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A thesis submitted for the degree of Doctor of Philosophy (PhD)
January 2009

By

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ABSTRACT

Vitamin A deficiency primarily affects young children in developing countries, the symptoms of which initially present as nyctalopia, an inability of the eyes to "see" in low luminance levels, specifically at twilight or at night. Vitamin A deficiency is a major cause of blindness in developing countries and is associated with significant increases in child morbidity and mortality.

Nyctalopia may be examined using dark adaptometry; however, current methods of dark adaptometry have many practical limitations, including their unsuitability for use with children. This thesis reports on the design, construction, testing and evaluation of a novel automated dark adaptometer for use as a diagnostic tool in order to screen individuals and/or populations at risk from hypovitaminosis A, or other causes of night vision defects - in either third or first world situations. An instrument was devised and designed which was portable, robust, easy to use outside the clinical environment, and used solid state devices, allowing digital data capture, retrieval and display.

The construction of a fully working concept prototype adaptometer model is reported, from conception phase through to data evaluation. A comprehensive description is provided on the design rationale, construction details, circuit diagrams and circuit schematics and test protocol procedures. The successful evaluation of the concept prototype adaptometer led to the development of a more sophisticated post prototype instrument which is similarly described. Repeat dark adaptation data is reported on both the concept prototype adaptometer and post prototype instrument.
Data is presented on the evaluation and analysis of the concept prototype adaptometer which involved the examination of 22 healthy test volunteers. In excess of 60 repeat investigations were successfully completed on the majority of these subjects to establish the variation in subject performance and consistency of the data collected. The elevation of the rod threshold with advancing age was examined and confirmed.

Results on the evaluation of the post prototype (automatic dark adaptometer) are similarly presented with the results compared to the conventional dark adaptometry methodology; specifically the Goldmann-Weekers Adaptometer. Evidence is presented on the new instrument's repeatability and precision; and its suitability as a clinical measurement tool. Data is presented on test-retest repeatability using the new instrument on 31 subjects comprising 50 repeat investigations.

The instrument described in the thesis has been successfully patented.
Declaration

I certify that this thesis which I now submit for examination for the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others save to the extent such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate studies by research of the Dublin Institute of Technology and has not been submitted in whole or in part for an award in any other Institute or University.

The work reported on in this thesis conforms to the principles and requirements of the Institute’s guidelines for ethics in research,

The Institute has permission to keep, or lend or copy this thesis in whole or in part, on condition that any such use of the material of the thesis is duly acknowledged.

Signature  
Candidate

Date September 2009

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Many thanks to Gwent Tool Moulding (Wales) who were responsible for the tool mould construction and injection moulding of the pre-production units.

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Not least, I would like to express my sincere gratitude to my wife, Mary and our children Ciarán, Aoife and Róisín for their patience and understanding during my long absences from family life which were taken up with writing this thesis.
Dedication

This thesis is dedicated to my late mother and brother; Maura Stratton and John D. O'Brien.
## Common Abbreviations

<table>
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<tr>
<td>CPA</td>
<td>Concept Prototype Adaptometer</td>
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<tr>
<td>ADA</td>
<td>Automatic Dark Adaptometer</td>
</tr>
<tr>
<td>GWA</td>
<td>Goldmann Weekers Adaptometer</td>
</tr>
<tr>
<td>RPE</td>
<td>Retinal Pigment Epithelium</td>
</tr>
<tr>
<td>DA</td>
<td>Dark Adaptation</td>
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Summary

This thesis is the result of an extensive and detailed investigation into the development of a novel new dark adaptation device.

Chapter 1 introduces the basic ideas surrounding dark adaptation and how it is adversely affected by vitamin A deficiency and other diseases. The theory and experimental methods required for accurate dark adaptation determination is outlined.

Chapter 2 details the new Concept Prototype Adaptometer (CPA) outlining the fundamentals of its design and construction.

Chapter 3 presents the circuit design used to implement the design specifications outlined in Chapter 2.

Chapter 4 describes the calibration and initial commissioning of the CPA.

Chapter 5 provides details of clinical trials on 21 volunteer subjects using the CPA.

