, dullness, etc). However, similar to the response to light preference there were large differences in the results of the mood scale between submarine crews.

Unfortunately the results of this study are of limited practical value because of the large differences between the three submarines, a factor for which Kinney et al. (1982) had no explanation.

In a study on the effects of instrument panel luminance and chromaticity (colour) on reading performance and preference in simulated driving the subjects were asked to rate the 8 different colours used with regard to attractiveness and comfort. Their results showed that light blue was least attractive; red, blue/green, and green had neutral ratings; and orange, reddish orange, white and amber were rated most attractive. In regard to comfort no significant differences were revealed among the chromaticities. It is interesting to note that the warm colours (long wavelengths) were preferred in this study. In a study conducted by Galer and Simmonds (1985) on driver's responses to five different colours used for the lighting of car instrument panels the shorter wavelengths or colder colours such as green and blue/green were preferred.

Because the present study was mainly concerned with the effect of light of different wavelengths (colour) on certain human visual functions (physiological) it was deemed necessary to briefly discuss the psychological effects of colour. The *"psychological effects"* of colour refer to the optical illusions and other psychological phenomena that are triggered of by colour. According to Grandjean (1982) these effects are caused in part by subconscious associations with previous sights or experience and partly by hereditary factors. They influence the psychological activity and thus the whole of a person's behaviour. Psychological effects can be induced, too, by colours arousing strong affective feelings of "like" or "dislike". It is clearly evident that colours do not only have physiological effects as being explored by this study but psychological effects and aesthetic consequences should also be taken into account (Grandjean, 1982).

According to Grandjean (1982) particular colours have their special psychological effects which are all more or less similar in character, though with great individual variation. The most important chromatic illusions concern distance, temperature and the effects of the general psychical affectivity. These illusory effects of individual colours are summarised in Table I.

Table I : Psychological effects of colour (after Grandjean, 1982)

COLOUR	DISTANCE EFFECT	TEMPERATURE EFFECT	PSYCHICAL EFFECT
Blue	Further away	Cold	Restful
Green	Further away	Cold to neutral	Very restful
Red	Close	Warm	Very stimulating, not restful
Orange	Very close	Very warm	Exciting
Yellow	Close	Very warm	Exciting
Brown	Very close, claustrophobic	Neutral	Exciting
Violet	Very close	Cold	Aggressive, unrestful, tiring

According to (Grandjean, 1982) all dark colours are generally oppressive and tiring and these surfaces also absorb the light. All light colours are bright, friendly and cheerful, whilst such surfaces scatter light and brighten up an area.

2.1.3 Important Criteria for Measurement of Dark Adaptation

The difficulty in making reproducible measurements of night visual capacity is evidenced by the multiplicity of procedures which have been employed (Donaldson, 1983). For meaningful estimates of visual threshold which are comparable between individuals, a number of variables must be controlled in the apparatus and technique. All those variables important for measurement of dark adaptation are briefly reviewed in the following paragraphs.

2.1.3.1 Pre-adaptation Stimulus

The effects of prior ambient light levels have been discussed in paragraph 2.1.2.12. That the course of dark adaptation varies with pre-adaptation light intensities was established as early as 1937 by Hecht and his co-workers. Pre-adaptation intensities below 200 photons (a photon is the retinal illumination produced when the eye looks through a 1 mm^2 pupil at a surface whose brightness is 0.314 millilamberts) were followed only by rod adaptation and intensities above 4 000 photons were followed first by cone adaptation and then by rod adaptation. Rapid rod adaptation was evident after pre-adaptation to low intensities and delayed rod adaptation followed high intensity pre-adaptation stimulation (Hecht et al., 1937). These findings were elaborated on by Mote and Riopelle (1953). Their results showed that if the pre-adaptation intensity was increased over a constant duration or if the duration was extended at constant intensity, the initial threshold rose and dark adaptation was prolonged. However, they found that a given increase in intensity exerts a greater effect than a corresponding increase in duration. At lower intensities of pre-adaptation, coloured stimuli are seen at lower threshold values.

Hecht and Hsia (1945) established that dark adaptation is much faster following red light pre-adaptation, demonstrating that it may be 30 times as bright as a white light and still be followed by the same speed of dark adaptation. The value of red light in pilot ready rooms was demonstrated by research conducted at the American Air Force School of Aviation Medicine (Rowland and Sloan, 1944). An exposure time to red light of 3.5 to 5 min was found to result in the most effective adaptation (Polinsky and Young, 1956). Hulbert (1951) also demonstrated the advantage of red illumination for dark adaptation. A dominant wavelength of 626 nm resulted in the most rapid adaptation and the maximum difference between threshold levels obtained following exposure to light having a dominant wavelength of 626 nm and white (neutral) light was 0.5 log units (Rowland and Sloan, 1944). Connors (1966) some years later determined that after 1 min. of pre-adaptation to light of 610 nm recovery was faster than after exposure to an equally bright light of 595 nm, but after 5 min. of pre-adaptation exposure, recovery time was progressively shortened by lengthening the wave length to 640 nm. Beyond 640 nm, lengthening the wave length resulted in no meaningful increase in scotopic sensitivity.

These advantages of red light for dark adaptation are predictable from the luminosity curves of scotopic and photopic vision.

2.1.3.2 Test Stimulus

As the visual system is capable of spatial summation over a limited time interval, the larger the test field used in a threshold measurement, the lower will the threshold luminance be. Constant energy in a test flash luminance and area are reciprocally related within the limits of complete spatial summation. However, spatial summation capability appears to change during the course of dark adaptation, according to Records (1979).

Research conducted by Burg (1967) demonstrated that different test light wavelengths can give different forms of the dark adaptation curve. With red light as the test stimulus there may be no rod branch evident in a dark adaptation curve and if blue light is used, the rod branch will fall to the lowest threshold level.

Within the time interval for spatial summation by the visual system, luminance and flash duration are reciprocally related up to a critical duration which is longer in the dark-adapted eye. If the flash duration (test stimulus duration) exceeds the critical duration, the threshold energy and the dark adaptation curve may be altered (Records, 1979).

2.1.3.3 Retinal Location

Hecht and his co-workers (1935) determined that the observed differences in dark adaptation for centrally and peripherally located fields were related to real changes in sensitivity. Riopelle and Bevan (1953) were able to plot contours of equal sensitivity of the retina for the dark-adapted eye. They found maximum sensitivity on either side of the fovea on a horizontal meridian 20^0 to 30^0 eccentrically. Experiments by Sloan (1950) and Zuege and Drance (1967) support this view.

2.1.3.4 Size of the Pupil

The pupil is capable of changes in diameter by a factor 5 or 6 and this is associated with a change in retinal illumination by a factor of approximately 20. This must be taken into account during threshold measurements (Donaldson, 1983). Sloan (1950) computed a correction factor in log units to compensate for the reduction in the amount of light reaching the retina due to a decrease in the effective diameter of the pupil with the distance from the axis of fixation.

2.1.4 Variability in Threshold

Having regard for the many environmental, physiological and psychological influences described and the limitations of the apparatus and technique for measuring dark adaptation, it is no surprise that there is considerable variability in the threshold values even in large series.

In the frequently referenced work of Hecht and Mandelbaum (1939) who used a Hecht-Schlaer adaptometer, a pre-adaptation exposure level of 4 775 cd/m^2 and a pre-adaptation field occupying 35° of visual angle for 3 min, the authors plotted the course of dark adaptation in 110 subjects drawn from a university population. They found the range to be approximately 4 log units and a total spread of the final rod thresholds to be 1 log unit (0.3 log unit was held to be the expected day-to-day variation) about a mean of 1 000 micro-microlamberts.

Using a group of 45 airline pilots, Sheard (1944) found a variation of 0.5 to 0.7 log units about a mean of 100 000 micro-microlamberts. Sloan (1947) assessed normal variation in 101 subjects ranging in age from 14 to 70 years. The mean log threshold (micro-microlamberts) at 19 different retinal locations was 4.41 with a standard deviation of 0.25 log units.

Mc Farland and Fisher (1955), using the Hecht and Shlaer apparatus and technique with 201 subjects between 20 and 60 years of age, found a final threshold mean of 2.92 log units micro-microlamberts and standard deviation of 0.2 log units. These figures are in a close agreement with those of Hecht and Mandelbaum (1939).

2.2 Critical Review

From the general overview of the literature it is evident that there are a large number of variables that have an effect on human dark adaption. Since there will certainly be difficulty controlling all these variables, it is the aim of this critical review to reduce these variables. Only those variables closely related to the objective of the present study are, therefore, reviewed in the following paragraphs.

As indicated previously the wavelength (colour) of the light is important with regard to whether or not it is detected using an electro-optical device. From the preceding general literature overview it is also apparent that the wave-length of the pre-adaptation stimulus plays an important role in the speed of dark adaptation. Similarly the pre-adaption intensity and duration will exert a significant influence on dark adaptation levels. In order to be able to justify further research, it is necessary to more critically review the closely related research conducted previously, pertaining to the effect of the wavelength and intensity of pre-adaption stimuli on dark adaptation and other selected visual functions.

In one of the earliest studies of the influence of light adaptation on subsequent dark adaptation of the eye, Hecht and co-workers (1937) determined that the course of dark adaptation of the human eye varies with the intensity used in the light adaptation which precedes it. Pre-adaptation to intensities of white light below 200 photons is followed by only rod adaptation, while pre-adaptation to intensities above 4000 photons is followed first by cone adaptation and then by rod adaptation.

In 1944 Rowland and Sloan studied the relative merits of red and white light of low intensity for adapting the eyes to darkness. They demonstrated that dark adaption proceeds much more rapidly after pre-exposure to red than to white light of the same photopic intensity of 185 cd/m^2. They furthermore demonstrated that, in order to provide the same degree of dark adaptation as is provided by exposure to 38.2 cd/m^2 of red light, about 9.55 cd/m^2 of white light could be used. One problem with their experiments is that they only used one subject, which raises questions regarding the reliability and validity of the results.

Ferguson and McKellar (1944) studied the influence of chromatic light stimulation on the subsequent rate of perception under conditions of low illuminance. They used various broad band wavelengths of light for pre-adaptation, viz. red (600 - 660 nm); amber (520 - 660 nm); green (490 - 600 nm); blue (433 - 525 nm) and white (400 - 750 nm). They also used various pre-adaptation intensities ranging from 5 to 200 lux. Unfortunately there are certain irregularities in their data. The general rule is that it takes longer to perceive the test stimulus with more intense pre-adaptation exposure. Some of the subjects on one or several occasions took a shorter time to perceive the test stimulus after having been subjected to a more intense pre-adaptation light source. The authors attributed these irregularities to the test method used, the mental characteristics of the subjects, the nature of the test stimulus, fluctuations of perception and the limitations of the test apparatus used.

Hecht and Hsia (1945) studied dark adaptation following light pre-adaptation to red and white lights and their results supported the findings of Rowland and Sloan (1944) mentioned previously. They also found that red and white lights, when equated for photopic (cone) vision and used for light adaptation, influence subsequent dark adaptation unequally. Following red light pre-adaptation, dark adaptation is much faster than following white. Hecht and Hsia (1945) also showed that, to produce the same dark adaptation in the same time, red pre-adaptation light may be held 4 times (in cd/m^2) as bright as white.

Hulbert (1951) carried out experiments in which an observer, previously dark-adapted, was stimulated for 3 min. by fields of various brightnesses and colours and the time required for him to become dark-adapted again was measured. They found that for pre-adaptation stimulation at 65 lux by photopic equally bright fields of various colours, the times to become dark-adapted were about 4, 5, 7, 11 and 13 min. for wave-lengths of 650, 550, 500 and 450 nm. There are, however, some doubts about the equal brightness of the various colours since only the white light was measured, whilst the others were either calculated or determined by hetero-chromatic comparison of each colour with a suitable one of the other colours. Since there are doubts regarding the exact intensity of the pre-adaptation stimulus colours the results are, to a large extent, invalid. Hulbert (1951) furthermore found that for equally bright white and red (650 nm) pre-adaptation stimuli at 1.1, 10.8, 107.6 and 1 076 lux, the times to become dark adapted were about 4, 5, 10 and 21 min. for white and 3, 4, 5 and 7 min. for red respectively. Although the results indicate that the time to become dark-adapted after red light stimulation is faster than after white stimulation, especially at higher brightnesses (intensities) the problems with the determination of equal brightnesses calls to question the validity of the results.

In order to answer a practical question as to the most effective red light to be used in military situations requiring dark adaptation, Smith and co-workers (1955) undertook an experiment to compare the effects of four "red" filters at constant brightness levels. Having problems with the then traditional methods of measuring dark adaptation, they developed an application of the method of constant stimuli which to their mind gave adequate accuracy of measurement. Their results show differences in the affects of adapting to 5.7 cd/m^2 of light having dominant wavelengths of 601, 626, 640, 690 nm and white (neutral). Dark adaptation proceeded most rapidly following pre-adaptation to 626 nm. As was the case with the previous experiment by Hulbert (1951), the equal brightness levels of 5.7 cd/m^2 for the various *"reds"* were calculated rather than measured.

In a study conducted by Hanson and Anderson (1960) of the effect of pre-adaptation stimulus colour (blue, green and red) on foveal dark adaptation they stated that the relatively low luminances (342.6 and 34.3 cd/m^2) and short duration of the pre-adaptation stimuli (100 and 10 s) which were used may not have been of sufficient magnitude to demonstrate additional colour effects. In addition, the variability of the thresholds obtained may have masked such effects. They conclude that these effects, if they do exist, are slight and would be of little importance in applied situations. Criticism that can be levied against their experimental procedure is that they used only 2 subjects. According to Hanson and Anderson they tried to avoid many of the problems inherent in hetero-chromatic photometry when they used the method of absolute thresholds to determine the equal brightness levels of the colours used for the pre-adaptation stimuli. The assumption underlying the method of absolute thresholds is that for the rod-free fovea, the absolute threshold corresponds to the photopic luminous efficiency determined at supra-threshold intensities and hence, that the various colours are equal in luminance at threshold. Unfortunately this method introduced the problem of fluctuations in the absolute threshold.

Connors (1966) studied the effect of wavelength and bandwidth of red light on recovery of dark adaptation. Recovery curves were determined following 1 and 5 min. pre-adaptation to wavelengths ranging from 595 to 670 nm taken at 15 nm intervals at a pre-adaptation luminance of 342,6 cd/m^2. The results indicate that after 1 min. of pre-adaptation to light of 610 nm, recovery was faster than after exposure to an equally bright light of 595 nm. Lengthening the wavelength caused no further reduction in recovery time. After 5 min. of similar pre-adaptation, recovery time was progressively shortened by lengthening the wavelength to 640 nm. Only three subjects were used and the brightness of the various wavelengths was equated for each subject by a direct match between each of the red pre-adapting lights and a red standard. This raises doubts regarding the validity of the results since brightness is an extremely critical factor to insure equality among the many conditions.

Cavonius and Hilz (1970) conducted research using 6 subjects to perform visual acuity and light detection tasks after exposure to monochromatic lights matched in photopic luminance. As in other studies reported here they found that visual sensitivity to dim lights recovers most rapidly after exposure to long wavelength (red) light. However, if a person is required to discriminate detail, his sensitivity recovers more rapidly after exposure to wavelengths around 600 nm than after exposure to other regions of the spectrum. Cavonius and Hilz stated that this unexpected result may have been due to interference by the scotopic system when viewing test objects it cannot resolve. According to them the traditional deep red filters used to preserve dark adaptation are therefore appropriate only when the subsequent visual task can be performed with scotopic vision alone.

A more recent study was conducted by Blouin (1982) to determine the effects of electroluminescent versus incandescent light sources on dark adaptation. Some of the parameters that were tested were the absolute luminance threshold of vision and the resolution of visual detail as provided by square wave spatial frequency gratings. Their results show that electroluminescent and incandescent light sources have the same effect on the absolute luminance threshold and the resolution of visual detail.

Apart from the influence of pre-adaptation wavelength (colour) and intensity of light on dark adaptation there is also the question regarding the influence thereof on other selected visual functions. In a study conducted by Reynolds (1971) photopically balanced white, green and yellow electroluminescent and red incandescent light at 0.17 cd/m^2 was compared in terms of legibility of a transilluminated letter - acuity chart as well as for their effects on scotopic acuity thresholds. Exposure to the red incandescent lighting at 0.17 cd/m^2 produced the lowest scotopic acuity threshold, with white and green electroluminescent producing higher thresholds in that order. Although threshold differences between lighting colours were statistically significant, the absolute differences in visual sensitivity were small for practical purposes. Luminances required for equal legibility of transilluminated letters of various sizes were about the same for red incandescent, and white, green and yellow electroluminescent lamps.

The effects of target wavelength (colour) on the resolution of moving targets were investigated by Long and Garvey (1988) over a range of target velocities under both photopic and scotopic viewing conditions. They determined that the wavelength of the photopically matched targets had no effect on dynamic visual acuity under the bright (37, 69 cd/m²) background condition. However with low background luminance the wavelength of the targets had pronounced effects with blue targets producing far superior resolution and red targets, the poorest resolution. The results of Long and Garvey indicated that at least under some conditions there is a strong effect of target wavelength on dynamic visual acuity. According to them these obtained colour effects do not mimic those reported for stationary targets (static visual acuity) in which blue targets typically exhibit a distinct disadvantage. Rather, mesopic-level blue targets were found by them to be much more easily resolved on the dynamic visual acuity task than other colours of equivalent photopic brightness but only under dark-adaptation viewing conditions. Under photopic viewing conditions there were no clear effects of target wavelength or colour.

Imbeau et al. (1989) studied the effects of Instrument Panel luminance and chromaticity (colour) on reading performance and preference in simulated driving. Subjects were required to read aloud words presented on two displays emulating written legends on automobile instrument panels while driving a simulated vehicle in night-time conditions. The words were presented in eight different colours, two luminance levels, four character sizes (7, 11, 17 and 25 min of arc) and two levels of word complexity. Their results indicated that colour of illuminance per se had little effect on reading and driving performance but did have a reliable effect on subjective preference. Luminance had an effect on performance only for the two smaller character sizes (visual acuity). The two smaller character sizes yielded significant performance decrements for older drivers. Only two luminances (low and high) were used and these were determined and equated subjectively for the different colours. Luminance thresholds were therefore not at issue in this study.

When studying photopically balanced white, red and blue ambient illumination of 1.3 Lux, Neri and Kinney (1982) failed to find any significant effect on contrast sensitivity as measured with vertically orientated sine wave gratings.

Conducting further research Neri et al. (1986) determined that red, blue and low-level white ambient illumination has no effect on detection of coloured targets on coloured backgrounds. They state however that this should not be construed to mean that the colour of ambient illumination is never an important factor in the choice of CRT display colours. They furthermore state that it probably had no effect in their study because it was very dim (2.2 Lux) compared to the CRT luminances of 13.7 cd/m^2. They expect the ambient illumination to affect CRT colour if they were the same intensity or if the CRT were dimmer.

Overall one or more of the following forms of critique can be levied against the research discussed previously. Rather small samples were used i.e. between 1 and 4 subjects. Durations of pre-adaptation ranging between 2 and 5 min., were too short. There are doubts regarding the accuracy of the determination of equal brightnesses of the pre-adaptation stimuli. Virtually all the dark adaptation studies cited considered only monocular vision and the number of pre-adaptation intensities were, in most cases, limited to one or at the most two. In some of the experiments cited, the test stimulus light was increased or decreased in brightness until it was *"just visible"*. In others, the test stimulus is of fixed brightness and the time at which it is first *"seen"* is recorded. These methods yield only one judgement at each brightness or time and since judgements are subject to normal variation, *"thresholds"* are not reliably determined.

To summarize, the following can be concluded from the literature reviewed:

1. If red and white light are photopically equated they will influence subsequent dark adaptation unequally.

Following red light pre-adaptation, dark adaptation is much faster than following white.

2. In order to provide the same degree of dark adaptation in the same time, red pre-adaptation light may be held 4 times as bright as white light.

3. If subsequent photopic sensitivity is required, red is not appropriate.

4. There appear to be conflicting results when comparing the effects of low intensity coloured ambient lighting, and the effect thereof on visual acuity and contrast sensitivity.

5. From the literature available there is no information regarding the effect of blue/green and red coloured light on colour discrimination and the quantification thereof.

6. Blue/green light with broadband wavelengths of less than 570 nm have apparently not been included in any experimental studies to date.

The results of the previously mentioned research are therefore of limited practical value in providing answers to the important issues raised in the problem statement. Prior to introducing the blue/green filters into military, and other possible commercial applications, it is therefore necessary to conduct a series of empirical studies in order to provide quantitative as well as qualitative data on the issues raised.

3. METHOD

3.1 Experimental Design

A 5 x 3 factorial design was used. The first independent variable i.e. the intensity of the pre-adaptation stimuli was represented by 5 different intensity levels. As for the second independent variable i.e. colour of the pre-adaptation stimuli, three colours were used.

All the possible combinations of the selected values of each of the independent variables are provided in Table II. There were 15 treatments in total.

Table II : 5 x 3 factorial design

	COLOUR OF PRE-ADAPTATION STIMULI		
	BLUE/GREEN	RED	WHITE
0,1 cd/m²	I	II	III
0,4 cd/m²	IV	V	VI
1,6 cd/m²	VII	VIII	IX
6,4 cd/m²	X	XI	XII
25,6 cd/m²	XIII	XIV	XV

3.2 Subjects

The experiment was conducted using ninety 20 to 40 year old male military and civilian personnel. Each subject received a preliminary ophthalmologic examination. No subject with less than 6/6 visual acuity (corrected), as measured with a standard eye chart, was included in the experiment. Subjects exhibited normal contrast sensitivity and colour discrimination as measured with the Vision Contrast Test System from Vistech and the Ishihara Colour Test respectively. An example of the recording sheet used for the preliminary ophthalmologic examination is provided in Appendix 1.

The sample was not entirely random, but there is no reason to suspect that the night vision capacity of the group would be different from a random sample's capacity. The subjects were, however, randomly allocated to the treatments, which resulted in 6 subjects per treatment.

3.3 Instrumentation and Procedures

3.3.1 Instrumentation

The Goldmann/Weekers Adaptometer (See Figure 6) was used during the experiments to provide the pre-adapting stimuli and measure the various visual functions (dependent variables). This adaptometer is the most commonly used modern adaptometer for clinical studies and was made to replace multiple instruments required for testing the various functions for the dark-adapted eye with one instrument.

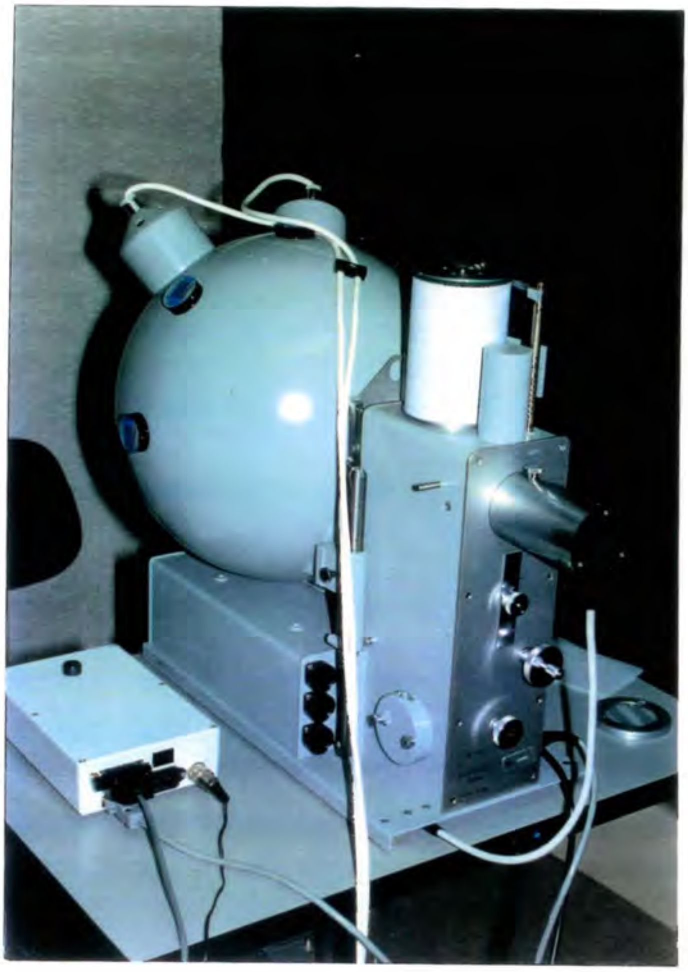

Figure 6 : Goldmann/Weekers adaptometer

Some modifications were added to the standard Goldmann/Weekers adaptometer. With the standard Goldmann/ Weekers adaptometer (See Figure 6) the determination of the luminance threshold is made in the usual manual manner by progressively increasing the intensity of the test light until the subject reports that he sees it. This value, of course, does not represent the absolute threshold itself but a slightly higher threshold, depending on the rate at which the intensity had been increased. The determination can be made more complete by subsequently decreasing the intensity until the subject reports that he no longer sees the test target. The true threshold (correctly defined as a luminance at which the test field is seen with a probability of 0.5) is presumed to be somewhere between the "threshold of appearance" and the "threshold of disappearance" determined in the manner described above. Usually the mean of both values is regarded as the luminance threshold on the absolute threshold of light perception. To have comparable probabilities of seeing, the rate of increasing and decreasing the intensity should be a uniform one:

$$\left(\frac{d \log I}{dt} = constant\right)$$

This is obviously impossible when the intensity is manipulated by hand by the experimenter. The first improvement/modification therefore made to the Goldmann/Weekers adaptometer was to design an automatic device operating the intensity control of the adaptometer.