Chapter 6 contrasts and compares the results obtained on the CPA with published results, particularly age related effects.

Chapter 7 describes the improved design to the successor to the CPA called the Automatic Dark Adaptometer (ADA) which was based on the results and findings in Chapters 3, 4, 5 and 6.

Chapter 8 describes the initial commissioning results obtained using the ADA.

Chapter 9 presents results obtained on the ADA which includes a comparative study with the Goldmann Weekers Adaptometer. (GWA).

Chapter 10, the thesis concludes by outlining the progress and the conclusions reached.

All chapters are liberally cross referenced to allow the reader to refer to relevant ideas in other sections as the results observed in one section are often due to a combination of different considerations which may have been dealt with in another chapter.
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1. Introductory Background to Human Dark Adaptation, Adaptometry and Vitamin-A Deficiency

1.1 Adaptation Changes in the Human Retina

Human light adaptation can be defined as the ability of the eye and retina to alter sensitivity to visible light as the surrounding illumination is altered. The visual physiological response produced by a stimulus of fixed intensity, varies with the state of adaptation of the observer. Consider two individuals, one of whom is kept in a dark room for some time and the other in bright sunshine. For each, the perceived brightness of a moderately lit room will significantly differ. For the individual entering the moderately lit room from the dark room, the room appears considerably brighter than for the individual entering the room from bright sunlight; this individual finds the room quite dim. Following a period of time the perceived difference between the two observers disappears as their eyes become adjusted or adapted to the altered ambient light of their surroundings; the room will then appear equally bright to both.

When the eyes are exposed to a bright light, compared to the surrounding, they become accustomed to the brighter light, a process called light adaptation\(^{(1,2)}\).

In contrast as the surrounding light illumination decreases the eyes become accustomed to the lower light level, a process termed dark adaptation\(^{(2,3)}\). Between the two extremes there is an infinite number of adaptation or thresholds states\(^{(4)}\).
1.1.1 Dark Adaptation

Dark adaptation, first described by Aubert\(^5\) in 1865, is the process whereby there is an observed increase in sensitivity of the visual system to light as the ambient light level decreases. On entering a dimly light room from the sunny outdoors, it is difficult initially to see anything in the room; one is quite blind for a period of minutes; gradually visual function is restored with objects in the room becoming slowly visible. When the retina has reached maximum sensitivity it has fully dark adapted\(^2,6\), thus the visual system increases its sensitivity to light as the surrounding light level falls.

The dynamic luminance range of the human eye can safely adapt to extremes of bright and dark lighting conditions. The sensitivity range covers the mid-day summer sun directly overhead to the faintest light from the Andromeda galaxy (M62) at a distance 2 million light years\(^7,8,9\). Quantitatively, this corresponds to about 16000mL (50929 cd m\(^{-2}\)) for the brightest photopic luminance, to the dimmest scotopic luminance of about 1.0×10\(^{-5}\)mL (3.2×10\(^{-5}\)cd m\(^{-2}\)) after 10 hours dark adaptation\(^10\): a huge range of about 1×10\(^{10}\): 1. The SI unit of luminance is the candela per meter squared, cd m\(^{-2}\), whereas the non SI unit is the Lambert, L: the rationale for including non SI units will be discussed later.

1.1.2 Threshold, Sensitivity and the Dark Adaptation Curve

When the fully dark adapted eye is suddenly exposed to light, it is observed that on return to darkness, more light is required to produce a visual sensation. The eyes sensitivity to light has been temporarily decreased, thus more light is required to evoke a response from a subject under examination\(^11,12\). The threshold luminance may be defined as the degree of stimulation just required for perceptual response in the test area\(^12\). Large changes in the ambient light level are required for the light
adapted eye to perceive any change, in contrast the dark adapted eye is extremely sensitive to light perceiving very small variations in the luminance\(^{(8,9)}\). The threshold luminance refers to the smallest difference between two light levels that can be distinguished by a subject. The eyes sensitivity and threshold are inversely proportional;

\[
\text{Sensitivity} = \frac{1}{\text{Threshold Level}}
\]

As the sensitivity of the retina increases the light level or threshold decreases i.e. a lower light threshold luminance evokes a response. Alternatively as sensitivity decreases a higher light threshold is required to evoke a visual response in a subject and the threshold is raised.