This automatisation not only provided a better standardisation of the tests but also increased the accuracy and reliability thereof.

The method utilizes a technique devised by Bekesy (1947) for human audiometry. The intensity of repeated light flashes used for the determination of the absolute threshold of light perception during the course of dark adaptation is increased automatically until perception occurs. At this moment the subject presses a switch, causing an automatically continuous decrease of the intensity. When perception is completely lost the subject is required to press the switch again to increase the intensity and so on. The luminance of the test patch/target at each press of the switch is recorded continuously by computer as well as the time elapsed from the start of the test. The result is a curve oscillating above and below the threshold (See Figure 7).

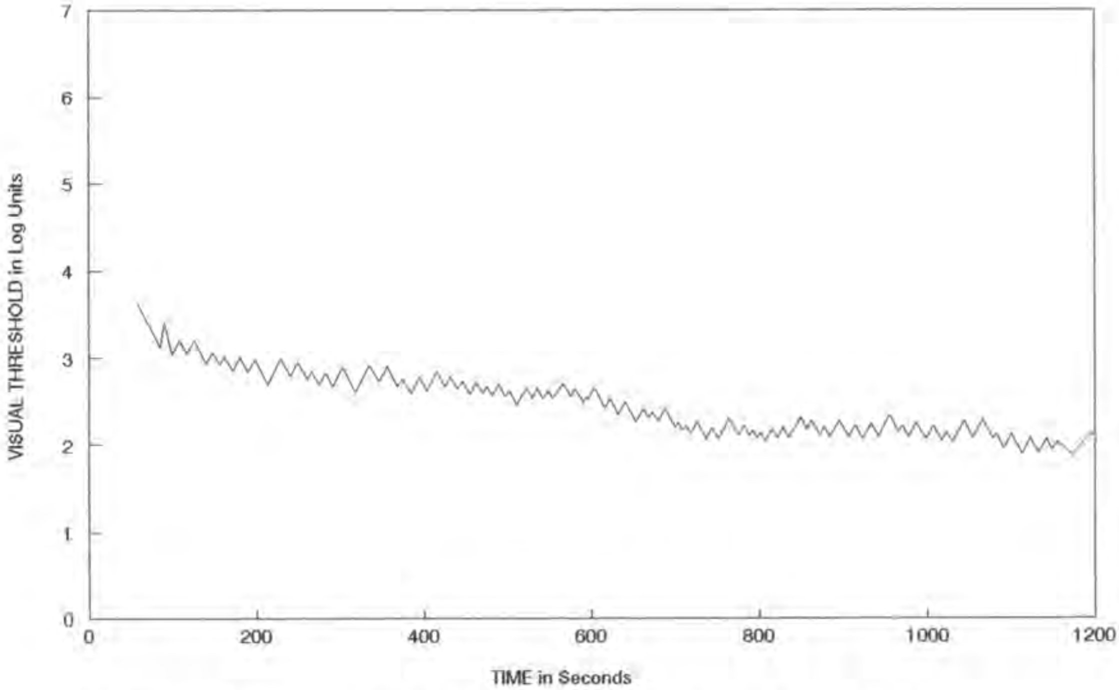

Figure 7 : An example of the adaptation curve result provided by the continuous method

The hardware comprised of a stepper motor which was used via a 1 : 4 gearbox to drive the intensity control of the adaptometer. The stepper motor was controlled using a MATSUSHITA 12 V, 1°/step control card. The control arc was powered by a 12 V, 1 A powersource. The quadrature pulses required to drive the control card were provided by a 386 SX Notebook Computer via its printer port. A copy of the software used to drive the control card of the stepper motor as well as record and store each individual subject's data is provided in Appendix 4. To enable the subjects to respond to the test stimuli, a press-switch was installed into the box housing the control card for the stepper motor. This box (See Figure 8) was placed in a convenient location for the subject's dominant hand as required.

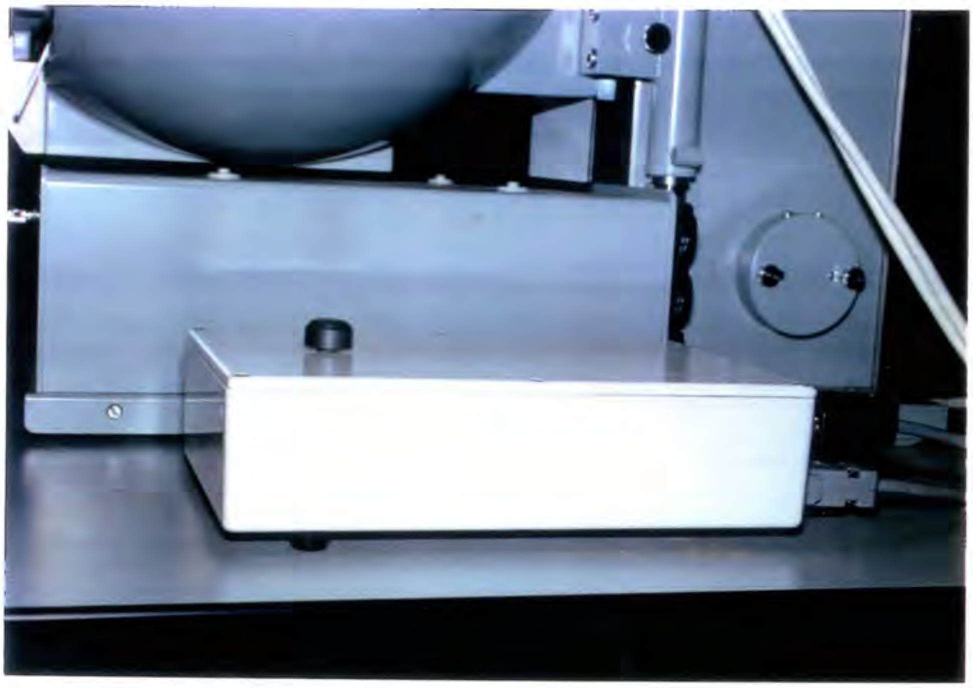

Figure 8 : Box housing the press switch and control card for the steppermotor

A gear ratio (1 : 4) was chosen which changed the intensity at the rate of 1.2 logarithmic units per minute. In the case of the visual acuity and contrast tests the luminance of the test target was increased continuously at the rate of 0.02 logarithmic units per second until perception of the targets occurred where upon it was required of the subject to immediately press the switch on the control box. The luminance of the test patch/target at the press of the switch was then recorded by the Notebook Computer, as was as the time elapsed from the start of the test.

In the case of the determination of the absolute threshold of light perception during the course of dark adaptation, the interruptor provided by the adaptometer gave a light-dark ratio of 1 : 1 with a frequency of 0.5 Hertz. The intensity difference between any two consecutive flashes was, therefore 0.04 logarithmic units.

Special filters were placed in filter holders in front of the two white lamps to produce the blue/green and red pre-adaptation lights. The transmission levels and wavelengths of these filters are provided in Figure 9. The blue/green filter is a broadband filter which effectively cuts off all light with wavelengths above 600 nm. The red filter is also a broadband filter which cuts off red light below 590 nm. The specially designed blue/green filter consists of a 3 mm thickness of EBG-38 glass. The glass is coated on the lower side by using the Physical Vapour Deposition (PVD) process with a layer of magnesium fluoride (MgF_2) as a protection layer. The other side of the glass is coated with 19 layers of titanium dioxide ($Ti\ O_2$) and Silicon dioxide ($Si\ O_2$) using the same PVD process. Because of the size of the filter holders housing the coloured filters the standard lamps supplied with the adaptometer could not be used since they were too large. Instead, low voltage (12 V 50 W) dichroic lamps with a colour temperature of 3 100 K were used as the white light source. A regulated constant power supply was also used in order to provide a steady brightness and colour of the two lamps during the test. The power supply was checked before and after each test.

The red filter was a commercially available Schott filter. The white light was produced by the abovementioned lamps of the adaptometer.

In order to produce the pre-adaptation intensities in the sphere of 0.1, 0.4, 1.6, 6.4 and 25.6 cd/m^2, neutral density filters were used in conjunction with the blue/green and red filters as well as for the white light condition. Two such neutral density filters which differ as to the percentage of light they transmit are illustrated in Figure 9. As can be seen, these filters effectively transmit all wavelengths between 400 and 800 nm to the same extent, the only difference being the amount of light transmitted; 13 %

Illuminance measurements were also conducted at the test plate inside the sphere of the adaptometer of the pre-adaptation intensities using a National Digital Luxmeter. The approximate illuminance (lux) values for the comparative luminance (cd/m^2) values were as follows:

0.1	cd/m^2	0.4	lux
0.4	cd/m^2	1.7	lux
1.6	cd/m^2	6.5	lux
6.4	cd/m^2	27.3	lux
25.6	cd/m^2	109.3	lux

The luminance of the visual field (test field) was calibrated to 7 logarithmic units = 1 cd/m^2 at maximum intensity using the illuminance meter provided with the Goldmann/Weekers Adaptometer. For recording and data analysis purposes logarithmic units were used rather than the luminance values in cd/m^2. The luminance values for the comparative log units were as follows :

7 logarithmic units = 1 cd/m^2

6 logarithmic units = 0.1 cd/m^2

5 logarithmic units = 0.01 cd/m^2

4 logarithmic units = 0.001 cd/m^2

3 logarithmic units = 0.0001 cd/m^2

2 logarithmic units = 0.00001 cd/m^2

1 logarithmic units = 0.000001 cd/m^2

0 logarithmic units = 0.0000001 cd/m^2

3.3.2 Procedures

After having passed the ophthalmologic screening test, each subject received the test instructions (See Appendix 2) and signed the consent form (See Appendix 3). Each subject was then informed as to his role as participant, the objectives, and the procedures for the test. Each subject was shown the various test plates/targets that were to be presented during the tests and was given the opportunity to try out the press switch. The procedures followed during the different tests were as follows:

3.3.2.1 Visual Acuity and Contrast Tests

For the first 20 min. each subject was required to remain in complete darkness in order to dark adapt. For the next 20 min. of light pre-adaptation at the selected intensity and colour as defined by the treatment condition the subject was asked to sit with his chin in place on the pad of the instrument, both eyes open (binocular viewing), the diaphragm slide closed and both lamps lighted. During the first 10 min. of light pre-adaptation the computer program was prepared by typing in the subject number, treatment condition and subthreshold starting position (5 log units or 0.01 cd/m^2) for the visual acuity test. The visual acuity test plate with the test area subtending 5 min. of arc was then placed in position behind the diaphragm slide. At the end of the 10 min. of light pre-adaptation the two lamps were switched off, the diaphragm slide was opened, the computer controlling the automatic intensity control was started and the test target lamp switched on. The subject, with his hand on the press switch was instructed to depress the switch the moment he felt he could correctly identify the three numbers, each subtending 5 min. of arc (6/30) situated in the centre of the 11° test field.

After having pressed the switch and correctly identified the three numbers subtending 5 min. of arc at the eye, the diaphragm slide was again closed and the pre-adaptation lights switched back on and the test lamp switched off. The visual acuity test plate was removed and the 20% contrast sensitivity test plate placed in position. A subthreshold starting position of 4 log units or 0.001 cd/m^2 was then selected for the contrast test. At the end of the 15 min. of light pre-adaptation the two lamps were switched off and the subject pressed the switch the moment he felt that he could correctly identify the orientation of the gratings of the 20% contrast target subtending 11° of visual angle (total test field area).

After having pressed the switch and correctly identified the orientation of the gratings of the test plate the diaphragm slide was again closed and the pre-adaptation lights switched back on and test lamp switched off. The 20% contrast test plate was removed and replaced with the 100% contrast test plate. The computer program was then used to instruct the automatic intensity control to adjust the starting position of the luminance threshold to a subthreshold starting position of 2.5 log units or 0.000015 cd/m^2. The knob on the adaptometer which produces intermittent illuminance of the test field was then activated.

3.3.2.2 Dark Adaptation Test

At the end of the 20 min. of light pre-adaptation the two lamps were switched off, the diaphragm slide was opened, the computer controlling the automatic intensity was started and the test target lamp switched on. The subject, with his hand on the press switch, was instructed to depress the switch the moment he felt he could correctly identify the orientation of the gratings of the 100% contrast test field and indicate the orientation to the experimenter. With the luminance of the flashing test field decreasing, the subject was then instructed to press the switch the moment he could not identify the orientation of the gratings, at which time the experimenter would change the orientation. With the luminance of the flashing test field increasing again the subject was instructed to press the switch the moment he felt he could correctly identify the orientation of the gratings and then indicate the orientation as either vertical, to the right, horizontal or to the left. The test continued in this manner for 20 min. with the experimenter changing the orientation of the gratings of the test field each time that the subject pressed the switch indicating he could no longer correctly identify the orientation of the gratings on the test field. At the end of 20 min. of determining the absolute threshold of light perception during the course of dark adaptation of the whole retina (integral dark adaptation) the test was stopped and the room lights turned back on. The total experimental procedure per individual did not take longer than 01h30.

3.4 Measurement of Dependent and Independent Variables

The following dependent variables were measured. In the case of the visual acuity test the luminance of the visual field in cd/m^2 necessary to obtain a visual acuity of 5 min of arc after a specific pre-adaptation exposure period, of 10 min was measured.

For the contrast sensitivity test, the luminance of the visual field in cd/m^2 necessary to obtain a contrast sensitivity level of 20% after a specific pre-adaptation period of 15 min, was measured.

In order to determine the absolute threshold of light perception in the course of dark adaptation, the luminance of the target stimulus (100% contrast) in cd/m^2 as well as the time course in seconds were recorded per individual subject. The measurement of the independent variables i.e. intensity of the pre-adaptation stimuli and the colour thereof has been described in section 3.3.

3.5 Statistical Analyses

All statistical analyses were done using the statistical software (PC) packages Statgraphics (Ver 5.0) and SAS (Ver 6.04).

The first step in the procedure was to calculate the descriptive measures and, where applicable, to draw graphs. Secondly, analysis of variance was carried out independently for the data produced in each test. Finally, curve fitting was done for the data captured during the adaptation test.

3.5.1 Analysis of Variance

Separate analyses of variance were conducted for the results of the visual acuity, contrast sensitivity and absolute visual threshold observations at the start of the dark adaptation process, the independent variables being the colour of the pre-adaptation stimuli (3 colours) and the intensity of pre-adaptation stimuli (5 levels). Additionally, for time intervals 60, 180, 300, 600 and 1 080 seconds, analyses of variance were conducted to determine differences between colours of pre-adaptation stimuli at specific intensities of pre-adaptation stimuli.

The 90 observations (individual results) may be described by the linear statistical model:

$$y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \epsilon_{ijk} \quad \begin{cases} i = 1,2,3,4,5 \\ j = 1,2,3 \\ k = 1,2,3,4,5,6 \end{cases}$$

with i being the intensity of the pre-adaptation stimuli
with j being the colour of the pre-adaptation stimuli
with k being the number of subjects per treatment condition.

where μ is the overall mean effect; τ_i the effect of the i[th] level of the row factor A; β_j the effect of the j[th] level of the column factor β; $(\tau\beta)_{ij}$ the effect of the interaction between τ_i and β_j, and ϵ_{ijk}, a random error component.

The following hypotheses about the equality of row treatments (intensity of pre-adaptation stimuli) were tested:

$H_0 : \tau_i = \tau_2 = \tau_3 = \tau_4 = \tau_5$

H_1 : at least one $\tau_i \neq 0$

and the equality of column treatment effects (colour of pre-adaptation stimuli) :

$H_0 : \beta_1 = \beta_2 = \beta_3$

H_1 : at least one $\beta_i \neq 0$

To determine whether column and row treatments interacted the following hypothesis was also tested:

$H_0 : (\tau\beta)_{ij} = 0$

H_1 : at least one $(\tau\beta)_{ij} \neq 0$

When the analysis of variance indicated that row and column means differed, the multiple comparison method known as Duncan's Multiple Range Test was used. This method enabled the discovery of specific differences between individual row or column means.

The adequacy of the model assumptions was also tested. The diagnostic tool used was residual analysis. The residuals should be normally distributed, independent and with a constant variance. Residuals were plotted in time sequence, versus fitted values $\hat{Y}_{ijk}$ and versus the independent variables : colour of pre-adaptation stimuli and intensity of pre-adaptation stimuli.

Examination of the different plots did not reveal any obvious inadequacies and the results obtained where therefore accepted.

3.5.2 Regression Curve Fitting

The data obtained from the 90 subjects when determining their absolute threshold of light perception in the course of dark adaptation consisted of the independent variable (X), i.e. Time (unequally spaced) and the dependent variable (Y), i.e. the Intensity of the Target Stimulus.

For each subject the following functions were evaluated:

- $Y = a + b x$ (Linear)
- $Y = ae^{(bx)}$ (Exponential)
- $Y = a + b \log x$ (Reciprocal)
- $Y = a x^b$ (Multiplicative)
- $Y = a + bx + cx^2$ (Quadratic)

The best fit was then selected using the coefficient of determination R^2 as criterion for the best fit. R^2, the coefficient of determination, is a measure which determines the adequacy of the model fitted to the data. A total of 450 curves were fitted and evaluated by R^2. Next the individuals were grouped into the 15 different treatment categories, each consisting of six individuals. For each of these categories the best fit was selected, again using the R^2-value to determine best fit. An additional 75 curves were fitted and evaluated.

3.5.3 Statistical Confidence

In order to test the significance of differences, variability and/or relationships the 0.01 level of probability was employed throughout the statistical treatment of the data. Judgements based on the results of these analyses must, therefore, be tempered with the knowledge that a 1 chance out of a 100 exists that a Type I error could have been committed. The Type 1 error, i.e. the probability of incorrectly accepting the alternative hypothesis in favour of the null hypothesis, was set at 0.01. It was felt that this was a reasonable and acceptable level of risk attached to any decisions taken regarding the hypothesis. Craik and Vernon (1941) reported a 3% daily variation in the dark adaptation curve of one individual. Hecht and Mandelbaum (1939), as well as Sheard (1944), found a maximum day to day variation in threshold of 4%. David (1956), whilst deriving a standard dark adaptation curve for the Goldmann/Weekers adaptometer, obtained a 5% variation during the early phases of dark adaptation and 3% during the later stages. The level of 0.01 can therefore be regarded as being conservative.

The chances of committing a Type II error, i.e. the probability of failing to reject the null hypothesis, are dependent upon the number of subjects tested. The sample size of 6 subjects per treatment condition was therefore selected on the basis of employing a 0.01 level of probability of committing a Type II error.

Thus, in relation to Type I and II errors, and considering the inherent small variability of the dependent variables and availability of subjects, the choice of the 0.01 level of probability was considered justifiable.

4. RESULTS AND DISCUSSION

4.1 Visual Acuity

The practical question at issue with these results is as follows:

"After having been subjected to blue/green, red and white light of similar intensity when entering darkness, are there significant differences in the background illuminances required to obtain the same visual acuity?"

A summary providing the means and standard deviations of the luminance threshold levels in cd/m^2 of the visual field required to obtain a visual acuity of 5 min. of arc after the specified pre-adaptation exposure period of 10 min. is provided in Table III. The means are also illustrated graphically in Figure 10. As can be seen there are relatively small differences between the three colours at each intensity as well as between the different intensities of pre-adaptation light.

Table III : Summary of results of visual acuity test

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m^2)	COLOUR OF PRE-ADAPTATION LIGHT		
	BLUE/GREEN	RED	WHITE
0.1	5.23 (0.07)	5.26 (0.07)	5.43 (0.16)
0.4	5.41 (0.17)	5.36 (0.11)	5.43 (0.07)
1.6	5.43 (0.19)	5.43 (0.11)	5.51 (0.11)
6.4	5.49 (0.10)	5.63 (0.18)	5.55 (0.20)
25.6	5.66 (0.18)	5.77 (0.14)	5.65 (0.22)

*** Note : Standard deviations are provided in brackets.**

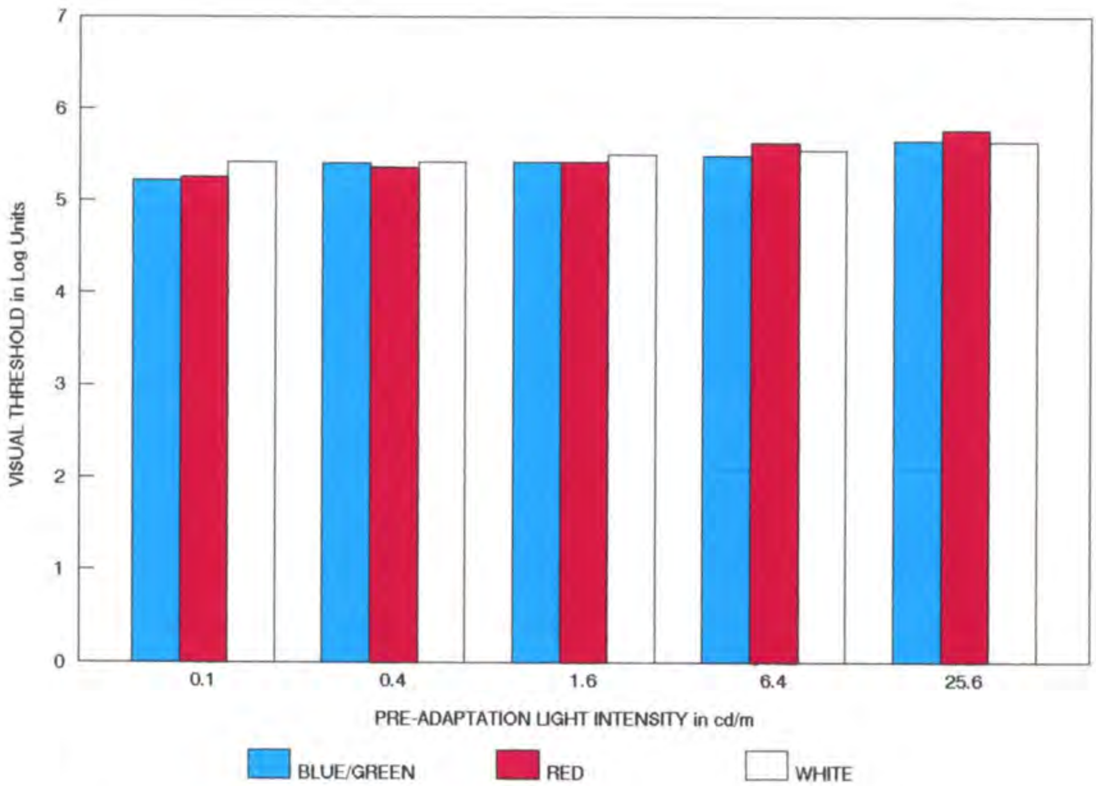

Figure 10 : Results (mean values) of visual acuity test

In order to identify whether there are significant differences between the colours and the intensity of the pre-adaptation light, all the visual acuity data were evaluated using analysis of variance. A summary of the results is given in Table IV.

Table IV : Summary of analysis of variance - visual acuity data

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main Effects					
A: Intensity	1.5676511	4	0.391913	17.920	0.0000
B: Colour	0.0776689	2	0.038837	1.776	0.1764
Interactions					
AB	0.2173422	8	0.027168	1.242	0.2869
Residual	1.6402500	75	0.021870		
TOTAL (CORRECTED)	3.5029122	89			

All F-ratios are based on the residual mean square error.

The results of the analysis of variance (Table IV) demonstrate no significant interaction between the intensity and colour of the pre-adaptation light. There were also no significant differences ($p < 0.01$) between the three colours of the pre-adaptation stimuli i.e. the luminance thresholds required to obtain a visual acuity of 5 min. of arc did not differ significantly between the three colours.

These results are contradictory to the results obtained by Reynolds (1971). Reynolds compared white and green electroluminescent and red incandescent light of 0.17 cd/m^2 intensity for their effect on scotopic (rod-mediated) acuity thresholds. Exposure to the red incandescent lighting with an intensity of 0.17 cd/m^2 produced the lowest scotopic acuity threshold, with white and green electroluminescent producing higher absolute thresholds in that order. Therefore the luminances required to obtain a visual acuity of 20 min. of arc were significantly lower for red incandescent pre-adaptation stimuli of 0.17 cd/m^2 than for the luminances required to obtain the same visual acuity of 20 min. of arc after pre-adaptation to white and green electroluminescent lighting of the same photopic intensity.