Dark adaptation primarily depends upon four processes; changes in pupil size, changes in the neural network, photochemical changes of the visual pigments and changes in the and sodium channels present in the photoreceptors\(^{(4,6)}\).

Certain eye diseases, inherited abnormalities, metabolic disorders and nutritional deficiencies may be identified by changes in dark adaptation thresholds as determined by investigation of the dark adaptation curve. Dark adaptometers are instruments used to evaluate dark adaptation and are important in the diagnosis, prognosis and monitoring of the symptoms identified.

1.1.3 Nyctalopia and Vitamin A
Night blindness and abnormal dark adaptation have long been associated with the earliest and mildest sign of vitamin A deficiency in both adults and children\(^{(8,9)}\).

Absence of the primary chromophore molecule, 11-cis-retinol, a derivative of vitamin A, disrupts the rhodopsin (visual) cycle thereby significantly diminishing the
synthesis of rod photoreceptor pigments in the retina (13,14,15,16). Vitamin A can only be obtained from dietary intake and cannot be synthesised in the body, vitamin A is a micro-nutrient essential for human health and well being.

Both the Egyptians and Greeks in ancient times had knowledge of night blindness and that it could be reversed by eating animal liver. The word Nyctalopia or night blindness was first mentioned by Hippocrates, 406 – 327 BC, in his second book "Prognostics" (17). It was first suggested by David Livingstone (1857) that eye lesions observed in African children were caused by a nutritional disorder (17). Many other researchers have found that as vitamin A concentrations in the body become exhausted there is a noticeable rise in the final rod threshold and slowed rates of adaptation. The degree of deficiency is closely associated with a rise in rod threshold (18). Abnormal dark adaptation is considered a sensitive indicator of sub-clinical vitamin A deficiency, occurring before other ocular or clinical signs (19,20). Psychophysical dark adaptation has been used since the 1930s for the early detection of mild or sub-clinical vitamin A deficiency (21).

1.1.4 Vitamin A Deficiency
Vitamin A is ingested as performed vitamin A (retinol) which is found in food of animal origin, such as milk, eggs and liver. Other sources are carotenoid pigments found in plants that contain inactive provitamin A, which is converted when eaten to vitamin A in the body (20,22). After absorption in the body, 90% of the retinol is removed from the circulation and stored in the liver (23) in the form of retinol esters and palmitic acid (24). Hundreds of carotenoids exist, the most important are the

---

* carotenoids - a group of naturally occurring plants containing yellow/red pigments e.g. carrots
† provitamin - a substance that can be converted to a vitamin in the body
‡ palmitic acid - a fatty acid obtained from the diet and an important constituent of lipids
carotenes*, of which the β-carotene form has the greatest activity in the human body and is the most plentiful in human foods. Dark green leafy vegetables are a good source of both β-carotene and α-carotene, another important dietary carotene(13). Vitamin A is important for good health and is essential for many bodily functions including; growth, reproduction(20,23) maintenance of epithelial cells(25) and immune system(23,26,27,28).

1.1.5 Hypovitaminosis A and Xerophthalmia in Children
Hypovitaminosis† A is a disease of the developing world(29) and is one of the most serious nutritional disorders affecting mankind; children because of their increased vitamin needs are particularly affected, showing abnormal dark adaptation earlier than adults. The ocular manifestations of vitamin A deficiency are termed Xerophthalmia which literally means dry eye. Several images showing this condition are reproduced, in Appendix 1, with the kind permission of the WHO. World wide more than 127 million school and pre-school children are vitamin A deficient, of whom it is estimated that more than 18 million have clinical signs including night blindness and Bitot’s spots(30); Bitot spots are irregularly shaped keratin deposits that form on the conjunctiva. As a consequence of Vitamin A deficiency more than 500,000 children go blind each year(31). Children with even mild xerophthalmia, are at increased risk from diarrhoea and respiratory infections, such as pneumonia, the major causes of childhood mortality in developing countries(32,33,34). Children with recent measles are up 11 times more likely to develop corneal xerophthalmia than whose who had not; measles in particular has a devastating effect on children by rapidly depleting vitamin A levels at a time when the dietary intake and absorption are reduced leading to severe

* carotene - one of the carotenoids occurring in four forms β, α, γ and δ
† hypervitaminosis – vitamin deficiency
xerophthalmia\textsuperscript{(17,23,35)}. Opportunistic diseases and vitamin A deficiency impact on each other, creating a cycle that induces and perpetuates xerophthalmia and disease\textsuperscript{(36,37)}.

Corneal dryness, nyctalopia and mortality rates are rapidly improved with supplementation in individuals\textsuperscript{(38,39)}: a single oral dose of vitamin A containing 110mg retinol palmitate or 66mg retinol acetate\textsuperscript{(40)} is administered to the individual or populations at risk.

1.1.6 Retinal Dystrophies
Dark adaptation thresholds are affected by many eye diseases which are associated with metabolic changes in the retina specifically diseases of the photoreceptors, retinal pigment epithelium (RPE) and choroid and are identified by abnormal dark adaptation: the anatomy of the retina is illustrated later in Figure 1.3. Localised vitamin A deficiency within the eye can occur due to Drusen\textsuperscript{(41)} which interrupt RPE–photoreceptor recycling (see Section 1.3.1) of vitamin A depleting the photoreceptors of vitamin A for necessary for photo-transduction. Thresholds are also adversely affected by the loss of transparency in the cornea, lens and vitreous fluids associated with ageing.

Poor dark adaptation and night blindness are the most common and earliest symptom of a group of hereditary retinal dystrophy’s\textsuperscript{(42)}. Abnormal adaptation typically results from damage to photoreceptor cells as a consequence of enzymatic deficiencies that are frequently hereditary in nature\textsuperscript{(43,44)}. Such conditions include Retinitis Pigmentosa (see Section 1.3.1); Congenital Stationary night blindness is an inherited non-progressive ocular diseases that seriously affect dark adaptation\textsuperscript{(2)} and which tends not to develop beyond nyctalopia; Flecked retinal syndrome is a series of conditions
characterised by yellowish-white lipofuscin engorged fundus lesions of the RPE without vascular or optic nerve abnormalities\(^{(45,46,47,48,49)}\), the flecks or raised drusen result in a progressive degeneration of the photoreceptor cells that may result in cell death\(^{(50)}\).

Besides inadequate dietary ingestion, low vitamin A levels can be observed in patients suffering from mal-absorption of food secondary to chronic small intestinal diseases and following intestinal surgery\(^{(51)}\). Many patients are found to have low vitamin A blood serum levels causing abnormal dark adaptation. Poor dark adaptation as a result of vitamin A deficiency is common in patients with cystic fibrosis\(^{(52,53,54)}\), Crohn’s disease\(^{(55)}\), celiac disease, duodenal/jejunal diverticulosis\(^{(56)}\) and jejunal bypass surgery\(^{(57)}\). Poor adaptation is found in patients with diabetes mellitus\(^{(58,59,60)}\) and in chronic alcoholics\(^{(61,62,63,64,65)}\) with related liver diseases. Many physiological\(^{(66)}\) factors influence human dark adaptation including; anoxia\(^{(59,67,68)}\) (oxygen deprivation), carbon monoxide poisoning\(^{(69)}\), solar exposure to UV light\(^{(7,50,70,71)}\) and polycythemia\(^{(72)}\) (excess red blood cell count).

1.1.7 Night Blindness - a Screening Tool
Summer et al\(^{(73)}\) considered that night blindness is an important index of mild Xerophthalmia which could be used as a screening method to assess individual and populations at risk. Sommers was the first to examine night-blindness in school and pre-school children and correlate his finding with the epidemiology of hypovitaminosis A in subsistence populations. Villard & Bates\(^{(74)}\) reported reliable measurements of dark adaptation could be obtained on illiterate adults from a rural unsophisticated third world society, even though they had little understanding of the
test. A number of researchers have attempted to use dark adaptation as an index of xerophthalmia\textsuperscript{(19,75,76)} with some success.