Reynolds (1971) furthermore stated that although most of the threshold differences obtained in his study between lighting colours were statistically significant, the absolute differences in visual sensitivity were quite small for practical purposes. Nevertheless his results do contradict those obtained in the present study. Reasons for the discrepancy may be found in the experimental procedures used in the two different studies.

It is evident that there were small differences in the procedures followed. Reynolds used only one pre-adaptation intensity i.e. 0.17 cd/m^2. The present study used five different pre-adaptation intensities; 0.1, 0.4, 1.6, 6.4 and 25.6 cd/m^2. In all cases no significant differences could be found between the three colours with regard to visual acuity thresholds. The reason for the discrepancy,may lie in the different visual acuity threshold required for the two studies. Reynolds used a visual acuity display subtending a visual angle of 20 min. of arc. The present study used a visual acuity display subtending a visual angle of 5 min. of arc. Reynolds therefore employed a test for scotopic or rod-mediated visual acuity whereas the present study was a test for photopic or cone-mediated visual acuity. The latter is in fact based on a study conducted by Brown and Graham in 1953.

Brown and his co-worker conducted research to determine the luminance (absolute) thresholds for the visual resolution of various widths of alternating light and dark lines at various times during dark adaptation. The visual acuity test objects used in their research subtended visual angles of 1, 1.6, 4, 12 and 24 min. of arc. They found that the small visual angles 1, 1.6, and 4 min. of arc showed only a single cone curve that drops from a high luminance (absolute) threshold during the first moments of dark adaptation to a final steady level. The larger visual angles of 12 and 24 min. of angle produced a duplex curve that showed an initial cone portion and a delayed rod portion. Visual acuity was determined to be a parameter that sets the position of a given adaptation curve on the luminance (absolute) threshold axis. The higher the degree of resolution (visual acuity) required, the higher the luminance (absolute) threshold. It has been identified (Hopkinson and Collins, 1970; Kantowitz and Sorkin, 1983) that the cones situated in the central region have the best capacity for resolving fine detail. The rods on the other hand, distributed more widely around the periphery of the eye, have an extremely high sensitivity, so that their function is to permit seeing at very low levels of light. The rods are far less closely packed than the cones, and so the resolution of detail by rod vision is very much less precise than with cone vision. In other words, for high resolution or visual acuity (small visual angles) cone vision is employed whereas when poor resolution or visual acuity (large visual angles) is required, rod vision is employed.

The 5 min. of angle, visual acuity used in the current study fits in nicely with the smaller visual angles used by Brown and Graham (1953), showing a single cone curve. The larger 20 min. of angle, visual acuity used by Reynolds (1971) is similar to the larger visual angles used by Brown and his co-worker which showed an initial cone and a delayed rod curve. It can thus be concluded that the 5 min. of arc tested photopic or cone-mediated visual acuity and 20 min. of arc tested scotopic or rod-mediated visual acuity.

In a continuation of his work with the effect of coloured lights on scotopic acuity thresholds, Reynolds (1971) determined the luminance threshold required to read a transilluminated letter acuity chart. He found no significant differences ($p < 0.01$) between the luminance thresholds of the different colours used for the smaller visual acuities, i.e. smaller than 12.09 min. of angle. This is supported by the present study. For Reynold's larger letter size, i.e. 24.17 min. of angle and above, the differences between red incandescent and green or yellow electroluminescent and between white and green electroluminescent, were statistically significant at the 0.01 level. Exposure to red incandescent lighting produced the lowest thresholds, with white and green electroluminescent lighting producing higher thresholds, in that order.

The present results reveal no significant differences ($p < 0.01$) were found between the lower intensities i.e. between 0.1 and 0.4 cd/m^2 as well as between 0.4 and 1.6 cd/m^2. At the higher intensities i.e. between 1.6 and 6.4 cd/m^2 as well as between 6.4 and 25.6 cd/m^2 the differences were statistically significant ($p < 0.01$). From Table III and Figure 10 it can be seen that the higher the pre-adaptation stimuli intensity the higher the visual (luminance) threshold. These results are in support of the research findings of Hecht (1937), elaborated on by Mote and Riopelle (1953) whose results also demonstrated that if the pre-adaptation intensity was increased the visual or absolute threshold is raised. With the present study, however, the raising of the pre-adaptation intensity from 0.1 cd/m^2 to 0.4 cd/m^2 was found not to raise the absolute threshold to a level that is statistically significant. This was true also when raising the pre-adaptation intensity from 0.4 cd/m^2 to 1.6 cd/m^2. However raising the pre-adaptation intensity from 1.6 cd/m^2 to 6.4 cd/m^2 and again to 25.6 cd/m^2, did raise the absolute threshold significantly ($p < 0.01$).

In summary, it was not possible to reject the null hypothesis and it can thus be stated that low level blue/green illuminance/luminance affected human (photopic) visual acuity in the same manner as white and red lighting of equal photopic efficiency.

The practical implication of these results is, therefore that after having been subjected to blue/green, red or white light at the intensities employed in this research and then entering darkness, there will be no difference in the luminance required to obtain a certain photopic visual acuity.

4.2 Contrast

The practical question at issue with these results is as follows:

"After having been subjected to blue/green, red and white light of similar intensity, when entering darkness are there significant differences in the background illuminescancies required to obtain the same contrast sensitivity?"

A summary providing the means and standard deviations of the luminance threshold levels in cd/m^2 of the visual field required to obtain a contrast sensitivity of 20% after the specified pre-adaptation exposure period of 15 min. is provided in Table V. The means are also illustrated graphically in Figure 11. As can be seen there are relatively small differences between the three colours at each intensity as well as between the different intensities of pre-adaptation light.

Table V : Summary of results of contrast test

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m^2)	COLOUR OF PRE-ADAPTATION LIGHT		
	BLUE/GREEN	RED	WHITE
0.1	4.43 (0.09)	4.29 (0.20)	4.38 (0.25)
0.4	4.55 (0.08)	4.39 (0.24)	4.43 (0.17)
1.6	4.71 (0.20)	4.58 (0.27)	4.52 (0.10)
6.4	4.78 (0.18)	4.83 (0.21)	4.77 (0.18)
25.6	4.96 (0.15)	4.90 (0.13)	4.92 (0.28)

*** Note : Standard deviations are provided in brackets.**

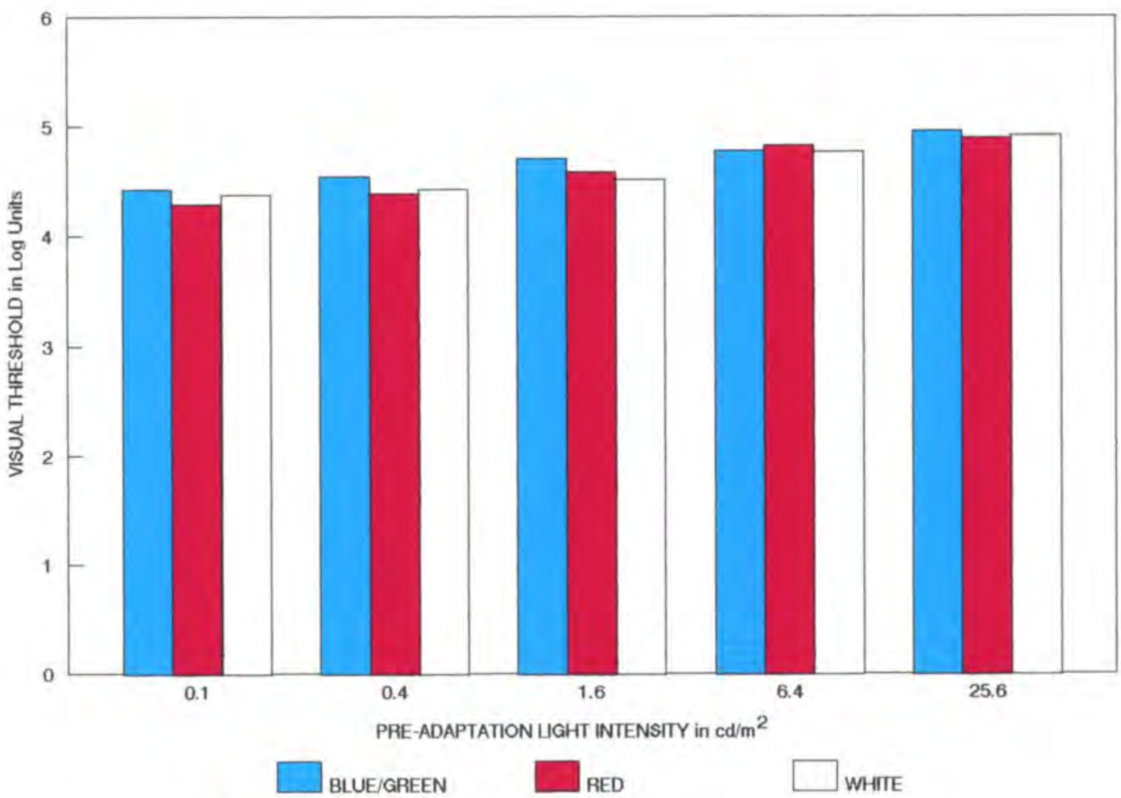

Figure 11 : Results (mean values) of contrast sensitivity test

In order to determine whether there are significant differences between the colours and the intensity of the pre-adaptation light, all the contrast data were evaluated using analysis of variance. A summary of the results is given in Table VI.

Table VI : Summary of analysis of variance - contrast data

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main Effects					
A: Intensity	3.8665622	4	0.9666406	26.002	0.0000
B: Colour	0.1475822	2	0.0737911	1.985	0.1445
Interactions					
AB	0.1296844	8	0.0162106	0.436	0.8957
Residual	2.7882167	75	0.0371762		
TOTAL (CORRECTED)	6.9320456	89			

All F-ratios are based on the residual mean square error.

The results of the analysis of variance (Table VI) reveal no significant interaction between the intensity and colour of the pre-adaptation light. There is also no significant difference ($p < 0.01$) between the three colours of the pre-adaptation stimuli i.e. the luminance thresholds required to obtain a contrast sensitivity of 20% did not differ significantly between the three colours.

These results are in support of the research findings of Neri and Kinney (1982), who enquired whether the colour of low intensity background illuminance had an effect on the visibility of low contrast targets of various sizes. No differences were found between low intensity white, blue and red background (ambient) illuminance (1.3 lux) in the detection of low contrast sine wave patterns presented both on a relatively dim and bright Cathcode Ray Tube (CRT) screen. They also found no differences on the same task between these colours and a dark ambient background condition.

In the study of Neri and Kinney (1982) the luminance thresholds were determined using the coloured background (ambient) illuminances as adaptation stimuli. In other words, the luminance thresholds were determined whilst being subjected to the different colours of ambient illuminance. In the present study the different colours and intensities were used as pre-adaptation stimuli. The pre-adaptation stimuli (ambient illuminance of a specific colour and intensity), as determined by the treatment condition, were switched off immediately, whereafter the luminance threshold for a 20% contrast target was determined. However the dark condition of Neri and Kinney can be compared with the test procedure of the present study since all lights were turned off prior to determining the luminance thresholds. As they found no significant differences between the dark ambient (background) condition and when using white, blue and red ambient illuminance it is possible to conclude that the present results support the findings of Neri and Kinney. In their study however they only used one intensity of ambient illuminance, whereas the present study used five different intensities and no significant differences ($p < 0.01$) could be found between the luminance thresholds for a 20% contrast sensitivity at all these intensities.

The results of the contrast sensitivity tests in the present study can in fact also be compared with the research of Brown and Graham (1953). In their research, to determine the luminance (absolute) thresholds for visual acuity, they also used test stimuli with alternating light and dark lines. The difference was that they used 100% contrast between the light and dark lines subtending the 5 different visual angles, whereas the present study used a test stimulus subtending a much larger visual angle but only with a 20% contrast between the light and dark lines. The high luminance (absolute) threshold results (Table V) for the contrasts sensitivity test indicate that a high level of resolution was required to correctly identify the orientation of the gratings of the 20% contrast test stimulus. As seen in the study of Brown and his collegue, the higher the degree of resolution required the higher the luminance (absolute) threshold. The high level of resolution, in the present study determined by the contrast level and not the angle subtended at the edge (visual acuity), necessitated the use of cone vision.

No significant differences ($p < 0.01$) were found between 0.1 and 0.4 cd/m². However, at higher intensities i.e. between 0.4 and 1.6 cd/m², between 1.6 and 6.4 cd/m² and between 6.4 and 25.6 cd/m² the differences were found to be statistically significant ($p < 0.01$). From Table IV and Figure 11 it is evident that the higher the pre-adaptation intensity the higher the absolute (luminance) threshold. As was the case with the visual acuity results, these contrast sensitivity results are in support of the research findings of Hecht (1937) and as elaborated on by those of Mote and Rioplelle (1953). Their results also showed that if the pre-adaptation intensity was increased the initial or absolute luminance threshold is raised. With the present study however, the raising of the pre-adaptation intensity from 0.1 cd/m² to 0.4 cd/m² was found not to raise the luminance threshold to a level that is statistically significant, suggesting that the effect of these two pre-adaptation intensities on resolving a 20% contrast target was very similar. Only at the higher intensities that were employed did the effect thereof begin to prove statistically significant.

In summary, it was therefore not possible to reject the null hypothesis and it can thus be stated that low level blue/green illuminance/luminance did affect human photopic contrast sensitivity (20%) in the same manner as white and red lighting of equal photopic efficiency. The practical implication of these results therefore is that, after having been subjected to a blue/green, red or white light at the intensities employed in this research and then experiencing darkness there will be no significant difference in the luminance required to obtain a certain photopic contrast sensitivity.

4.3 Dark Adaptation

The data obtained for each of the 90 subjects when determining their absolute thresholds of light perception in the course of dark adaptation were subjected to regression analysis. The functions for the individuals were next grouped into the 15 different treatment categories, each consisting of six individuals. For each of these categories one single function or curve was determined. The mathematical functions are provided in Table VII whereas the curves are presented graphically in Appendix 5.

Table VII : Mathematical functions for regression curves

COLOUR OF PRE-ADAPTATION STIMULI	INTENSITY OF PRE-ADAPTATION STIMULI (cd/m^2)	FUNCTION
BLUE/GREEN	0.1	$Y = 3.457247 - 0.1819836 \ln x$
	0.4	$Y = 3.88269 - 0.2468142 \ln x$
	1.6	$Y = 3.920741 - 0.2468715 \ln x$
	6.4	$Y = 4.502694 - 0.3338214 \ln x$
	25.6	$Y = 5.39324 - 0.444362 \ln x$
RED	0.1	$Y = 2.825181 - 0.105633 \ln x$
	0.4	$Y = 3.391315 - 0.2089645 \ln x$
	1.6	$Y = 3.034363 - 0.1321017 \ln x$
	6.4	$Y = 3.512647 - 0.193232 \ln x$
	25.6	$Y = 3.544766 - 0.1996228 \ln x$
WHITE	0.1	$Y = 3.265939 - 0.1572493 \ln x$
	0.4	$Y = 3.558035 - 0.2037878 \ln x$
	1.6	$Y = 4.120359 - 0.2930378 \ln x$
	6.4	$Y = 4.323144 - 0.298976 \ln x$
	25.6	$Y = 4.956897 - 0.3881498 \ln x$

x = Time course in seconds

y = Visual Threshold in Log Units

In Table VIII the means and standard deviations are provided for the visual thresholds at the start of the adaptation process, after 60, 180, 300, 600 and 1080 seconds for the different pre-adaptation light intensities of blue/green light. In Figure 12 the adaptation curves for the different intensities of blue/green lighting are presented graphically.

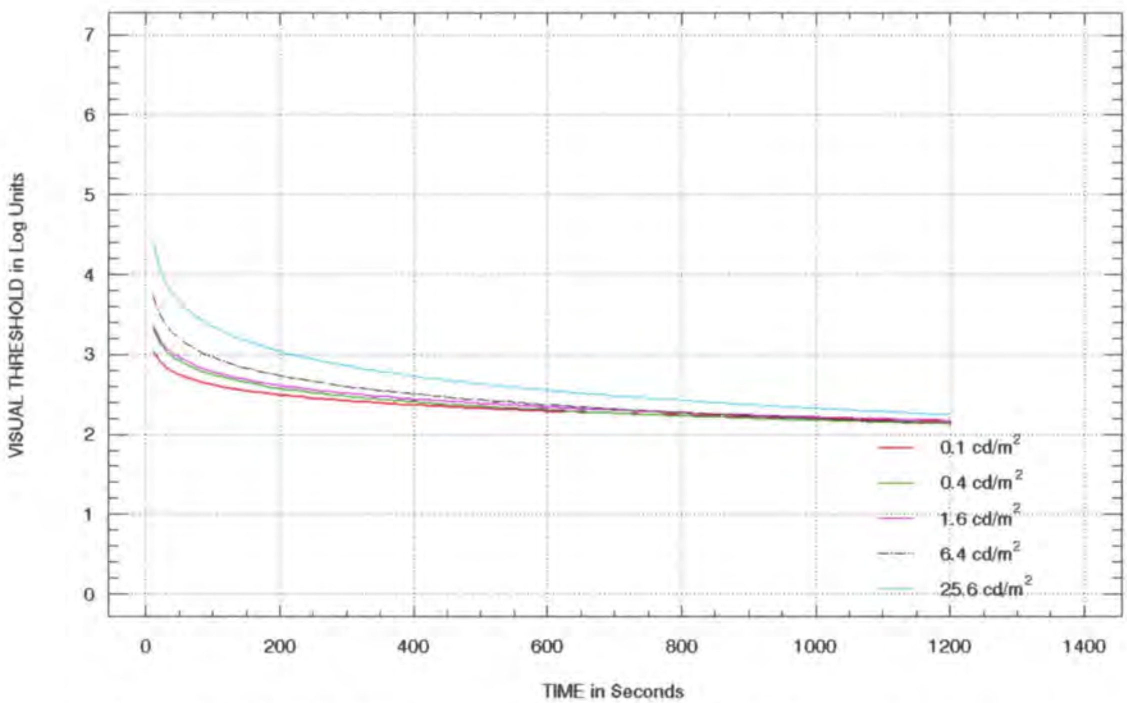

Figure 12 : Adaptation curves: blue/green pre-adaptation stimuli

Table VIII : Summary of blue/green adaptation results

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m²)	TIME COURSE IN SECONDS					
	START	60	180	300	600	1080
0.1	3.05 (0.13)	2.71 (0.25)	2.51 (0.19)	2.42 (0.17)	2.29 (0.15)	2.19 (0.15)
0.4	3.16 (0.11)	2.88 (0.30)	2.61 (0.17)	2.48 (0.15)	2.29 (0.16)	2.17 (0.17)
1.6	3.27 (0.18)	2.89 (0.25)	2.66 (0.29)	2.54 (0.32)	2.36 (0.34)	2.17 (0.17)
6.4	3.42 (0.09)	3.10 (0.14)	2.81 (0.14)	2.65 (0.15)	2.39 (0.13)	2.13 (0.11)
25.6	3.70 (0.16)	3.55 (0.32)	3.13 (0.18)	2.87 (0.11)	2.56 (0.08)	2.26 (0.07)

*** Note : Standard deviations are provided in brackets**

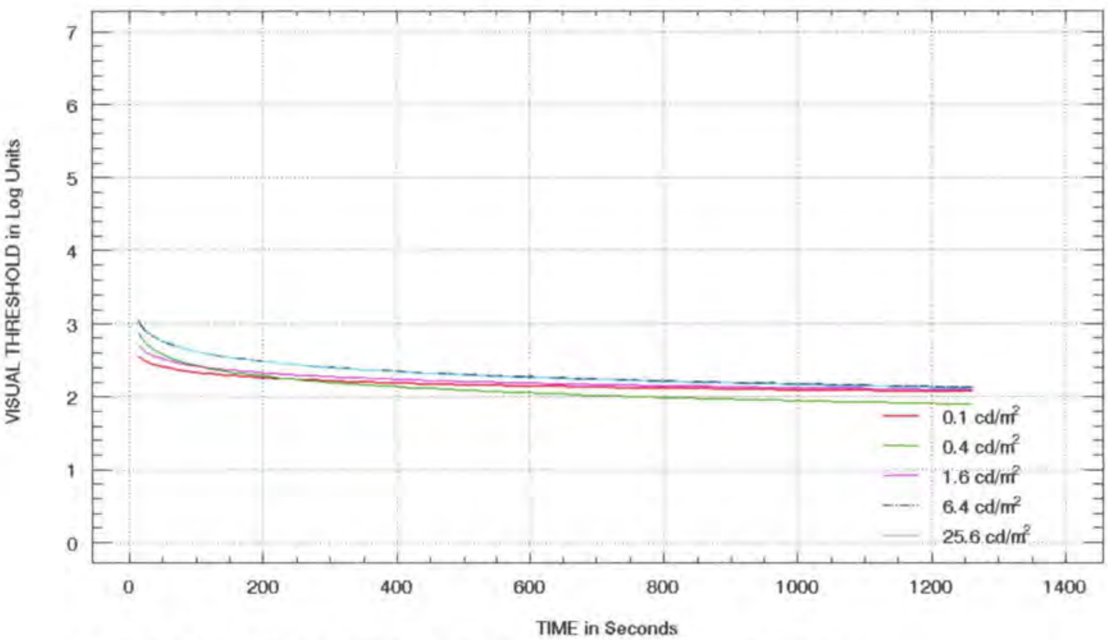

Figure 13 : Adaptation curves: red pre-adaptation stimuli

In Table IX the means and standard deviations are provided for visual threshold at the start of the adaptation process, after 60, 180, 300, 600 and 1080 seconds for the different pre-adaptation light intensities of red light. In Figure 13 the adaptation curves for the different intensities of red lighting are presented graphically.

Table IX : Summary of red adaptation results

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m²)	TIME COURSE IN SECONDS					
	START	60	180	300	600	1080
0.1	2.78 (0.06)	2.38 (0.13)	2.29 (0.16)	2.24 (0.17)	2.16 (0.15)	2.08 (0.17)
0.4	2.88 (0.13)	2.54 (0.14)	2.32 (0.19)	2.21 (0.22)	2.05 (0.26)	1.93 (0.29)
1.6	2.94 (0.16)	2.49 (0.09)	2.35 (0.14)	2.28 (0.13)	2.19 (0.13)	2.11 (0.14)
6.4	3.15 (0.08)	2.72 (0.09)	2.51 (0.08)	2.41 (0.09)	2.28 (0.11)	2.16 (0.13)
25.6	3.24 (0.06)	2.73 (0.10)	2.51 (0.07)	2.41 (0.09)	2.27 (0.12)	2.15 (0.10)

*** Note : Standard deviations are provided in brackets**

In Table X the means and standard deviations are provided for visual threshold at the start of the adaptation process, after 60, 180, 300, 600, 1080 seconds for the different pre-adaptation light intensities of white light. In Figure 14 the adaptation curves for the different intensities of white lighting are presented graphically.

Table X : Summary of white adaptation results

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m^2)	TIME COURSE IN SECONDS					
	START	60	180	300	600	1080
0.1	2.96 (0.07)	2.62 (0.15)	2.46 (0.15)	2.38 (0.14)	2.26 (0.12)	2.16 (0.13)
0.4	3.07 (0.15)	2.72 (0.26)	2.51 (0.15)	2.40 (0.11)	2.26 (0.08)	2.13 (0.08)
1.6	3.23 (0.08)	2.91 (0.16)	2.62 (0.15)	2.47 (0.15)	2.25 (0.15)	2.16 (0.18)
6.4	3.39 (0.15)	3.06 (0.16)	2.65 (0.15)	2.66 (0.10)	2.43 (0.05)	2.19 (0.10)
25.6	3.55 (0.17)	3.33 (0.23)	2.98 (0.15)	2.79 (0.15)	2.49 (0.16)	2.19 (0.20)

*** Note : Standard deviations are provided in brackets**

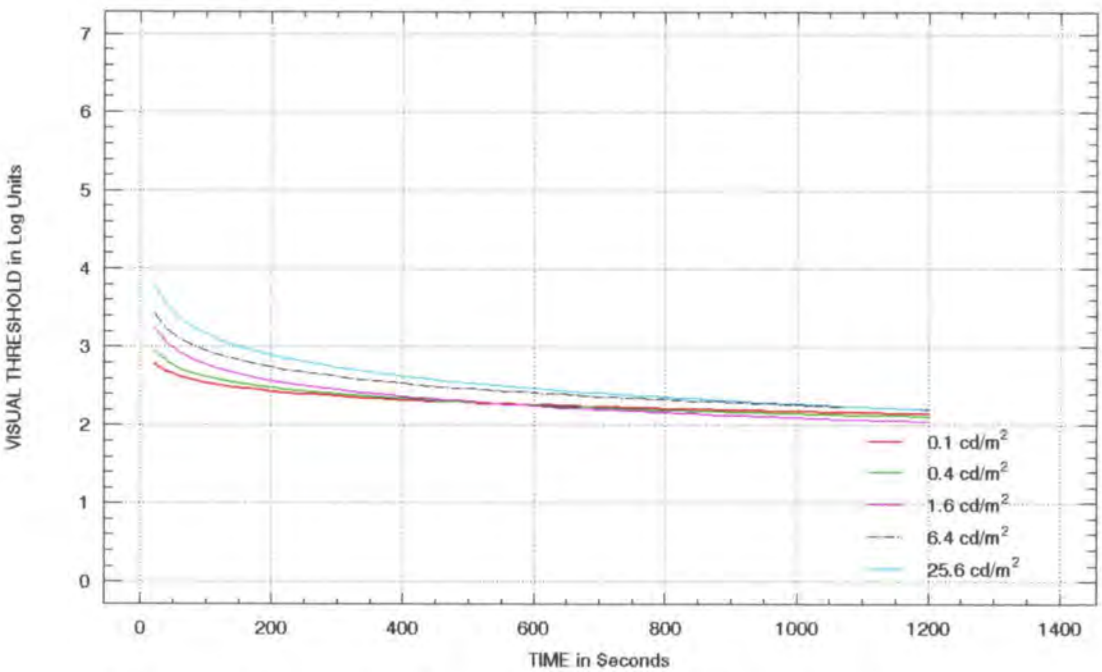

Figure 14 : Adaptation curves: white pre-adaptation stimuli

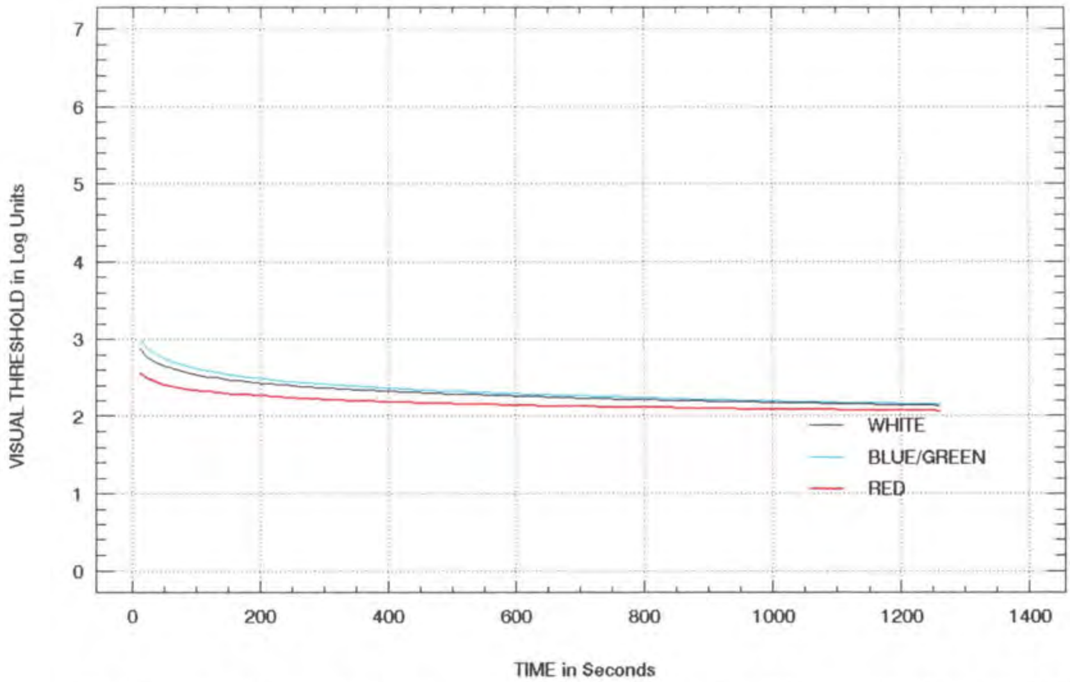

Figure 15 : Adaptation curves: pre-adaptation stimuli intensity of 0.1 cd/m^2

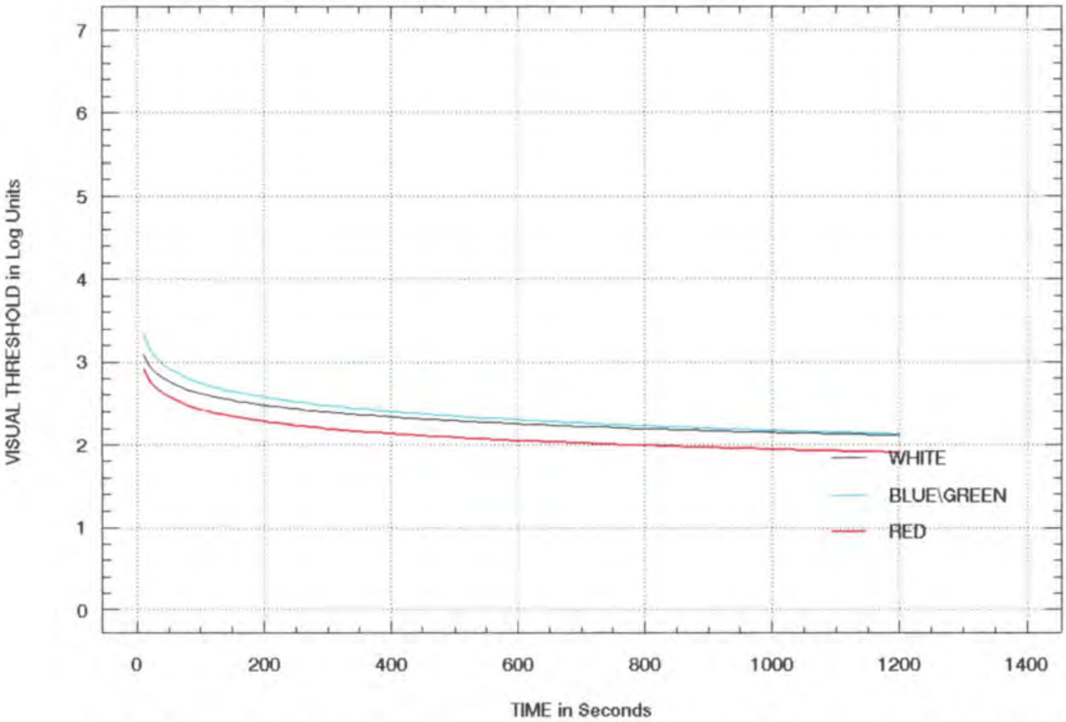

Figure 16 : Adaptation curves: pre-adaptation stimuli intensity of 0.4 cd/m^2

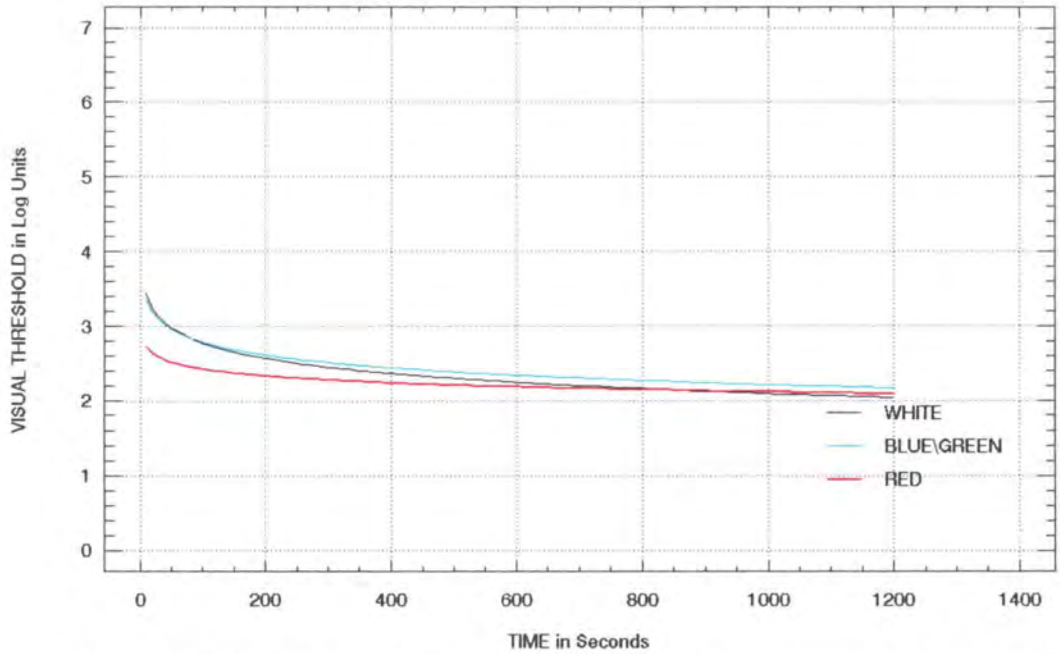

Figure 17 : Adaptation curves: pre-adaptation stimuli intensity of 1.6 cd/m^2

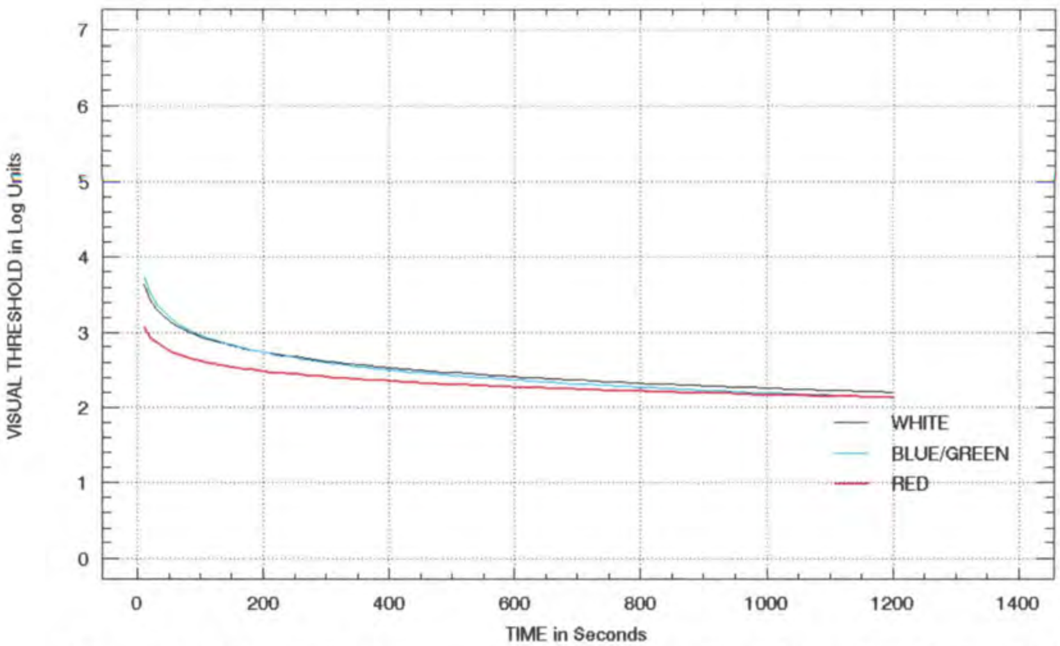

Figure 18 : Adaptation curves: pre-adaptation stimuli intensity of 6.4 cd/m^2

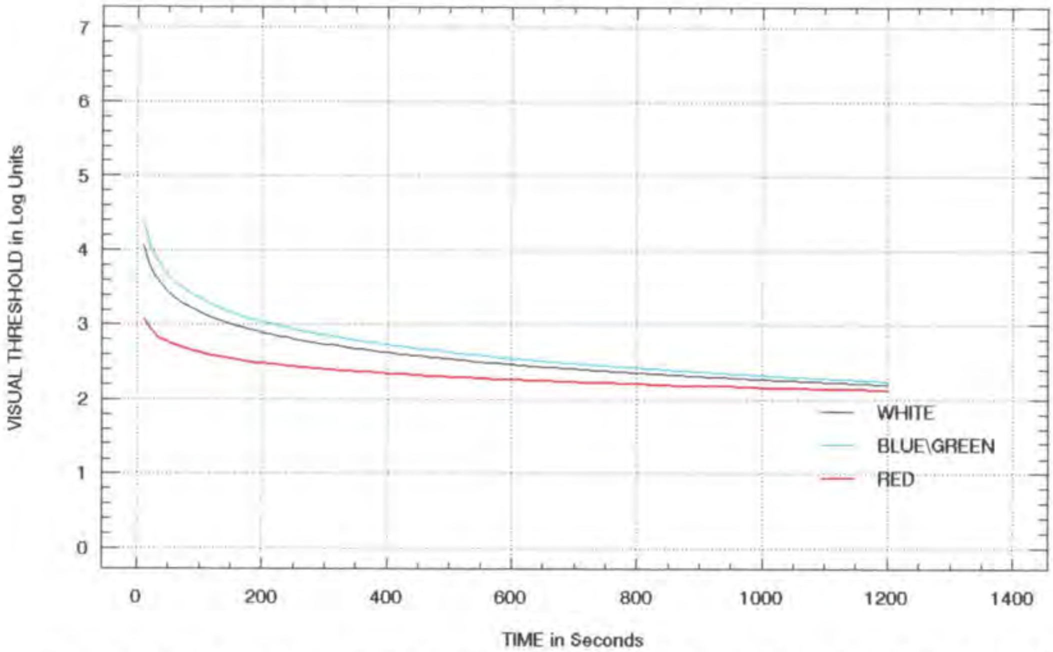

Figure 19 : Adaptation curves: pre-adaptation stimuli intensity of 25.6 cd/m^2

As can be seen from Figures 12, 13 and 14 there are differences between the curves for the different pre-adaptation intensities. In Figures 15 to 19 the dark adaptation curves are grouped together for the different intensities of pre-adaptation stimuli respectively, to facilitate visual comparison of the adaptation curves for the three colours at a specific intensity.

The adaptation curves presented in Figures 12 to 19 all share the same mathematical function i.e. $y = a + b \ln x$ as indicated in Table VII. These regression curves are very similar in form to those obtained by other researchers (Rowland and Sloan, 1944; Hecht and Hsia, 1945; Mote and Riopelle, 1953). From Figures 12 to 19 and Tables VIII, IX and X it is apparent that the visual (luminance) threshold increases as the pre-adaptation stimuli intensity increases. The speed of dark adaptation decreases as the intensity of the pre-adaptation stimuli increases. The difference in the rate of dark adaptation appears to be greater at the higher pre-adaptation intensities especially in the case of blue/green and white light.

From Figures 12 to 19 it is apparent that the curves show no cusp separating the cone and rod components of these curves. They therefore appear only to display the rod component i.e. indicating only the thresholds for the rod receptor elements. Mote and Rioplelle (1953) determined that if the shape of the curves is taken as the criterion by which to judge whether both cone and rod thresholds have been measured, then their curve obtained after pre-adaptation to 2 113 cd/m^2 for 500 s is a clear indication of rod functioning only, with no cone component. Donaldson (1983) also found no clearly defined cone-rod break after pre-adaptation exposure to 137 cd/m^2. With the pre-adaptation intensities used in the present study being much lower than those employed by Mote and Riopelle as well as Donaldson (1983), one would therefore expect the curves presented in Figures 12 to 19 to show only the thresholds for the rod receptor elements.

If the standard deviations provided in Tables VIII, IX and X are calculated as a percentage of the luminance threshold at a specific time during the course of dark-adaptation and for a particular pre-adaptation intensity and then taken as an indication of variability, it appears that the latter increase towards the end of a test. The average variability, calculated for all 5 intensities, increased from 4% at the start of the adaptation process to 6% after 1 080 s for the blue/green treatment condition. In the case of red lighting it increased from 3.3% at the start, to 8% after 1 080 s. White adaptation results produced a variability of 3.8% at the start and 6.4% after the 1 080 s. The variability values at the start are in agreement with the 4% day-to-day variation in threshold found by Hecht and Mandelbaum (1939) as well as Sheard (1944). David (1956), whilst deriving a standard dark adaptation curve for the Goldmann/Weekers adoptometer, obtained a 5% variation during the early phases of dark adaptation and 3% during the later stages. It is evident that the variations of 6%, 8% and 6.4% found in present study towards the later stages of adaptation after pre-adaptation to blue/green, red and white lighting is somewhat higher than the 3% obtained by David (1956).

The relatively large standard deviations towards the later stages of adaptation, after having been subjected to red light of 0.4 cd/m^2 intensity (Table IX), were mainly caused by the curves of two subjects within the group who exhibited exceptionally low visual thresholds. These obviously affected the results of the particular group. Given that the variability evidenced is in agreement with that obtained by other researchers at the beginning of the adaptation process, suggests that the accuracy of the procedure and equipment used was acceptable.

It is suggested that the large variability experienced towards the end of the adaptation process was possibly caused by fatigue. The method of constant stimulus presentation in the present study, with the test field being presented at a rate of 0.5 Hz, required sustained attention from the subjects since they were being visually stimulated for the full test period of 20 min. Other researchers (Hecht and Hsia, 1945; Mote et al., 1954; Wolf et al.) in fact only presented the test field at intervals of 1 to 1.5 min. until dark adaptation reached a nearly steady level after 30 min. The process was therefore not as fatiguing as the one employed in the present study.

The final thresholds for the adaptation curves obtained in the present study were relatively higher than those obtained with the conventional technique as employed by Rowland and Sloan (1944), Hecht and Hsia (1945) and Wolf <u>et al.</u> (1960). The reason for this could have been the change of adaptation state due to continuous presentation of the test stimulus as well as the requirement of morphoscopic identification (orientation of the 100% contrast grating) rather than a simple light perception. In all probability the latter may also have contributed to the fatigue of the subjects with the resultant increase in variability towards the end of the dark-adaptation process. It was, however, decided to use the morphoscopic identification and continuous method because of the increased accuracy of the visual (luminance) thresholds obtained during the early stages of the dark-adaptation process. The difference caused by colour and intensity of the pre-adaptation stimuli is only distinguishable during the early stages of dark-adaptation (See Figures 12 to 19) and it was therefore imperative that the thresholds be as accurate as possible.

In order to determine whether there are significant differences between the colours and the intensities of the pre-adaptation light, all the first initial absolute thresholds of light perception recorded after the start of dark adaptation (i.e after the specified pre-adaptation exposure period of 20 min.) were evaluated using analysis of variance. A summary of the results is given in Table XI.

Table XI : Summary of analysis of variance - first absolute threshold data

SOURCE OF VARIATION	SUM OF SQUARES	d.f.	MEAN SQUARE	F-RATIO	SIG LEVEL
Main Effects					
A: Intensity	3.7286956	4	0.932174	56.454	0.000
B: Colour	1.6707800	2	0.835390	50.592	0.000
Interactions					
AB	0.1113978	8	0.013925	0.843	0.568
Residual	1.238416	75	0.016512		
TOTAL (CORRECTED)	6.7492900	89			

All F-ratios are based on the residual mean square error.

The results of the analysis of variance (Table XI) reveal no significant interaction between intensity and colour of the pre-adaptation light. The differences in visual (luminance) thresholds at the start of the dark-adaptation for the different intensities (0.1, 0.4, 1.6, 6.4 and 25.6 cd/m²) were found to be statistically significant ($p < 0.01$). From Tables VIII, IX, X and Figures 12, 13, 14 it is clear that the higher the pre-adaptation stimuli intensity the higher the visual (luminance) threshold. These results are similar to the research findings of Hecht (1937) and elaborated on by Mote and Rioplelle (1953), who also showed that if the intensity of the pre-adaptation stimuli was increased the visual or luminance threshold is raised. In the present study the raising of the intensity of the pre-adaptation stimuli resulted in statistically significant increases of the visual thresholds between all the intensities.

As was the case with intensity, it can be seen from Table XI that the differences in visual (luminance) thresholds at the start of the dark-adaptation process for the colours (blue/green, white and red) were found to be statistically significant ($p < 0.01$).

Based on the above-mentioned analysis the null hypothesis was rejected in favour of the alternative hypothesis. It may therefore be stated that blue/green illuminance/luminance does not affect the human visual threshold in the same manner as red and white lighting of equal photopic efficiency after 20 min. of pre-adaptation.

Additional statistical analysis in the form of a Duncan's Multiple Range Test, however, revealed that the mean summed absolute visual thresholds after red pre-adaptation lighting of 0.1 and 0.4 cd/m^2 were not significantly different from the mean summed absolute visual thresholds after white pre-adaptation lighting of 0.1 and 0.4 cd/m^2 respectively ($p < 0.01$). At the brighter pre-adaptation intensities of 1.6; 6.4 and 25.6 cd/m^2 the Duncan's Multiple range test however did reveal that absolute visual thresholds after red pre-adaptation lighting were significantly lower than the respective mean summed absolute visual thresholds after white pre-adaptation lighting ($p < 0.01$). As for blue/green and white pre-adaptation lighting the Duncan's Multiple Range Test revealed no significant differences between the mean summed absolute visual thresholds of the two colours at the intensities i.e. 0.1; 0.4; 1.6; 6,4 and 25,6 cd/m^2 ($p < 0.01$).

These previous findings from the results of the absolute visual thresholds obtained at the start of the dark-adaptation process made it necessary to a conduct an additional analysis of the results obtained during the course of dark-adaptation.

The results of the Duncan Multiple Range Test are summarized in Tables XII, XIII and XIV. In Table XII blue/green pre-adaptation stimuli are compared with red during the course of dark adaptation. In Table XIII blue/green pre-adaptation stimuli are compared with white and in Table XIV red with white pre-adaptation stimuli. In these three tables, "YES" denotes a statistically significant difference ($p < 0.01$) whereas "NO" indicates no significant difference between the two colours compared at the same intensity and at a specific point in time.

Table XII : Summary of comparison between blue/green and red adaptation curves

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m^2)	TIME COURSE IN SECONDS					
	START	60	180	300	600	1080
0.1	YES	YES	NO	NO	NO	NO
0.4	YES	NO	NO	NO	NO	NO
1.6	YES	YES	NO	NO	NO	NO
6.4	YES	YES	YES	YES	NO	NO
25.6	YES	YES	YES	YES	YES	NO

Table XIII : Summary of comparison between blue/green and white adaptation curves

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m^2)	TIME COURSE IN SECONDS					
	START	60	180	300	600	1080
0.1	NO	NO	NO	NO	NO	NO
0.4	NO	NO	NO	NO	NO	NO
1.6	NO	NO	NO	NO	NO	NO
6.4	NO	NO	NO	NO	NO	NO
25.6	NO	NO	NO	NO	NO	NO

Table XIV : Summary of comparison between red and white adaptation curves

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m²)	TIME COURSE IN SECONDS					
	START	60	180	300	600	1080
0.1	NO	NO	NO	NO	NO	NO
0.4	NO	NO	NO	NO	NO	NO
1.6	YES	YES	NO	NO	NO	NO
6.4	YES	YES	YES	YES	NO	NO
25.6	YES	YES	YES	YES	YES	NO

The need for the additional analysis becomes apparent when studying Tables XII, XIII and XIV. When comparing the curves for blue/green with those of red pre-adaptation lighting (Table XII) it is evident that although there are significant differences at the start of dark-adaptation, these differences become insignificant with time. The higher the intensity of the pre-adaptation stimuli, the longer the differences remain significant ($p < 0.01$) The latter is also the case when comparing the adaptation curves obtained after pre-adaptation to red and white lighting (Table XIV). The results provided in Table XIII suggest that differences between the curves for blue/green and white pre-adaptation stimuli remain insignificant at all the intensities as indicated during the course of dark-adaptation.

Although none of the other cited researchers (Ferguson and McKellar, 1944; Hulbert, 1951; Hanson and Anderson, 1960; Cavonuis and Hulz, 1970; Reynolds, 1971) who studied the effects of shorter wavelength (coloured) stimuli on subsequent dark adaptation included blue/green light with broadband wavelength of less than 570 mm, the results obtained by the present study with regard to the comparison of blue/green and red lighting (Table XII) are in overall support of their findings. Bearing in mind the critique raised by the author with regard to the experiments performed by these researchers, it was generally demonstrated by them that dark-adaptation times increase slightly as the wavelength of the stimulating light changes from red to yellow and then increase more rapidly as the wavelength shifts to blue. After being subjected to short wavelength (blue/green) pre-adaptation lighting, it will take longer to reach the same level of dark-adaptation than after being subjected to the same photopic intensity of long wavelength (red) lighting. Cavonius and Hilz (1970) point out that, when the subsequent visual task must be performed by photopic vision, the use of red lighting becomes inappropriate. (The latter has already been discussed in detail in paragraph 4.1.) The advantage of red lighting over blue/green however decreases as the pre-adaptation intensity decreases, as can be seen in Table XII.

The results obtained when comparing the blue/green with the white dark adaptation curves (Table XIII) are largely in support of the findings of other researchers employing similar short wavelength pre-adaptation stimuli. Ferguson and McKellar (1944) could find no significant differences between green and white pre-adaptation stimuli due to "irregularities" in their data. Hanson and Anderson (1960) could not demonstrate significant differences between the effects of green, blue and white pre-adaptation stimuli on subsequent dark adaptation. Reynolds (1971) found that post-exposure thresholds for white electroluminescent did not differ significantly from post exposure to green electroluminescent lighting ($p < 0.01$).