Current instrumentation and methods used to measure dark adaptation/night-blindness are of limited use in developing countries. Classical dark adaptation instrumentation is cumbersome and expensive making it unsuitable for third world field conditions\textsuperscript{(79)}. Many instruments and techniques have been used to assess vitamin A status in school children using dark adaptation as a diagnostic tool however, results have been unreliable \textsuperscript{(77,78,79)}. A simple repeatable dark adaptation test is required to determine in hypovitaminosis A in children that is accurate, quantitative and reproducible in field and clinical conditions\textsuperscript{(20,80)}. The research reported in this thesis outlines the development and construction of such a dark adaptometer, capable of screening at risk populations for the early signs of deficiency by using night blindness and poor adaptation as the basis of a simple test, indicative of vitamin A malnutrition.

1.1.8 Psychophysical Measurement of Human Dark Adaptation
Subjective measurement by its nature requires the co-operation, patience and motivation from the subject under investigation\textsuperscript{(81)}. The subjective determination of human dark adaptation has provided important information on the structure and functioning of the retina and continues to be a useful investigative tool despite the use of more objective modern instrumentation\textsuperscript{(82,83)}.

Subjective measurement of dark adaptation typically involves the presentation of a stimulus which may comprise an ascending or descending threshold\textsuperscript{(55)}, with the subject indicating (verbally), when the stimulus appears or alternatively disappears\textsuperscript{(1,11)}, the ascending threshold method provides a more accurate
measurement. The time taken for the stimulus to become visible to the observer\textsuperscript{(84,85)} is recorded. When carrying out dark adaptation testing the stimulus is always presented against a completely dark background field with the subject in complete darkness or blackout. At the start of the test the threshold luminance is initially high and decreases as one dark adapts. Repeated measurement of light threshold as a function of time for normal individuals yields the dark adaptation curve. The dark adaptation curve is obtained by plotting a graph of each measured light threshold against the time\textsuperscript{(1,86)}. Each datum represents the time it takes the subject to perceive the light stimulus.

The typical range from highest threshold luminance to absolute rod threshold covers about 5 log units of luminance\textsuperscript{(87)} which on a linear scale is too large to show detail, consequently light thresholds are plotted on a logarithmic scale on the vertical axis with time plotted as a linear scale on the horizontal axis. Another advantage of using a logarithmic scale is the even distribution of errors, see Figure 1.1.

\subsection*{1.2. Dark Adaptation Curves}

A typical dark adaptation curve is presented in Figure 1.1. The first part of the curve is the photopic phase or alpha phase which identifies cone adaptation. The last part of the curve is the scotopic phase or beta phase and identifies rod adaptation\textsuperscript{(11)}. The interval between the two phases is referred to as the cone-rod transition phase or commonly as the cone-rod break or mesopic phase.

It can be seen in Figure 1.1 that as the luminance is reduced, there is an increase in light sensitivity which is initially very rapid before levelling off after 5 to 10 minutes (see Section 1.4.1) at the final or absolute cone threshold\textsuperscript{(7)}. At this point the foveal
cone cells are fully dark adapted, they have reached their maximum sensitivity\(^{(88)}\), in contrast the rod cells are saturated and inactive\(^{(1)}\) (see Section 1.3.6).

![Diagram of dark adaptation curve]

*Figure 1.1. Normal dark adaptation curve obtained on the author using the Goldmann Weekers Adaptometer with time is the independent variable. The red points are discrete recorded thresholds, whereas the best fit line, coloured purple, identifies the dark adaptation curve. The dark adaptation curve is a subjective plot of the data points by a skilled clinician, in this case by Dr. Peter Davison. The pre-adaptation light duration was 2 minutes at 1500mL. Over 80 data points are shown. Luminance is shown in both \(\mu\)L and \(cdm^2\).*

From Figure 1.1 it can be seen that with time (the luminance of the stimulus is reduced), a second slower fall in the threshold luminance is observed as the peripheral rod cells become activated, as rhodopsin is regenerated. Rod adaptation is slower than the cone adaptation\(^{(89)}\) because of the regeneration half life of the visual pigments. However, unlike cone cells, light of very low intensity is capable of stimulating the rod cells, when given sufficient time to accumulate rhodopsin\(^{(2)}\) (see Section 1.3.6). After approximately 30-40 minutes in total darkness final or absolute rod threshold is achieved. Dark adaptation is now complete and no further increase in sensitivity of the rods photoreceptors is possible. The time required to reach maximum sensitivity or
absolute rod threshold is dependent on the amount of pigment bleached by the previous light exposure\(^{(90)}\) and neural adaptation.