With regard to the comparison of the dark-adaptation curves obtained after exposure to red and white pre-adaptation stimuli, it is clear when studying Table XIV that at the lower intensities, 0.1 and 0.4 cd/m^2, there are no significant differences between these two photopicly equated light sources. From intensities of 1.6 to 25.6 cd/m^2, red holds distinct advantages over white lighting as to subsequent dark-adaptation. Findings by other researchers on this comparison are rather contradictory. Rowland and Sloan (1944) stated that in order to provide the same degree of dark adaptation as provided by exposure to 9.5 cd/m^2 of white light, about 38.2 cd/m^2 of red light could be used. Hecht and Hsia (1945) found dark-adaptation following exposure to white light (83.7 cd/m^2) slower than that following red light (123.8 cd/m^2). Hanson and Anderson (1960) also found red pre-adaptation stimuli of 342 and 34 cd/m^2 to be superior to photopically equated white light. Lowry (1943) on the other hand, failed to find any significant differences between photopically equated red and white light of 10 cd/m². Trying to resolve this contradiction Hecht and Hsia (1944) repeated Lowry's experiments but failed to find the same result. They concluded that the reason that Lowry showed nearly the same results following red and white adaptation was that his red and white lights were of nearly equal stimulating power to rods but not to cones. The intensities were therefore scotopically rather than photopically equated. Intensities employed by these researchers were in most cases much higher than those employed in the present study, but are to a large extent supported by the results of the higher intensities (1.6 to 25.6 cd/m²), obtained by this study.

At the lower intensities (0.1 and 0.4 cd/m²) the present results contradict the finding of Reynolds (1971) that exposure to red incandescent lighting produced significantly lower absolute (scotopic) thresholds than did white electroluminescent lighting of equal intensity (0.17 cd/m²). Hecht and Hsia (1945) state that "regardless of brightness level, dark adaptation is always faster after red light adaptation than after white of comparable brightness." The fact of the matter is that this advantage in speed becomes insignificant at the lower intensities, as is clearly illustrated in their own paper where the adaptation curves following exposure to various intensities of white and red lighting are presented. The disappearance of the advantages of red lighting over white pre-adaptation stimuli at low intensities is also seen illustrated in the article by Hulbert (1951).

It is suggested that contradictory results regarding the influence of low intensity coloured lighting on subsequent dark-adaptation, are due to the inability to accurately equate coloured lights with respect to luminance in the mesopic range of the human visual system, i.e. 10^{-3} to 3 cd/m^2. It has become apparent in recent years that there are a number of instances in which two lights that measure the same do not look equally bright or have the same effect on vision. This is especially true for coloured lights (Kinney, 1983; Segawa and Takeichi, 1986).

Before continuing with the discussion of the results it is deemed necessary to provide some background on the measurement of light. This background information could have been included in the literature section but since it forms such an important part of the discussion of the results that it was decided to include it in this section.

The problems or inconsistencies in equating coloured lights, stem directly from diverse definitions of light: radiant power evaluated by the spectral sensitivity of the human eye. More precisely, light is the integration of radiant power with the Commission Internationale de l' Eclairage (CIE) spectral luminous efficiency function; $V(\lambda)$, over the range from 360 to 830 nm. It is defined quantitatively as:

$$L = K\int_{360}^{830} Le\lambda \, V(\lambda) d\lambda$$

Where L is some unit of light

K is a constant depending upon the specific unit

$Le\lambda$ is the spectral radiance in watts/m^2

$V(\lambda)$ is the spectral efficiency of human photopic vision from 360 to 830 nm

λ is the wavelength of the energy

$V(\lambda)$ was established in 1924 by the CIE and has been the international foundation for the measurement of light ever since. In the early days the system functioned well since the major source of artificial light was tungsten-filament incendescent lamps, for which discrepancies between measurement and visual impression were minor. Now there are many new coloured light sources, LED's, chemical and electroluminescent lights, CRTs and plasma displays whose spectral power distributions are quite different from that of incandescent tungsten. The culprit behind most of the inconsistancies between the visual impression and the measured quantities is quite simple according to Kinney (1983). If light is the integration of spectral radiant power with $V(\lambda)$ and if the use of $V(\lambda)$ is wrong, for whatever reason, the measurement of light will not agree with the visual impression.

One major misuse of the V(λ) function is for low light levels, which are not in the range of daylight or photopic vision. At night or under scotopic levels of illumination, the spectral sensitivity of eye shifts toward the shorter wavelengths, as shown in Figure 20. The use of V(λ) values to evaluate the electromagnetic energy when scotopic or night vision values apply, results in sizable errors. The contributions of the short wavelengths (violets, blues and blue/green) are underestimated and they appear much brighter than measurements indicate, while long wavelengths (yellows and reds) are overevaluated and appear dimmer (Kinney, 1983).

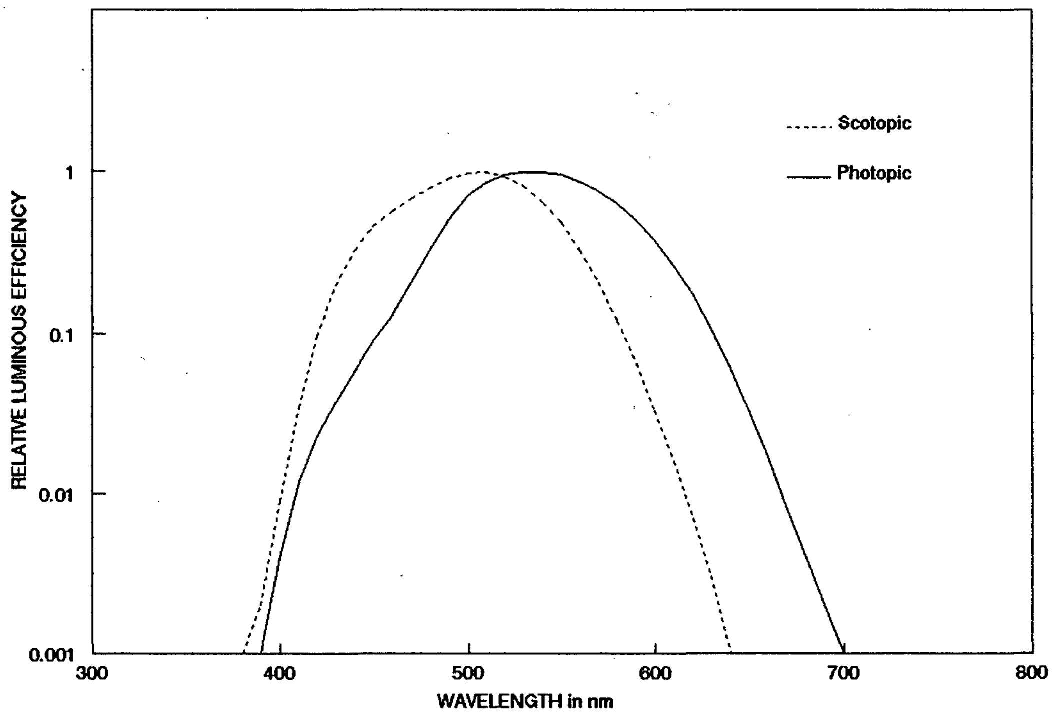

Figure 20 : Comparison of the photopic and scotopic spectral luminous efficiency functions

This problem was recognized years ago by the CIE and a scotopic luminous efficiency curve, V'(λ) was established in 1951. This function should be used to evaluate electromagnetic radiation at low light levels (below 10^{-3} cd/m²), in a manner completely analogous to the use of V(λ) at high light levels (above 3 cd/m²). Unfortunately, too few people recognize the problem and there are only a few light meters that are equiped to measure scotopic levels. The result is that almost all measurements of light are done with V(λ) meters, whether appropriate or not.

Between photopic and scotopic levels of illuminance there is a range of levels (10^{-3} to 3 cd/m²) over which spectral sensitivity shifts gradually and irregularly from photopic to scotopic. There is no standard procedure for evaluating electromagnetic energy in this region, although there have been several systems proposed and the CIE expects to standardize one in the future. Solutions proposed by Kinney (1983) and Sagawa and Takeichi (1986) in the form of brightness-based ratios or equations also have problems. Strictly speaking these solutions should be employed only for monochromatic sources because of additivity failures. This implies that the brightness of a nonmonochromatic or broad band light source, as used in the present study, can no longer be obtained by a simple weighted integration over the spectral domain.

Since some of the intensities employed in the present study (0.1, 0.4, 1.6 cd/m^2) were within this range, commonly referred to as mesopic, it is therefore important to consider to what extent the inability to equate coloured lights with regard to brightness in the mesopic range had an effect on the results. From the results presented it appears that it did have some effect. The results obtained at the photopically equated intensities i.e. 1.6, 6.4 and 25.6 cd/m^2, are in support of the findings of other researchers (Rowland and Soan (1944); Hecht and Hsia (1945); Hulbert (1951); Hanson and Anderson (1960)). The present research results support the fact that in the lower photopic region, photopic measurements will underestimate the brightness of blue/green and overestimate the brightness of red ambient illuminance. This explains why red pre-adaptation stimuli, although photopically equated with blue/green and white light, did not affect subsequent dark-adaptation to the same degree.

The unexpected and contradictory results obtained with the mesopic intensities (0.1 and 0.4 cd/m^2) do not corroborate with the abovementioned research findings. These results clearly support the findings that the photopic and scotopic luminious efficiency curves ($V(\lambda)$ and $V'(\lambda)$) do not accurately predict the spectral sensitivity of the human eye in the mesopic region. It appears that there is a shift in the spectral sensitivity of the human eye but that this shift is irregular, which would explain the results obtained at 0.1 and 0.4 cd/m². The present results also suggest that the upper mesopic border is below 3 cd/m² as indicated by Boyce (1981). The results obtained after pre-adaptation to 1.6 cd/m² suggest that this could form the lower border of the photopic sensitivity range of the eye. In conclusion, it is suggested that the present findings may be of use in trying to elucidate the spectral efficiency of human mesopic vision.

Rowland and Sloan (1944) demonstrated that, in order to provide the same degree of dark-adaptation as is provided by exposure to 38.2 cd/m² of red light, about 9.55 cd/m² of white light could be used. Hecht and Hsia (1945) also showed that, to produce the same dark-adaptation in the same time, red pre-adaptation light may be held 4 times (in cd/m²) as bright as white. To check whether the results of the present study would corroborate these findings, the first absolute thresholds at the start of the dark-adaptation process for all three the colours are summarized in Table XV.

Table XV : Summary (means) of first absolute thresholds at start of dark-adaptation

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m²)	COLOUR OF PRE-ADAPTATION LIGHT		
	BLUE/GREEN	RED	WHITE
0.1	3.05 (0.13)	2.78 (0.06)	2.96 (0.07)
0.4	3.16 (0.11)	2.88 (0.13)	3.07 (0.15)
1.6	3.27 (0.18)	2.94 (0.16)	3.23 (0.08)
6.4	3.42 (0.09)	3.15 (0.08)	3.39 (0.15)
25.6	3.70 (0.16)	3.24 (0.06)	3.55 (0.17)

*** Note : Standard deviations are provided in brackets.**

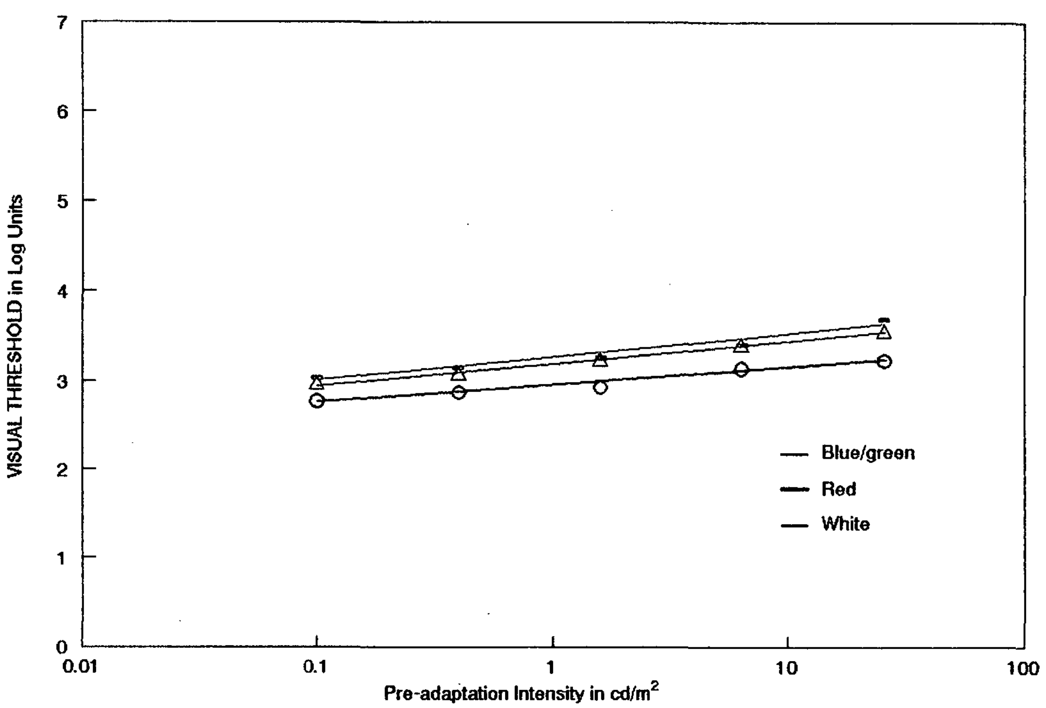

Figure 21 : Regression curves for visual thresholds at the start of dark-adaptation

As can be seen from Table XV, even though pre-adaptation intensities were selected to compare the ratio between red and white lighting, the luminance thresholds cannot be directly compared using the results presented in the Table. In Figure 21 these results are illustrated graphically. In order to predict values at intermediate intensities not employed in the experimental procedure, regression curves were determined using these results. The mathematical functions for the three patterns are as follows:

Blue/green : $Y = 3.26711 + 0.11253 \ln x$

Red : $Y = 2.957655 + 0.08584 \ln x$

White : $Y = 3.189145 + 0.108202 \ln x$

where X is the pre-adaptation intensity in cd/m²

Y is the visual (absolute) threshold in log units

These trends can be used to predict the pre-adaptation intensity for a visual threshold, or vice versa, for one of the three colours between 0.1 and 25.6 cd/m^2. Using the abovementioned trace for red pre-adaptation it was determined that red light with an intensity of 1.03 cd/m^2 would provide the same visual threshold (2.96 log units) at the start of the dark-adaptation process as 0.1 cd/m^2 of white light. Simularly red lighting of 3.7 and 26.8 cd/m^2 would provide the same visual thresholds (3.07 and 3.23 log units) as 0.4 and 1.6 cd/m^2 of white light respectively. The present results therefore do not support the research findings of

Rowland and Sloan (1944), or those of Hecht and Hsia (1945). The ratio of 4:1 with regard to red and white pre-adaptation stimuli could not be corroborated. The results of the present study indicate much larger ratios, in the order of 10 or more. The results also indicate that this ratio between the brightnesses of red and white pre-adaptation stimuli necessary to provide the same degree of dark-adaptation, would in fact increase with an increase in intensity. A much wider range of pre-adaptation intensities than those used in the present study would however be needed to corroborate or contradict the latter.

The differences in the speed of dark-adaptation after exposure to red and white lighting was investigated by Hulbert (1951). He found that for equally bright white and red pre-adaptation stimuli at 1.1, 10.8, 107.6 and 1 076 lux, time to become dark adapted was about 4, 5, 10 and 21 min. for white and 3, 4, 5 and 7 min. for red respectively. Using the functions provided in Table VII the times required after exposure to white and blue/green light to reach the same state of dark-adaptation as at the start of dark-adaptation after red lighting are provided in Table XVI.

Table XVI : Summary of time required for pre-adaptation after white and blue/green light to reach the same threshold as after red-lighting of equal photopic intensity

INTENSITY OF PRE-ADAPTATION LIGHT (cd/m^2)	WHITE	BLUE/GREEN
0.1	22 sec	41 sec
0.4	28 sec	58 sec
1.6	56 sec	53 sec
6.4	51 sec	57 sec
25.6	83 sec	127 sec

From Table XVI it is evident that it would take 22 s and 41 s longer after exposure to white and blue/green light (0.1 cd/m^2) respectively to reach the same visual threshold of 2.78 log units obtained after exposure to red lighting of 0.1 cd/m^2. As was the case with the findings of Hulbert (1951), the differences in the speed of adaptation increased as the intensity of the pre-adaptation stimuli increases.

The differences in visual threshold and therefore in the state of dark-adaptation between red and white light of 0.1 and 0.4 cd/m^2 were found not to be significant (Table XIV) at the start of the dark-adaptation process. Visual thresholds after exposure to blue/green and red lighting did prove to be statistically significant (Table XII). The 28 s difference between white and red light (0.4 cd/m^2) proved not to be significant whereas the 41 s between blue/green and red (0.1 cd/m^2) were found to be statistically significant ($p < 0.01$). The temporal difference for significance was somewhere between 28 and 41 s.

The aim of the present study was to resolve the practical issues already discussed. These findings have other obvious practical implications, apart from those already raised, for the specification of dark-adapting goggles, lighting systems and display colours in environments in which the ability to perceive detail and detect low brightness contrasts must be preserved.

In practice however, the selection of the colour of a light source and intensity will not only be guided by research findings such as are revealed in this study. Even though the differences between white and red lighting at low intensities are not statistically significant, it may be that a difference of 22 s could mean the difference between life and death for a military pilot needing that much longer to dark-adapt. In another case it could mean negating the advantage of approximately 60 s with regard to dark-adaptation after red lighting for the advantages of comfort and good colour-rendering when using white lighting (6.4 cd/m^2). Similarly when having to select between blue/green and red lighting, the military requirement for non detectability may just overrule the advantage of approximately 60 s which red has over blue/green at 6.4 cd/m^2 with regard to dark-adaptation. All-in-all, the practical applications of coloured lighting will largely be determined by the situation and its requirements; the findings of the present study and other related research acting as guidelines rather than clear-cut design recommendations.

5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Over the past 50 years or more a number of investigators have explored the relationship between coloured lighting and human visual functions such as dark-adaptation, visual acuity and contrast sensitivity. One consistent finding has been that, following pre-adaptation to red light, dark adaptation is much faster than following white. There appear to be conflicting results from research comparing the effect of low intensity coloured ambient lighting on visual acuity and contrast sensitivity. None, however, has included blue/green light with a broadband wavelength of less than 570 mm in these experimental studies. Automating the measurement process and applying the method of constant stimuli in this study provided a better standardisation of the tests and also increased the accuracy and reliability thereof in order to determine the influence of blue/green, red and white lighting at a number of equal photopic intensities on subsequent dark-adaptation, visual acuity and contrast sensitivity.

5.1 HYPOTHESES

It was hypothesized that:

1. Low level blue/green illuminance/luminance will affect human visual acuity in the same manner as white and red lighting of equal photopic efficiency.

2. Low level blue/green illuminance/luminance will affect human contrast sensitivity in the same manner as white and red lighting of equal photopic intensity.

3. Low level blue/green illuminance/luminance will affect the human visual (absolute) threshold in the same manner as white and red lighting of equal photopic efficiency.

4. Pre-adaptation to low level blue/green illuminance/luminance will affect human dark-adaptation in the same manner as white and red lighting of equal photopic efficiency.

5.2 SUMMARY OF PROCEDURES

A factorial (5 x 3) experimental design was used. The first independent variable i.e. the intensity of the pre-adaptation stimuli was represented by 5 different intensity levels i.e. 0.1, 0.4, 1.6, 6.4 and 25.6 cd/m². Three colours (blue/green, white and red) were used for the second independent variable i.e. the colour of the pre-adaptation stimuli.

Ninety male military and civilian personnel between 20 and 40 years of age were used as subjects after having passed a preliminary ophthalmologic examination. Only subjects with 6/6 visual acuity (corrected) and better, normal contrast sensitivity and colour discrimination were used. The subjects were not randomly selected but were randomly allocated to the 15 treatment conditions resulting in 6 subjects per treatment.

The Goldmann/Weekers adaptometer was used to provide the pre-adapting stimuli and measure the various visual functions (dependent variables). In order to automate the measurement process and apply the method of constant stimuli, some improvements/modifications were added to the standard Goldmann/Weekers Adaptometer.

The first improvement/modification was to design a simple automatic device operating the intensity control providing the luminance thresholds of the adaptometer. The intensity of the repeated light flashes used for the determination of the absolute (luminance) threshold of light perception during the course of dark-adaptation was increased automatically until perception occured. At this moment the subject pressed a switch, causing an automatic continuous decrease of the intensity. When perception was completely lost the subject had to press the switch to increase the intensity and so on. The luminance of the test patch/target at each press of the switch was recorded continuously by computer, as well as the time elapsed from the start of the test. The result was a curve oscillating above and below the threshold, the latter being determined using regression analysis.

In the case of the visual acuity and contrast test the luminance of the test target was increased continuously at the rate of 0.02 logarithmic units per second until perception of the targets occurred whereupon it was required of the subject to immediately press the switch on the control box. The luminance of the test patch/target at the press of the switch was then recorded on computer as well as the time elapsed from the start of the test. In the case of the determination of the absolute visual threshold of light perception during the course of dark-adaptation the test patch/target was presented at a frequency of 0.5 Hz and the intensity between any two consecutive flashes was 0.04 logarithmic units.

The coloured lighting used as pre-adaptation stimuli was obtained with the use of special filters. For the blue/green pre-adaptation stimuli a broadband filter cutting off all light with wavelengths above 600 nm was used. For the red lighting, a broadband filter was used that cut off all light below 580 nm. For the white light, lamps with a colour temperature of 3 100K were used. A regulated constant power supply was used to provide steady brightness and colour. In order to produce the pre-adaptation intensities in the sphere of the adaptometer of 0.1, 0.4, 1.6, 6.4 and 25.6 cd/m^2, neutral density filters were used in conjunction with the blue/green and red filters as well as for the white light condition. All luminance measurements conducted to photopically calibrate the pre-adaptation intensities were effected using a 3° measuring field. The luminance of the visual field (test patch/target) was calibrated to 7 logarithmic units = 1 cd/m² at maximum intensity. For recording and data analysis purposes, logarithmic units were used rather than the luminance values in cd/m².

After having passed the ophthalmologic screening test each subject received the test instructions, was informed as to his role as participant, the objectives and the procedures for the test. Each subject was shown the various test plates/targets that were to be presented during the tests and was given the opportunity to try-out the press switch of the automated intensity control. For the first 20 min. each subject was required to remain in the complete darkness in order to dark adapt. For the next 20 min. the subject was light pre-adapted at the selected intensity and colour as defined by the treatment condition. After the first 10 min. of light pre-adaptation the lights were switched off and the subject instructed to press the switch of the automatic intensity control the moment he felt that he could correctly identify, using binocular vision, the target subtending 5 min. of arc (6/30) at the eye and situated in the centre of the 11° test field.

Immediately after recording the luminance threshold and time on computer, the pre-adaptation lights were switched back on. At the end of 15 min. of light pre-adaptation, the lights were switched off again and the subject instructed to press the switch the moment he felt that he could correctly identify the orientation of the gratings of the 20% contrast target, subtending 11° of visual angle (total test field area). Immediately after recording the data i.e. at the press of the switch the pre-adaptation lights were switched back on.

At the end of the 20 min. of light pre-adaptation the lights were switched off and the subject was instructed to press the switch the moment he felt that he could correctly identify the orientation of the gratings of the 100% contrast test field (11°) and indicate the orientation to the experimenter. With the luminance of the flashing test field decreasing, the subject was then instructed to press the switch the moment he could no longer identify the orientation of the gratings, at which time the experimenter would change the orientation. With the luminance of the flashing test field increasing, he had to press the switch the moment he felt that he could correctly identify the orientation of the gratings and then indicate the orientation as being either vertical, to the right, horizontal or to the left. The test continued in this manner for 20 min. with the luminance of the test field, and time after onset, being recorded at each press of the control switch. At the end of 20 min. of determining the absolute (luminance) threshold of light perception during the course of dark adaptation of the whole retina (integral dark-adaptation) the test was stopped and the room lights turned back on. The whole experimental procedure per individual did not take longer than 90 min.

The statistical analysis of these recorded data was performed as follows: Descriptive measures for the results of the visual acuity, contrast sensitivity, absolute visual thresholds observations at the start of the dark-adaptation precess and additionally at time intervals 60, 180, 300, 600 and 1 080 seconds; two-factor Analyses of Variance (ANOVA) were conducted for the results of the visual acuity, contrast sensitivity and absolute visual thresholds at the start of the dark-adaptation process and at time intervals 60, 180, 300, 600 and 1 080 s; when the ANOVA's indicated that row and column means differed, a multiple comparison method was used (Duncan's Multiple Range Test); the adequacy of the model assumptions was tested; the data obtained during the course of dark-adaptation were evaluated using regression analysis. Five functions were evaluated for the data of each individual and the best fit then selected using the coefficient of determination R^2 as criterion of best fit. The individuals were then grouped into the 15 treatment conditions each consisting of six individuals. For each of these categories the best fit was again selected using the R^2 value.