Both cone and rod dark adaptation curves consist of an initial rapid non linear increase in sensitivity followed by a second longer section, of near linear slope and a third section where the curve asymptotically reaches the final cone and rod threshold respectively\(^{(89)}\). The first section of the cone phase curve may be explained by the rapid increase in pupillary diameter\(^{(6,91)}\). The near linear middle sections are determined by the regeneration of bleached visual pigments in the outer segment discs of the cone and rods\(^{(92)}\).

The difference in the decay curve of both cone and rod mediated vision may be explained by different regeneration half lives of the rod \(t_{5/4} = 5\) minutes and cone \(t_{5/4} = 90\) seconds cells thus cone pigments are regenerated at a faster rate than rhodopsin (see Section 1.3.7)\(^{(2,93)}\). Cone mediated vision is responsible for colour vision whereas rod vision is colourless.

1.2.1 Concept Prototype and Automatic Dark Adaptometers
Most dark adaptometers are based on the Hecht-Schlaer Adaptometer developed in the 1930's\(^{(90)}\), for example the benchmark adaptometer in use today is the Goldmann-Weekers Adaptometer\(^{(94)}\) (GWA) manufactured by Haag-Streit AG\(^{(95)}\) is one such instrument, however, there are significant disadvantages and limitations inherent in currently used instrumentation including;

1. the use of old and outdated technology;
2. most adaptometers are elaborate, large, heavy, non-portable and expensive;
3. test procedures require the full attention of highly trained operators in a clinical environment;
4. mains electrical supply required, thus making them immobile and unsuitable for field investigations;

5. the operator must carry out the test in total darkness with the subject under test;

6. test data acquisition is manually obtained by the operator;

7. data is recorded as a series of pin-pricks on a rotating drum;

8. data analysis is complex requiring additional operator time after the test has terminated;

9. frequently, only one area of the retina may be tested at any one time;

10. there is a test learning curve leading to the possibility of cheating;

11. excessive examination test times are the norm - typically 45 minutes;

12. unsuitability of test procedures for use with school or pre-school children;

This list is the summary of the author's deliberations and conclusions based on the totality of both the literature review and clinical experience of dark adaptation testing. For the reason listed above conventional dark adaptometers are unsuitable as a mass screening tool, consequently, in developing countries dark adaptation is not routinely used as a clinical technique because of the practical problems it presents\textsuperscript{(73,76,77,78,79)}, see Section 1.2.2 for a review of older instrumentation. It should be noted that direct blood analysis is the most precise method used in the determination of vitamin A status, however, it presents significant problems in developing countries\textsuperscript{(96)}. Conjunctival impression cytology has also been used with limited success\textsuperscript{(97)}.

The author, Dr. Peter Davison and Dr. Thomas Grennan formed the opinion that there was a requirement for a suitable dark adaptation apparatus which would overcome the associated problems with current instrumentation described above. This thesis outlines the design, construction and evaluation a novel dark adaptometer whose
purpose was to overcome the difficulties with existing instrumentation in order to provide apparatus that could be used in the identification of night blindness and vitamin A deficiency in developing countries. The author and Dr. Peter Davison established a list of operating features demanded of this instrument which included the following prerequisites;