5.3 SUMMARY OF RESULTS

5.3.1 Visual Acuity

The results indicated relatively small differences between the three colours at each intensity as well as between the different intensities of pre-adaptation light (Table III and Figure 10, page 75). The differences between the colours were found not to be statistically significant, $p < 0.01$ (Table IV, page 76). The three colours (blue/green, red and white) of pre-adaptation light had the same effect on subsequent photopic visual acuity (5 min. of arc or 6/30). No significant differences ($p < 0.01$) were found between the lower intensities i.e. between 0.1 and 0.4 cd/m^2 as well as between 0.4 and 1.6 cd/m^2. At the higher intensities of pre-adaptation light i.e. between 1.6 and 6.4 cd/m^2, as well as between 6.4 and 25.6 cd/m^2 the differences were statistically significant ($p < 0.01$). The higher the pre-adaptation light intensity, the higher the absolute (luminance) threshold required to obtain the photopic visual acuity of 5 min. of arc (Table III and Figure 10, page 75). The high levels of luminance (visual) threshold indicated cone-mediated visual acuity being employed to resolve the 5 min of arc test target.

5.3.2 Contrast

These results also indicated relatively small differences between the three colours at each intensity as well as between the different intensities of pre-adaptation light. (Table V and Figure 11, page 83). The differences between the colours were found to be not statistically significant, $p < 0.01$ (Table VI, Page 84). The three colours (blue/green, red and white) of pre-adaptation light had the same effect on subsequent photopic contrast sensitivity (20% contrast). The high level of resolution required by the low contrast level, necessitated the use of cone vision. (Table V and Figure 11, page 83). The raising of the intensity of the pre-adaptation light from 0.1 to 0.4 cd/m² was found not to raise the luminance (visual) threshold significantly ($p < 0.01$). Only at the higher intensities that were employed (1.6, 6.4 and 25.6 cd/m²) did the effect thereof prove to be significant with regard to resolving a 20% contrast. (Table VI, page 84). The higher the pre-adaptation light intensity, the higher the absolute (luminance) threshold required to obtain the 20% contrast sensitivity (Table V and Figure 11, page 83).

5.3.3 Dark Adaptation

These results indicated differences between the three colours at each intensity as well as between the different intensities of pre-adaptation light. These differences were found at the start as well as during the course of dark-adaptation. (Tables VIII, IX and X and Figures 12, 13, 14, pages 91, 92 and 93.) The differences between the intensities were found to be statistically significant ($p < 0.01$) (Table XI, page 101). Visual thresholds increased as the pre-adaptation stimulus intensity increased. The speed of dark-adaptation decreased as the intensity of the pre-adaptation stimuli increased (Figures 12, 13 and 14, pages 90, 91 and 93).

The dark-adaptation curves showed only the rod component of the receptor elements. The slightly larger variability than normal obtained towards the end of the dark-adaptation process was most probably caused by fatigue. The method of presenting constant stimuli and the requirement of morphoscopic identification also contributed to the variability (Tables VIII, IX and X, pages 91, 92 and 93).

The differences between blue/green and red pre-adaptation lighting were found to be statistically significant ($p < 0.01$) right from the start of the dark-adaptation process (Table XII, Page 104). With an increase in intensity, the differences in visual thresholds remained significant for a longer period. No significant differences were found between blue/green and white pre-adaptation lighting at all the intensities (Table XIII, page 104).

The differences between white and red pre-adaptation lighting at 0.1 and 0.4 cd/m² proved not to be significant. (Table XIV, Page 105). At 1.6, 6.4 and 25.6 cd/m² the differences in visual threshold during the course of dark-adaptation for white and red lighting proved to be statistically significant ($p < 0.01$). These differences remained significant, with an increase in pre-adaptation light intensity. The advantage of red over white lighting with regard to dark-adaptation increased with increased intensity of the pre-adaptation stimulus. After exposure to blue/green and white light, it takes longer to reach the same level of dark-adaptation as after being subjected to the same photopic intensity of red lighting. The exception to this is the insignificant difference found between white and red exposure of mesopic intensities (0.1 and 0.4 cd/m²), the latter being due to the inability to accurately equate non-monochromatic lights in the mesopic range of the human visual system by means of brightness measurements. The results did not show support for the view that to produce the same dark-adaptation in the same time, red pre-adaptation light must be held 4 times (in cd/m²) as bright as white light: the present study indicates much larger ratios, of the order of 10 times, or more. It was also demonstrated that this brightness ratio between red and white lighting will increase with an increas in intensity.

With regard to the difference in speed of adaptation between the colours at the same intensity, it was found that it would take longer after exposure to white and blue/green lighting to reach the same visual threshold as after exposure to red lighting of equal photopic intensity. These time differences increased with increased intensity (Table XVI, page 118).

5.4 CONCLUSIONS

Based on the findings of this study, the following conclusions were drawn:

5.4.1 The first hypothesis was retained. Low level blue/green illuminance/luminance does affect human visual (photopic) acuity in the same manner as do white and red lighting of equal photopic effeciency.

5.4.2 The second hypothesis was retained. Low Level blue/green illuminance/luminance does affect human contrast sensitivity in the same manner as do white and red lighting of equal photopic efficiency.

5.4.3 The third hypothesis was partly rejected and partly retained. Low level blue/green did affect human visual (absolute) threshold in the same manner as white lighting of equal photopic efficiency. Red lighting provided significantly lower thresholds than blue/green lighting of equal photopic efficiency. White and red lighting do not differ at low intensities (mesopic range i.e. 0.1 and 0.4 cd/m^2) but do at the higher intensities (photopic range i.e. 1.6, 6.4 and 25.6 cd/m^2).

5.4.4 The fourth hypothesis was partly rejected and partly retained. Low level blue/green illuminance/luminance does affect human dark-adaptation in the same manner as white lighting of equal photopic efficiency. Red lighting provided significantly lower visual thresholds than blue/green lighting of equal photopic efficiency. White and red lighting do not differ at low intensities (mesopic range i.e. 0.1 and 0.4 cd/m^2) but do at the higher intensities (photopic range i.e. 1.6, 6.4 and 25.6 cd/m^2).

5.4.5 The higher (photopic) degree of resolution (visual acuity and contrast sensitivity) require higher luminance thresholds and employ cone vision.

5.4.6 The higher the pre-adaptation stimulus-intensity, the higher the visual (luminance) threshold.

5.4.7 The speed of dark-adaptation decreases as the intensity of the pre-adaptation light increases.

5.4.8 Low pre-adaptation stimuli only produce rod components of dark-adaptation curves.

5.4.9 The method of constant stimulus presentation used and the requirement of morphoscopic identification provided accurate and reliable thresholds but contributed to larger variations than "normal" as determined in the literature towards the end of the dark-adaptation process, this suggesting visual fatigue.

5.4.10 After exposure to blue/green and white light, it will take longer to reach the same level of dark-adaptation as after being subjected to the same photopic intensity of red light. These time differences increase with increased intensities.

5.4.11 At the upper mesopic region the differences between the effects of white and red lighting on subsequent dark-adaptation become irregular due to inability to accurately equate non-monochromatic lights in the mesopic range of the human visual system.

5.4.12 The brightness ratio between red and white lights to produce the same dark-adaptation increases with an increase in intensity.

5.5 RECOMMENDATIONS

The following recommendations for future study merit consideration:

5.5.1 The influence of the colour of lighting and its intensity on subesquent mesopic visual acuity and contrast sensitivity should be explored.

5.5.2 The influence of the colour of lighting at lower mesopic intensities on subsequent dark-adaptation should be studied.

5.5.3 The spectral sensitivity of the eye in the mesopic range should be evaluated and should include not only monochromatic light sources but also broadband non-monochromatic light sources.

5.5.4 A comparison of the method of constant stimuli (continuous method) as used in the present study with the traditional method of sampling thresholds at 1 to 1.5 minute intervals. The two methods should be evaluated for accuracy and reliability for producing dark-adaptation curves.

5.5.5 The use of the variability in luminance threshold produced by the method of constant stimuli as an indication of visual fatigue should be studied. Data in the present study provide a method of inducing visual fatigue which is quantifiable.

5.5.6 The brightness ratio between red and white lights to produce the same dark-adaptation should be explored further.

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APPENDIX 1

RECORDING SHEET FOR PRELIMINARY OPHTHALMOLOGIC EXAMINATION

SUBJECT NAME : ______________________ AGE : ______________________

DATE : ______________________ NUMBER : ______________________

COLOUR OF PRE-ADAPTATION STIMULI : ______________________

INTENSITY OF PRE-ADAPTATION STIMULI : ______________________

RESULTS OF PRELIMINARY OPHTHALMOLOGICAL EXAMINATION

A VISUAL ACUITY (SCHNELLEN)

LEFT EYE : ______________________ [6/6]

RIGHT EYE : ______________________ [6/6]

BOTH EYES : ______________________ [6/6]

RESULT : | PASS | FAIL |

B CONTRAST SENSITIVITY (VISTECH)

SPATIAL FREQUENCY (CYCLES PER DEGREE)			SCORE LEFT EYE	SCORE RIGHT EYE
1,5	(A)	[5]		
3	(B)	[5]		
6	(C)	[4]		
12	(D)	[3]		
18	(E)	[1]		

RESULT : | PASS | FAIL |

C COLOUR-BLINDNESS (ISHIHARA)

SCORE : __________/15 [13/15]

RESULT : | PASS | FAIL |

TESTED BY : ______________________ RESULT : | PASS | FAIL |

APPENDIX 2

CONSENT FORM

CONSENT FORM

INFLUENCE OF BLUE/GREEN VERSUS RED AND WHITE LIGHT SOURCES ON HUMAN DARK ADAPTATION AND OTHER SELECTED VISUAL FUNCTIONS

I, ______________________________, having full capacity to consent, do hereby volunteer to participate in a research study entitled, *"Influence of Blue/Green Versus Red and White Light Sources on Human Dark Adaptation and other selected Visual Functions"* under the direction of Mr EJ Hendrikse. The implications of my voluntary participation, the nature, duration and purpose, the methods and means by which it is to be conducted, and inconveniences and hazards which may reasonably be expected have been explained to me by ______________________________ and are set forth in the instructions on the reverse side of this agreement, which I have initialed. I have been given the opportunity to ask questions concerning this research project, and any such questions have been answered to full and complete satisfaction. I understand that I may at any time during the course of this project revoke my consent, and withdraw from the project without prejudice.

I FULLY UNDERSTAND TAHT I AM MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. MY SIGNATURE INDICATES I HAVE DECIDED TO PARTICIPATE HAVING READ THE INFORMATION PROVIDED ABOVE.

AM
PM

____
Signature Date Time

I was present during the explanation referred to above, as well as the volunteer's opportunity for questions, and hereby witness the signature.

____
Signature Date

I have briefed the volunteer and answered questions concerning the research project.

____
Signature Date

APPENDIX 3

INSTRUCTIONS

INSTRUCTIONS

INFLUENCE OF BLUE/GREEN VERSUS RED AND WHITE LIGHT SOURCES ON HUMAN DARK ADAPTATION AND OTHER SELECTED VISUAL FUNCTIONS

You are invited to participate in an experiment entitled *"Influence of Blue/Green Versus Red and White Light Sources on Human Dark Adaptation and other selected visual funcitons"*. We hope to study and measure any differences in these light sources.

If you decide to participate, you will first be asked to undergo a preliminary ophthalmologic examination. Unfortunately we cannot use anybody who has less than 6/6 uncorrected visual acuity. You must also have normal contrast sensitivity and colour discrimination.

The procedure to be followed after you have passed the ophthalmologic screening test is as follows. For the first 20 minutes you will be pre-adapted to a certain colour and intensity of light as determined by the treatment condition. During the last 10 minutes of this pre-adaptation phase your visual threshold to obtain a certain visual acuity and contrast sensitivity will be determined. You will first of all be required to increase the luminance until you can correctly identify the three numbers presented (visual acuity). Secondly for the contrast test you will be required to increase the luminance until you can correctly identify the direction of the gratings. After the 20 minutes of pre-adaptation to light, it will be turned off and your absolute threshold of light perception during the course of dark adaptation will be determined during the next 20 minutes. You will be required to first of all increase the luminance until you can correctly identify the direction of the gratings of the target. Immediately thereafter you will decrease the luminance until you cannot correctly identify the direction of the gratings whereafter you will again increase the luminance until you can identify the gratings. You will carry on until stopped by the experimenter after approximately 20 minutes. The total experimental procedure should not take longer than 01h30

Your confidentiality as a participant in this program will be protected. Your name will not be revealed without your written permission. Statistical data collected during the test program may be published in scientific literature without identifying individual subjects.

You will receive no monetary benefits for participating in the study. No alternative exists to obtain the required information. If you do decide to participate, you are still free to withdraw your consent and to discontinue participation at any time without prejudice. If you have any questions we will be happy to answer them.

You will be given a copy of this form to keep.

______________________________ ______________________________

DATE VOLUNTEER'S INITIALS

APPENDIX 4

AUTOMATIC INTENSITY CONTROL AND DATA ACQUISITION SOFTWARE

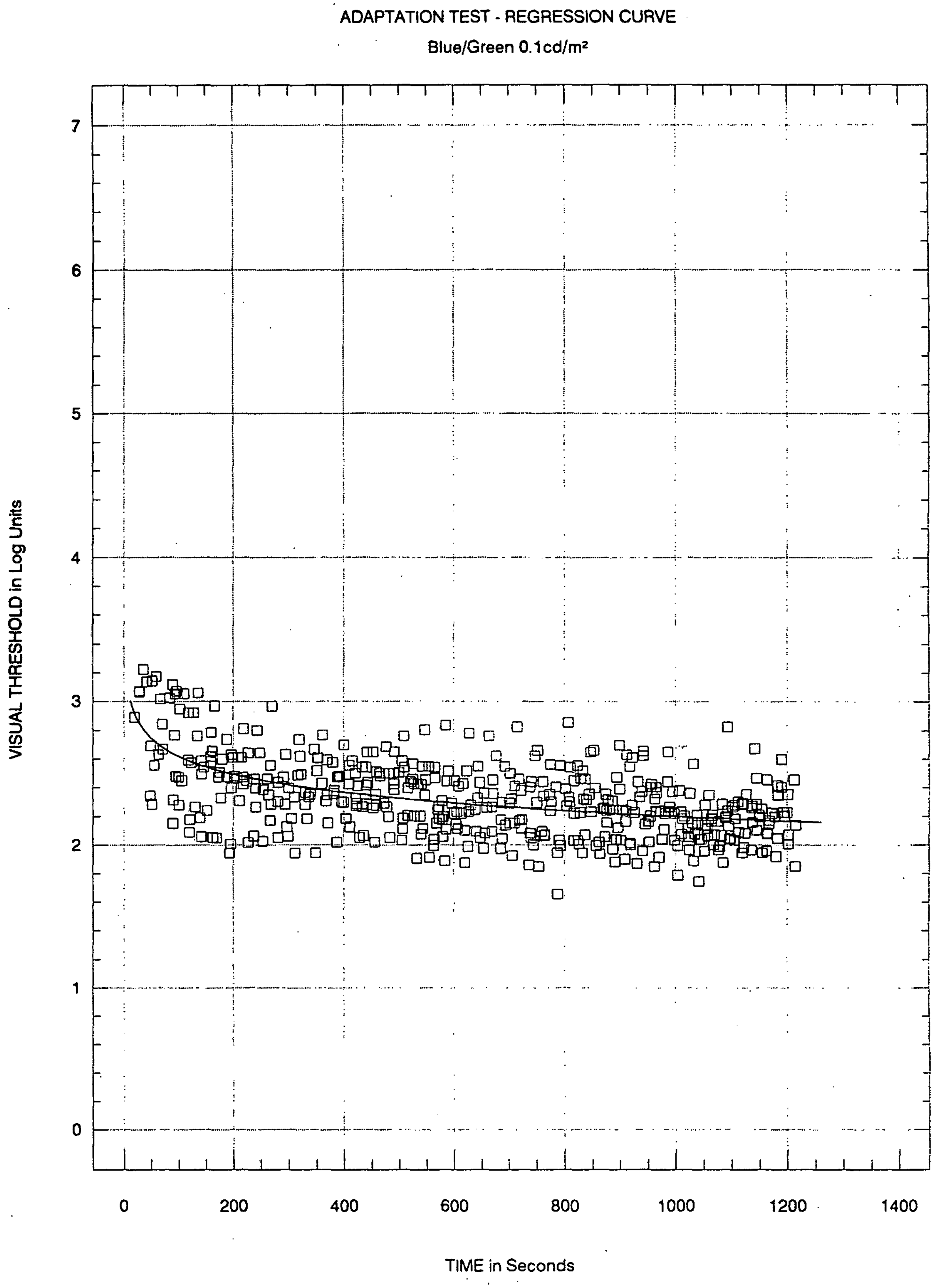
```
1 SD=26
2 GOTO 8000
50 FOR N=1 TO 180
100 OUT &H378,3:GOSUB 3000 REM CLOCKWISE
200 OUT &H378,2:GOSUB 3000
300 OUT &H378,0:GOSUB 3000
400 OUT &H378,1:GOSUB 3000
450 NEXT N
500 FOR N=1 TO 800
600 OUT &H378,3:FOR I=1 TO 100:NEXT I
700 OUT &H378,1:FOR I=1 TO 100:NEXT I
800 OUT &H378,0:FOR I=1 TO 100:NEXT I
900 OUT &H378,2:FOR I=1 TO 100:NEXT I
950 NEXT N
970 STOP
1000 X1=X:TR=TIMER
1001 X-X+1
1005 IF X>1116 THEN GOTO 1070 :   REM UPPER LIMIT STOP
1010 OUT &H378,3:GOSUB 3000   REM UPWARDS MOVEMENT
1020 OUT &H378,2:GOSUB 3000
1030 OUT &H378,0:GOSUB 3000
1040 OUT &H378,1:GOSUB 3000
1050 IF S=1 THEN GOTO 1060 ELSE GOTO 1001
1060 S=0
1070 RETURN
2000 X1=X:TR=TIMER
2001 X=X-1
2005 IF X<0 THEN GOTO 2070 :   REM LOWER LIMIT
2010 OUT &H378,3:GOSUB 3000   REM DOWNWARDS MOVEMENT
2020 OUT &H378,1:GOSUB 3000
2030 OUT &H378,0:GOSUB 3000
2040 OUT &H378,2:GOSUB 3000
2050 IF S=1 THEN TOTO 2060 ELSE GOTO 2001
2060 S=0
2070 RETURN
2500 OUT &H378,3:GOSUB 3000   REM CAL CYCLE
2510 OUT &H378,2:GOSUB 3000
2520 OUT &H378,0:GOSUB 3000
2530 OUT &H378,1:GOSUB 3000
2540 Q=INP (&H379)
2550 IF (Q AND 128)=0 GOTO 2500 ELSE GOTO 2560
2560 X=1116        :REM CAL FULL SCALE VALUE
2570 RETURN
3000 FOR A=1 TO SP
3002 IF SP<11 THEN GOTO 3004 ELSE Q-INP(&H379)
3003 IF (Q AND 64)=0 THEN S=1
3004 NEXT A
3005  IF  SP>10  THEN  LOCATE  25,1"PRINT  USING"\
\####.###";"POSITION
=";X/1116*7;" TIME ELAPSED=";TIMER-T;" SPEED=";(X-X1);/(TIMER-
TR)/1116*7;:
REM COUNTER SCREEN POSITION
3010 RETURN
3020 FOR A=1 TO 10000!:NEXT A : REM DELAY REVERSE DIRECTION
3030 RETURN
4000 A=INP(&H379)
```

```
4010 B=A AND 128:C+A AND 64
4020 GOTO 4000
5000 PRINT#1,X1116*7,TIMER-T:   REM WRITE TO FILE
5010 RETURN
5100  INPUT  "STARTING  POSITION";w:Z=w*1116/7:  REM  MOVE  TO
STARTING POSITION SUB
5105 X=X-1
5110 OUT &H378,3:GOSUB 3000
5120 OUT &H378,1:GOSUB 3000
5130 OUT &H378,0:GOSUB 3000
5140 OUT &H378,2:GOSUB 3000
5150 IF X>Z TEHN GOTO 5105 ELSE GOTO 5155
5155 LOCATE 23,20 : INPUT" PRESS RETURN TO START TEST ", M$
5156 T=TIMER
5157 PRINT#1,X/1116*7;" ";TIME$
5160 RETURN
7000 INPUT "FILENAME";R$
7003 OPEN R$ FOR OUTPUT AS#1
7006 SCREEN0:WIDTH 80
7007 SP=1:CLS:GOSUB 2500
7008 GOSUB 5100
7009 SP-47
7010 GOSUB 1000
7011 GOSUB 5000
7015 GOSUB 3020
7020 GOSUB 2000
7022 GOSUB 5000
7025 GOSUB 3020
7030 GOTO 7010
8000 CLS
8001 SP=1:CLS:GOSUB 2500
8010 ON ERROR GOTO 9000
8020  LOCATE  1,1:INPUT  "SUBJECT  NUMBER
?",NUM$:FILENAME$=NUM$+".prn"
8025 OPEN FILENAM$ FOR INPUT AS#1
8026 LOCATE 23,20 "PRINT"  File already exists
8028 CLOSE #1: goto 8020
8030 LOCATE 2,1:INPUT "COLOUR ? (White, Red, Bluegreen) ",COL$
8040 IF COL$="W" OR COL$="w" THEN GOTO 10100
8041 IF COL$="R" OR COL$="r" THEN GOTO 10200
8042 IF COL$="B" OR COL$="b" THEN GOTO 10300
8043 LOCATE 23,20:PRINT"ERROR:wrong colour - type first letter
of colour"
8045 GOTO 8030
8050  INPUT"Preadaptation  Luminance  (0.1;0.4;1.6;6.4;25.6)  ?
",LUM$
8060  PRINT#1,"SUBJECT  ";NUM$,"COLOUR  ";COLOUR$,"LUMINANCE
";LUM$,DATE$
8100 LOCATE 7,1:PRINT "VISUAL AQUITY TEST "
8105 GOSUB 5100
8200 SP=SD
8210 GOSUB 1000
8220 GOSUB 5000
8230 LOCATE 9,1:PRINT 'Visual Threshold = ";X/1116*7
8240 LOCATE 23,20:PRINT"press RETURN to accept and save or ESC
to quit"
```

```
8245 A$ = INKEY$ :IF A$+"" THEN 8245 ELSE IF A$=CHR$(27) THEN
STOP
8270 LOCATE 11,1:PRINT "CONTRAST TEST"
8275 SP=1
8280 GOSUB 5100
8300 SP-SD
8310 GOSUB 1000
8315 GOSUB 5000
8320 LOCATE 13,1:PRINT "VISUAL THRESHOLD = ";x/116*7
8340 LOCATE 23,20:PRINT"press RETURN to accept and save or ESC
to quit"
8345 A$ = INKEY$:IF A$ = "" THEN 8345 ELSE IF A$=CHR$(27) THEN
STOP
8400 LOCATE 15,1:PRINT "ADAPTATION TEST"
8410 SP=1
8420 GOSUB 5100
8435 LOCATE 23,30:PRINT"press ESC to stop test     "
8440 SP=SD
8450 GOSUB 1000
8460 GOSUB 5000
8470 IF INKEY$ = CHR$(27) THEN GOTO 8600 ELSE GOSUB 3020
8480 GOSUB 2000
8490 GOSUB 5000
8500 IF INKEY$ = CHR$(27) THEN GOTO 8600 ELSE GOSUB 3020
8510 GOTO 8450
8600 CLOSE #1
8610 SP=1:GOSUB 1000
8640 LOCATE 23,20:PRINT"press ESC to exit to dos or RETURN to
do another test"
8645 A$ = INKEY$ :IF A$ ="" THEN 8645 ELSE IF A$=CHR$(27) THEN
SYSTEM
8650 GOTO 8000
9000 OPEN "o",#1, FILENAME$
9100 RESUME 8030
10100 COLOUR$ = "White"
10110 GOTO 8050
10200 COLOUR$ = "Red"
10210 GOTO 8050
10300 COLOUR$ = "Bluegreen"
10310 GOTO 8050
```

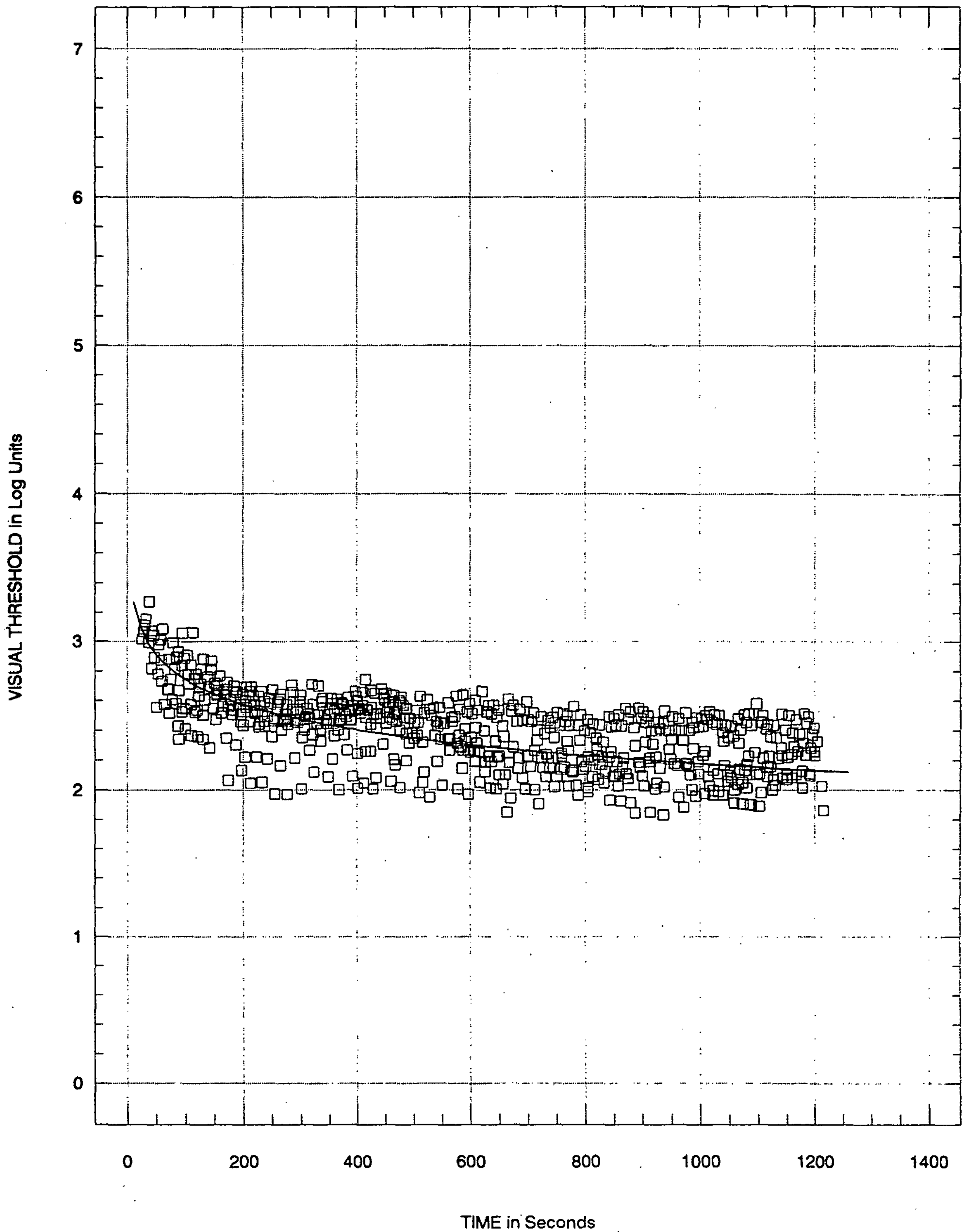
APPENDIX 5

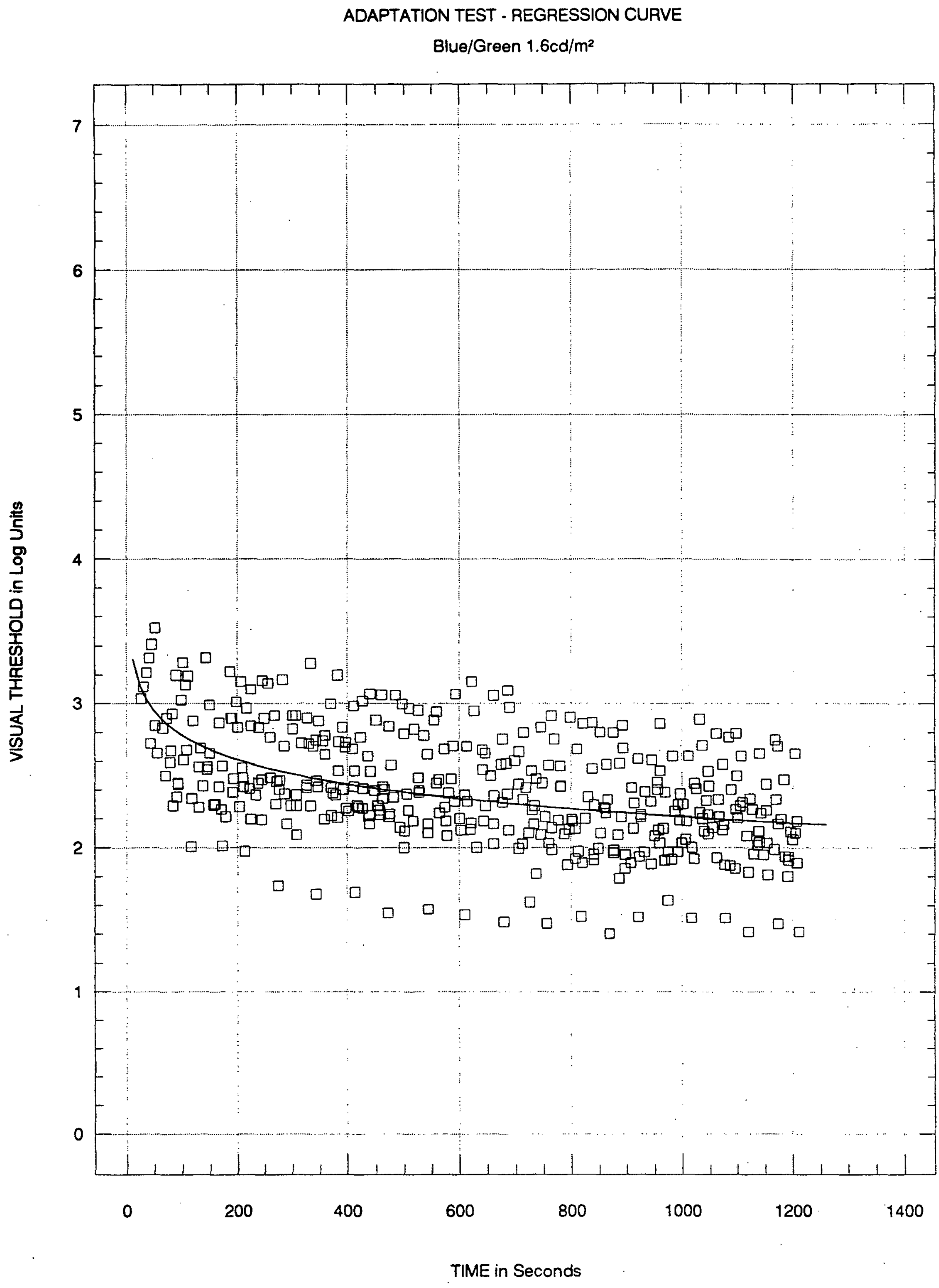
DARK ADAPTATION CURVES (REGRESSION) FOR EACH TREATMENT CONDITION SEPERATELY


ADAPTATION TEST - REGRESSION CURVE
Blue/Green 0.1cd/m²
VISUAL THRESHOLD in Log Units
0
1
2
3
4
5
6
7
0
200
400
600
800
1000
1200
1400
TIME in Seconds

ADAPTATION TEST - REGRESSION CURVE

Blue/Green 0.4cd/m²

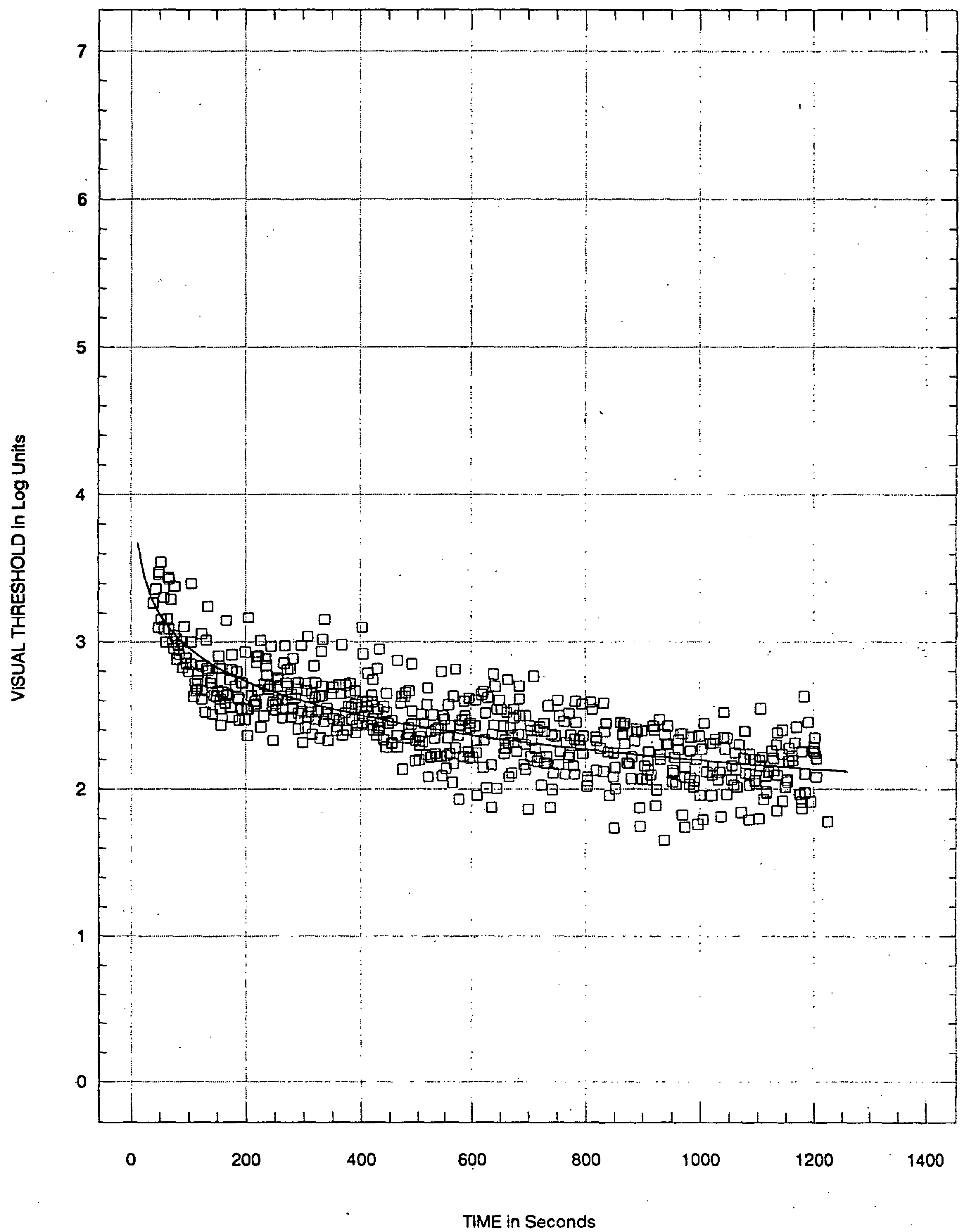




ADAPTATION TEST - REGRESSION CURVE
Blue/Green 1.6cd/m²
VISUAL THRESHOLD in Log Units
7
6
5
4
3
2
1
0
0
200
400
600
800
1000
1200
1400
TIME in Seconds

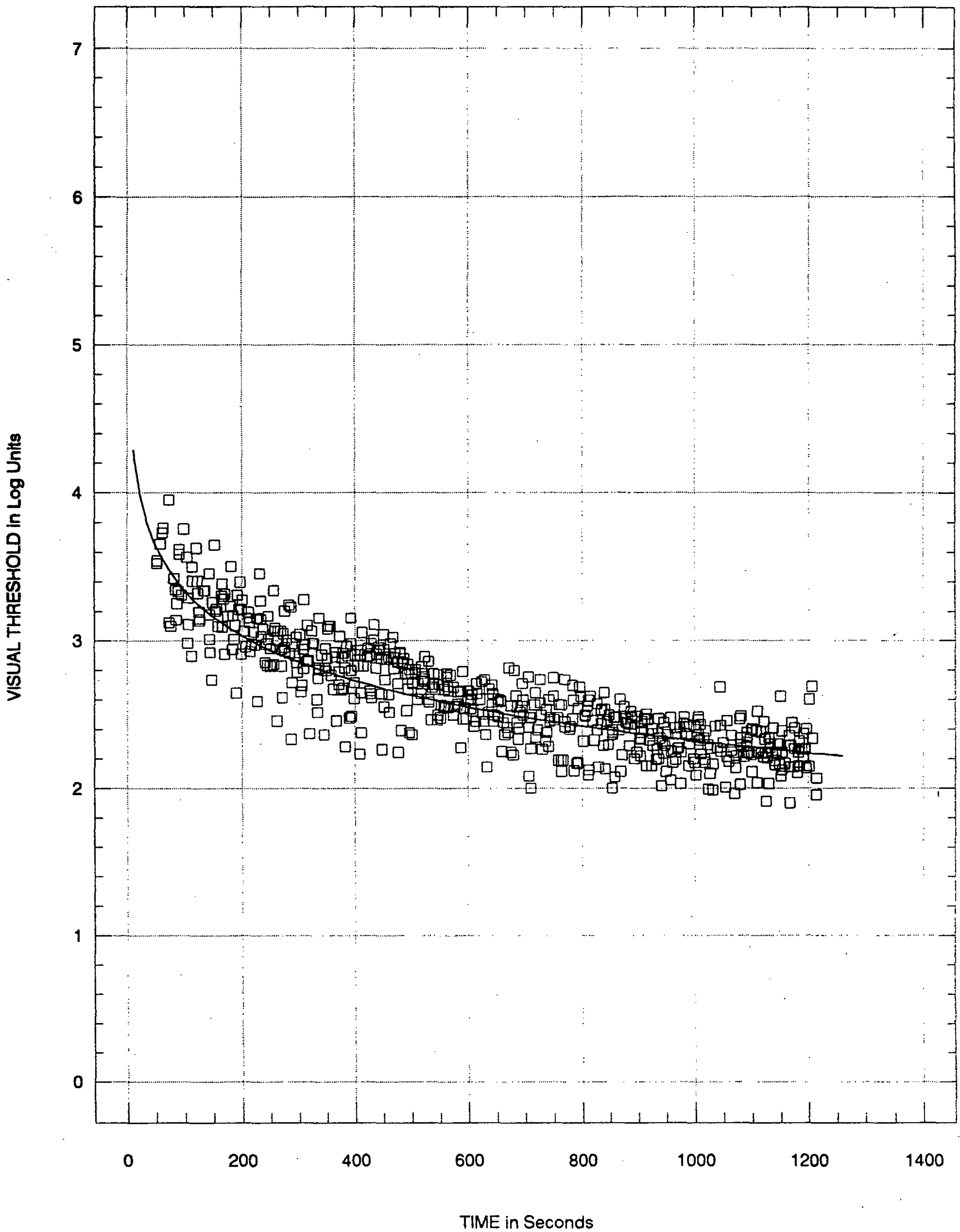
ADAPTATION TEST - REGRESSION CURVE

Blue/Green 6.4cd/m²



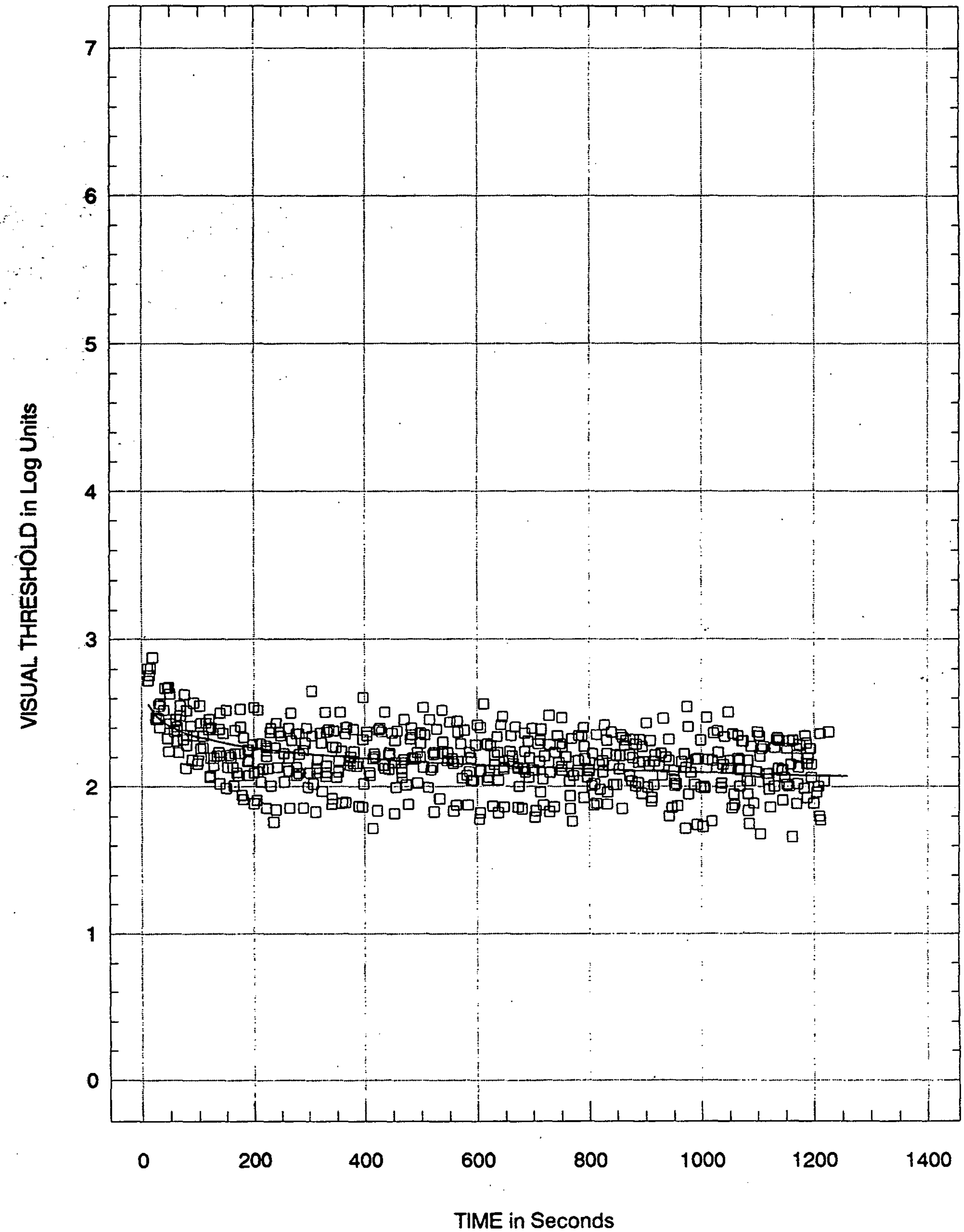
ADAPTATION TEST - REGRESSION CURVE

Blue/Green 25.6cd/m²



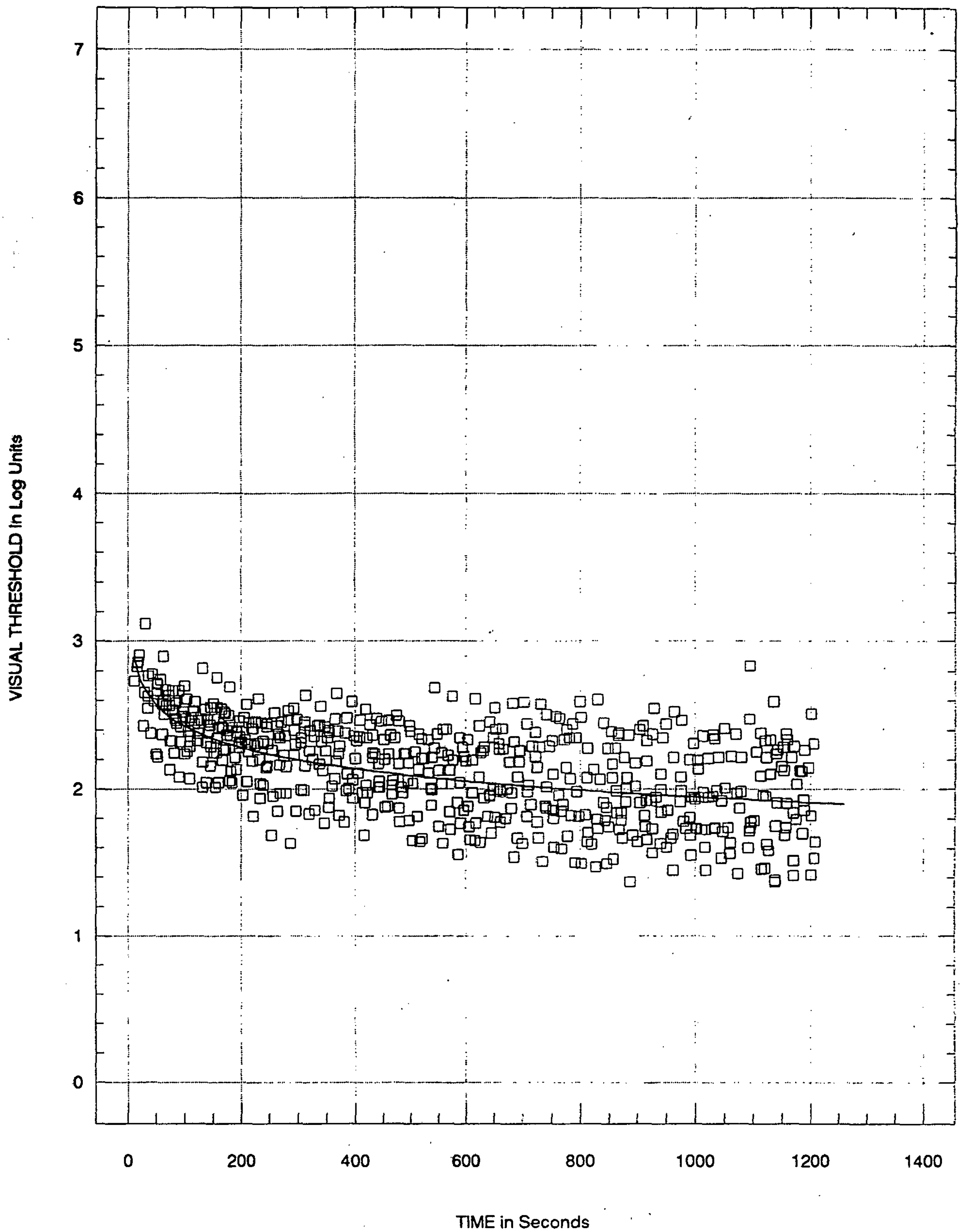
ADAPTATION TEST - REGRESSION CURVE

Red 0.1 cd/m²



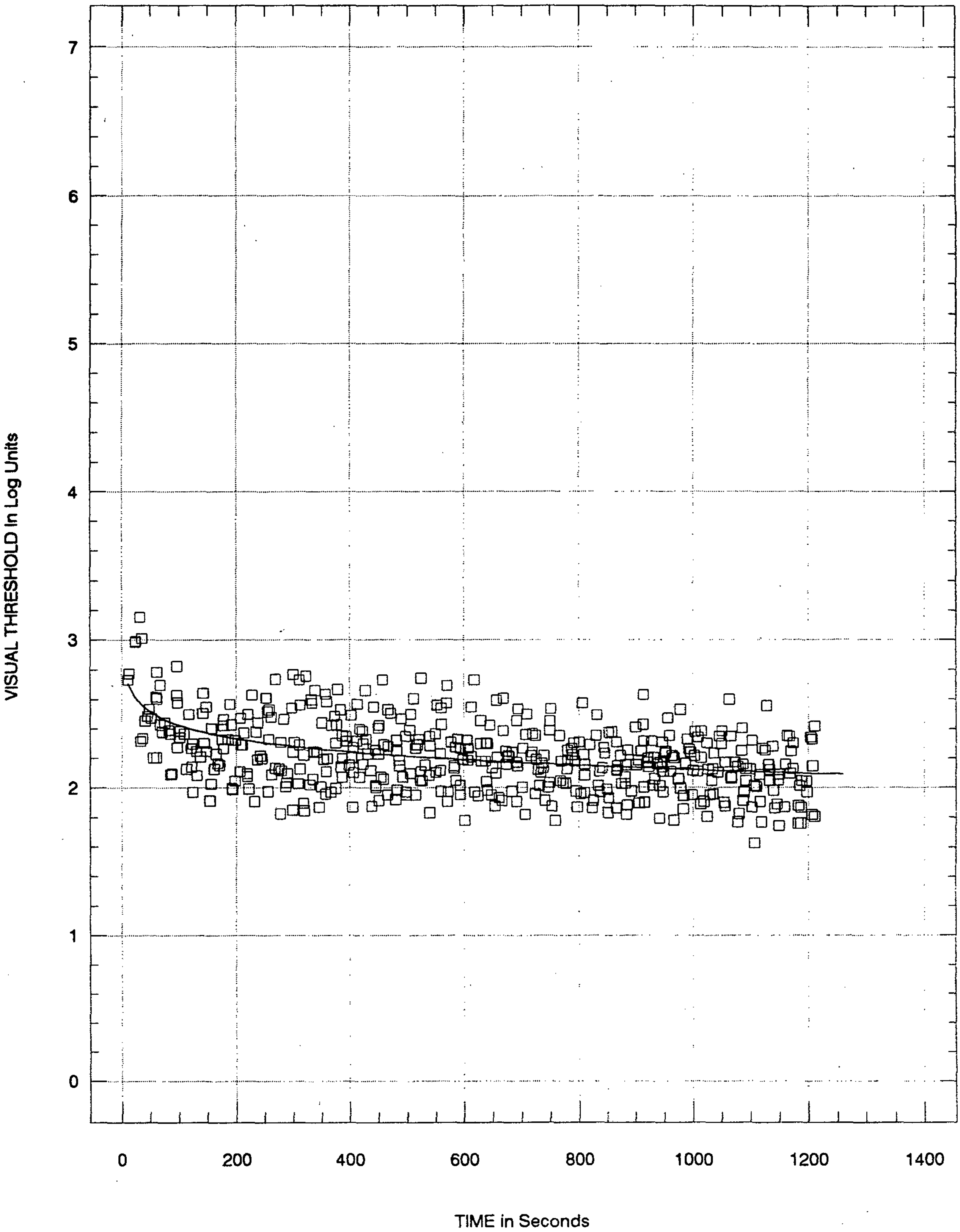
ADAPTION TEST - REGRESSION CURVE

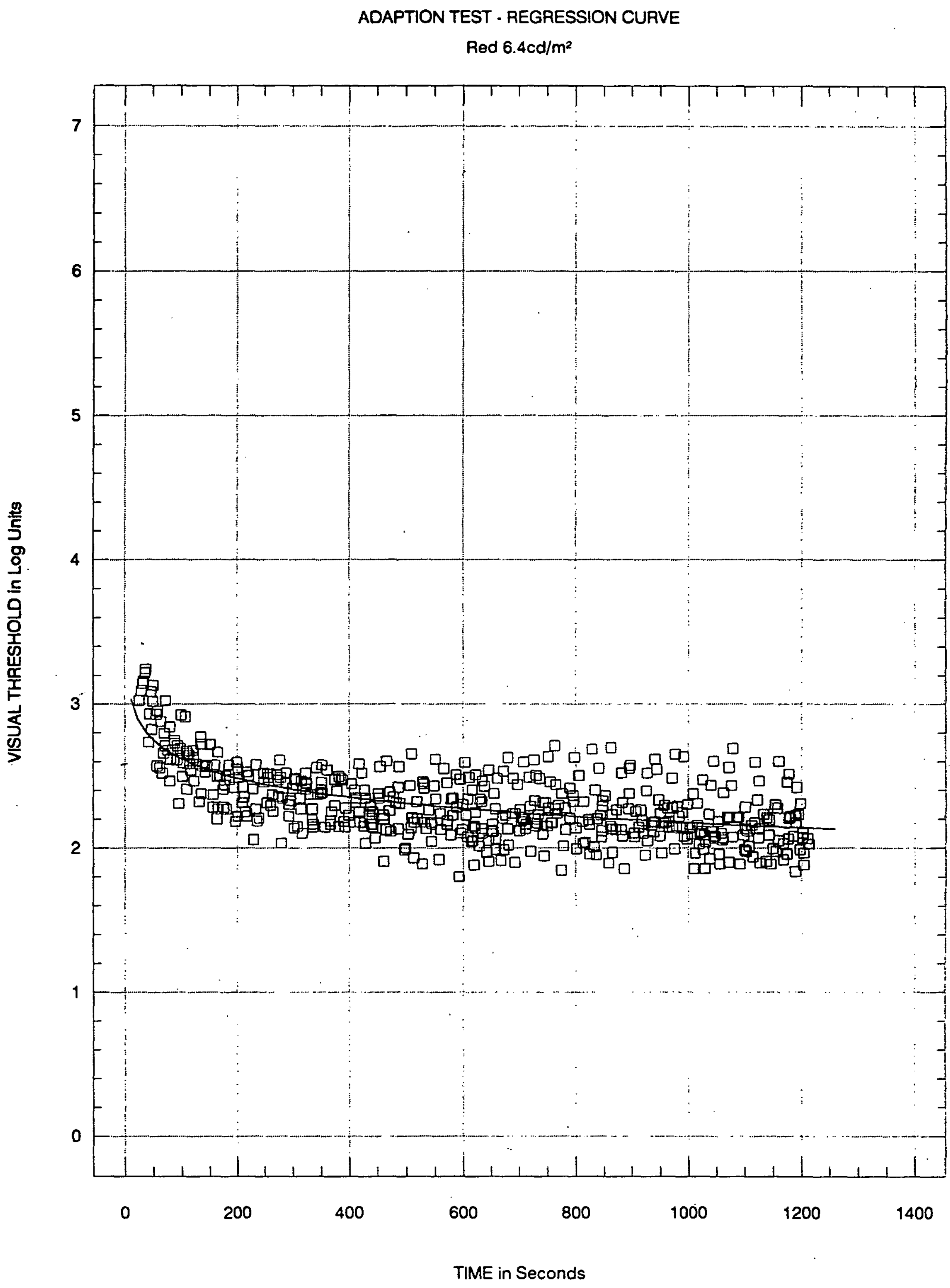
Red 0.4cd/m²



ADAPTION TEST - REGRESSION CURVE

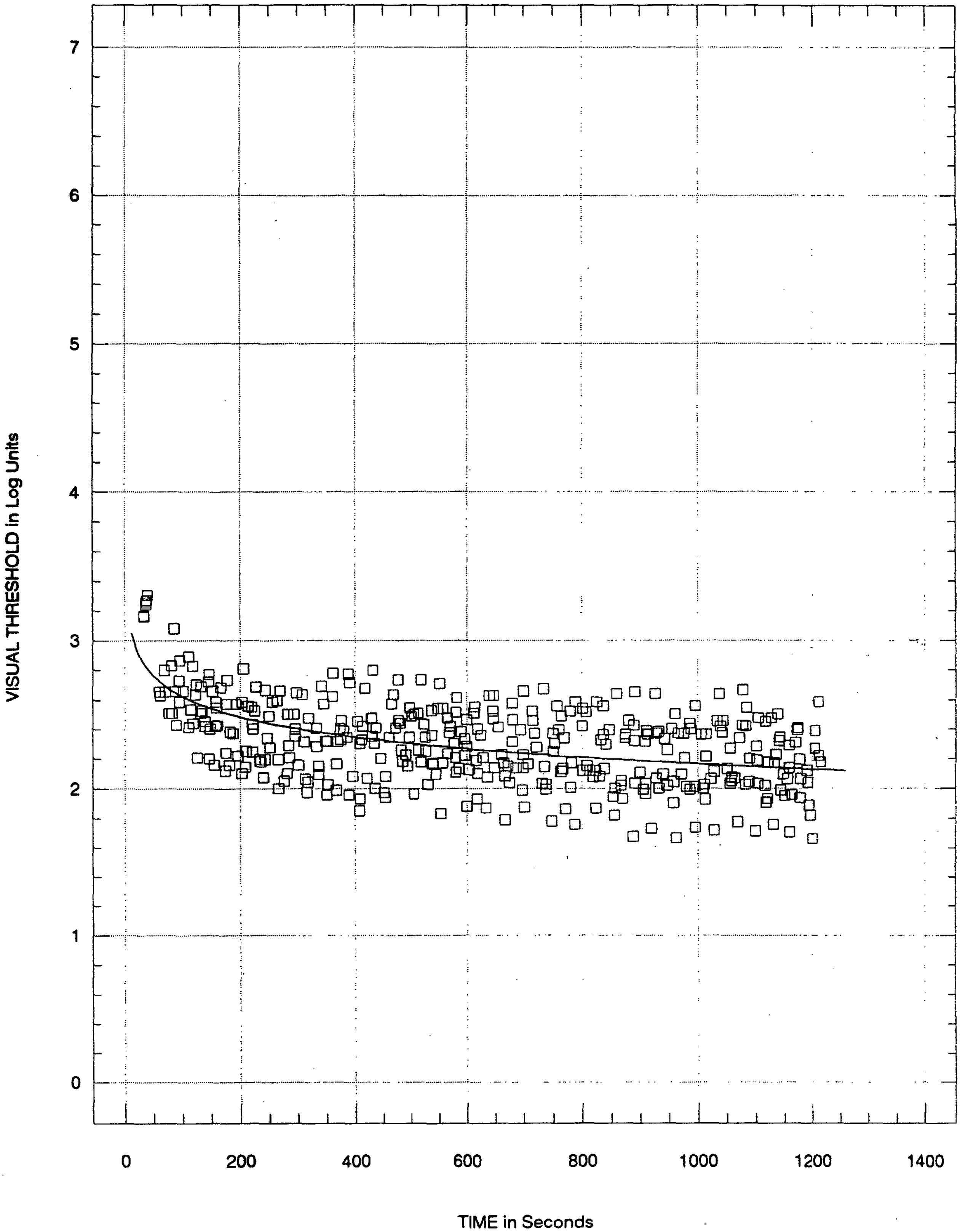
Red 1.6cd/m²




ADAPTION TEST - REGRESSION CURVE
Red 6.4cd/m²
VISUAL THRESHOLD in Log Units
7
6
5
4
3
2
1
0
0
200
400
600
800
1000
1200
1400
TIME in Seconds

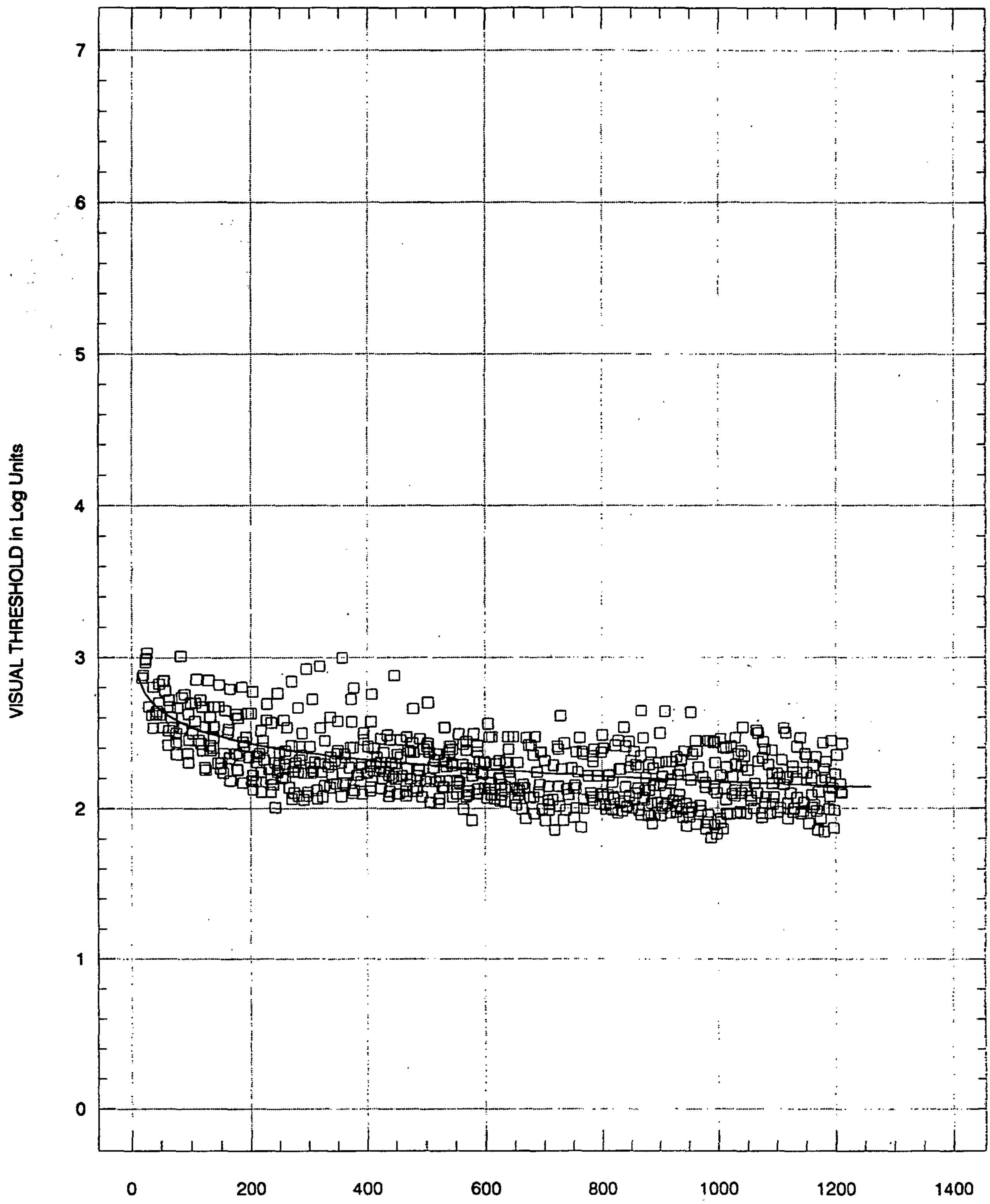
ADAPTION TEST - REGRESSION CURVE

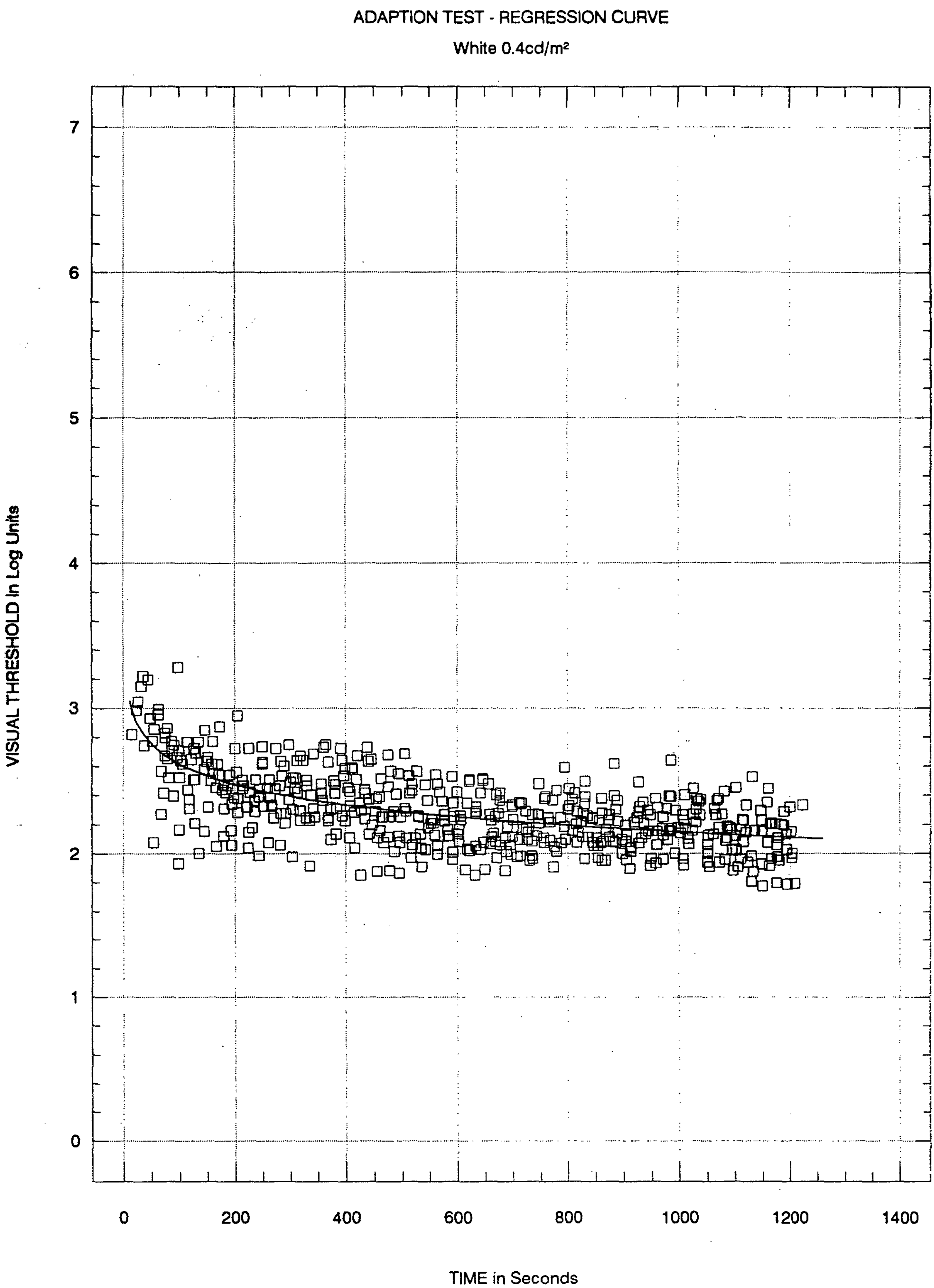
Red 25.6cd/m²

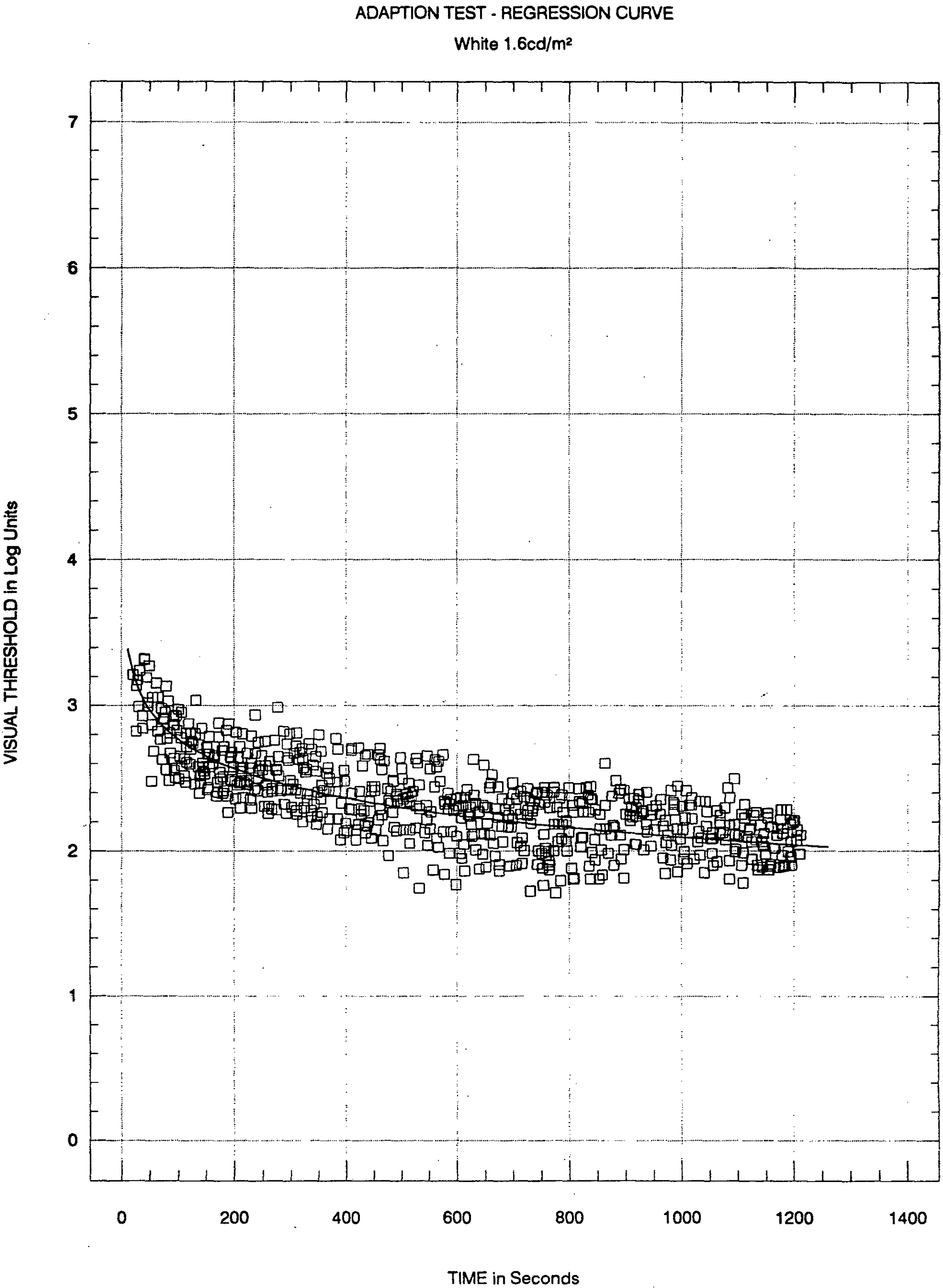


ADAPTATION TEST - REGRESSION CURVE

White 0.1cd/m²

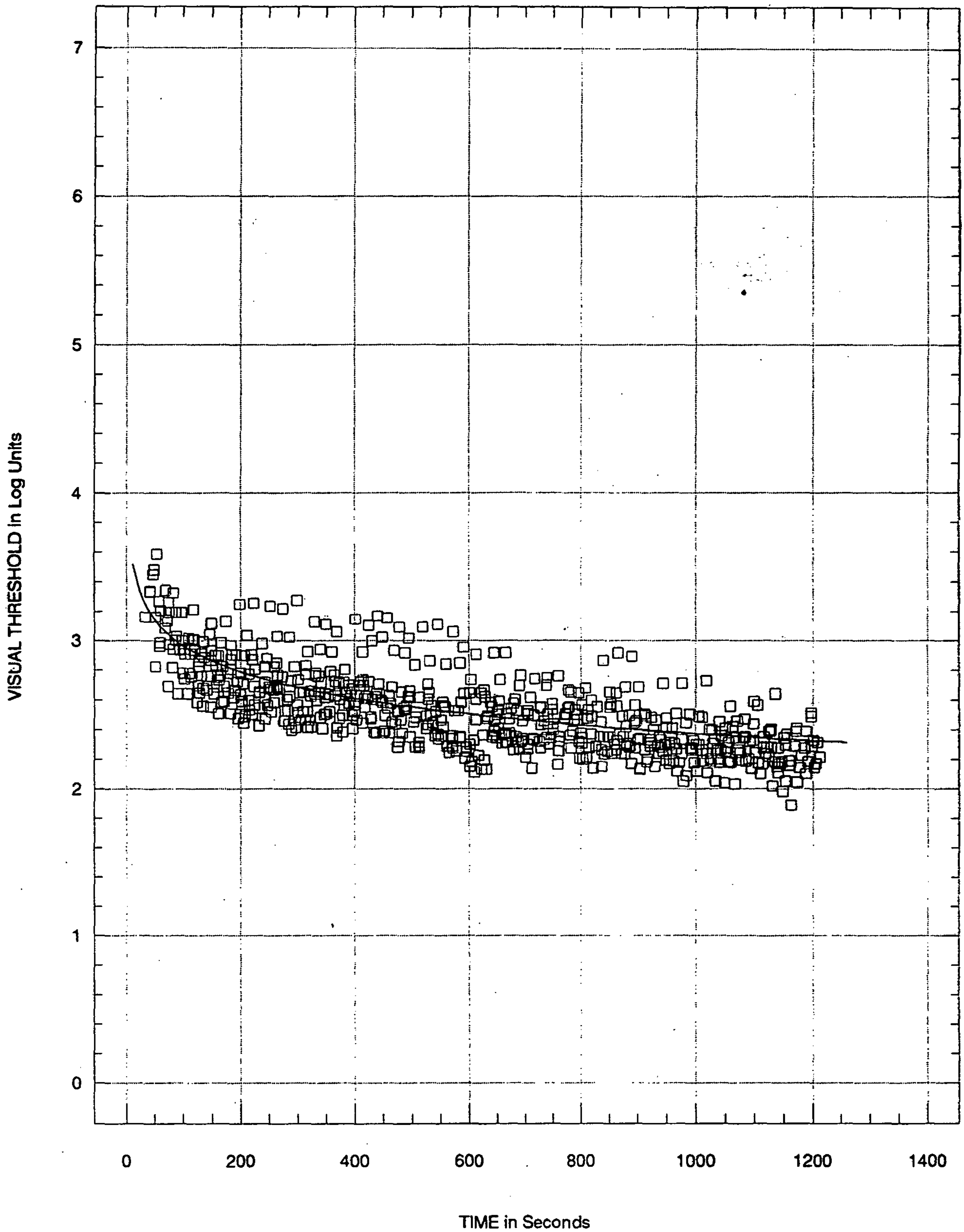



ADAPTION TEST - REGRESSION CURVE
White 0.4cd/m²
VISUAL THRESHOLD In Log Units
0
1
2
3
4
5
6
7
0
200
400
600
800
1000
1200
1400
TIME in Seconds


ADAPTION TEST - REGRESSION CURVE
White 1.6cd/m²
VISUAL THRESHOLD in Log Units
TIME in Seconds
0
1
2
3
4
5
6
7
0
200
400
600
800
1000
1200
1400

ADAPTATION TEST - REGRESSION CURVE

White 6.4cd/m²



ADAPTION TEST - REGRESSION CURVE

White 25.6cd/m²