1. the test shall be simple to use and operate thereby avoiding the use of a skilled operator;
2. the instrument shall employ a plurality of test stimuli (four in this embodiment) to test different areas of the retina;
3. a single test stimulus shall be chosen randomly from the four test stimuli thereby minimising cheating;
4. the test be interactive like a game; when a stimulus is perceived by a subject they shall interact with the apparatus by depressing the chosen stimulus;
5. the operator shall possess the ability to monitor the test in real time by downloading data to a numerical logger or lab-top/notebook;
6. at the end of the test the subjects' particulars may be stored digitally;
7. the instrument shall allow data to be printed and compared with normal population performance;
8. consumption of power must be low allowing for the use of a rechargeable battery, making the unit portable;
9. the instrument must be versatile and portable with light/durable enclosure;
10. to provide long life operation and stable light output the test stimuli shall comprise light emitting matrix display arrays;
11. audio reinforcement shall be provided to the subject to monitor their performance - correct or incorrect subject choice;
12. the test shall be ease for children to use;
13. the instrument shall require minimal operator training;
14. the test data must show good reproducibility and precision when compared to conventional instrumentation;
15. the instrument shall use low cost solid state devices;

These new specifications were intended to allow for greater use of dark adaptometry in adults and children both in technological societies and subsistence economies.

These prerequisite design features were implemented with the construction of (i) a fully working laboratory instrument called the Concept Prototype Adaptometer (CPA) and (ii) a subsequent microprocessor based prototype called the Automatic Dark Adaptometer (ADA). This dissertation describes the specification, design, construction and evaluation of these two instruments.

Patent applications were made to protect the work detailed in this thesis. Following rigorous investigations by various patents agencies globally, most notably in the USA, sufficient novelty was established that allowed the proposed instrument to be patented internationally. A full description of the automatic dark adaptometer is provided in this thesis and patents filed and granted in Ireland; Europe with designations in Great Britain, France and Germany; United States; Australia, New Zealand, Canada and Japan.

The US Patent is presented in full in Appendix 2 with a list of publications.
1.2.2 Dark Adaptometers: Past and Current Instrumentation

Quantitative measurement of human dark adaptation was first attempted by Piper\(^{(99)}\) in 1903. The Gullstrand Photometer in 1905 and the Nagel photometer\(^{(6)}\) in 1907 were two early instruments designed as dedicated instruments. In 1934 the Birch-Hirschfeld photometer described by Jeans & Zentmire\(^{(100)}\) examined dark adaptation in primary school children, subsequently Jeans et al\(^{(101)}\) modified this instrument, developing the biophotometer; in the 1930's such instruments became known as dark adaptometers.

Later researchers found these early instruments gave unsatisfactory and unreliable test data due to instrumentation deficiencies. They lacked fixation stimuli and an insufficient luminance range in order to obtain the full dark adaptation curve, in addition these instruments used a single target stimulus, thereby facilitating a learning curve by the subject\(^{(102)}\).

The first reliable instrument allowing for an accurate investigation of the various aspects of adaptation was the Hecht-Shlaer\(^{(90)}\) adaptometer developed in 1938. Variation of the light stimulus was obtained by inserting several neutral density filters in front of a tungsten light source. The test field subtended 3° and was presented 7° nasally to the fixation light (see Section 1.4.5). The fixation intensity was adjustable and was maintained so as to be just visible by the subject throughout the test. Dark adaptation data obtained from this device under controlled conditions were accurate, reliable and reproducible. Many subsequent instruments, are essentially modifications and improvements on this device\(^{(103,104,105,106)}\). Many dark adaptometer have been developed\(^{(107,108)}\) the most notable include; a device constructed by Wald\(^{(109)}\) in 1941 which was used to survey vitamin A deficiency in Newfoundland, with limited success.
A novel landmark, low cost instrument was developed by Henson and Allen\(^{110}\) in 1977 consisting of a single stimulus consisting of a green (565nm) solid state light emitting diodes (LED) as opposed to tungsten filaments used in earlier devices. The stimulus intensity control setting was via a manual position switch that corresponded to 12 discrete luminance light levels that were approximately half (or a quarter) the previous presentation luminance. The fixation distance was 33cm. Electronic circuitry controlled the LED light output to a quoted accuracy of 0.1%, which could be maintained over ten years of continuous use. A potential deficiency with this instrument was that the test was self administered/controlled leading to possible significant bias in the test results; in addition it lacked a chin rest, thus the distance between the stimulus and the subject appears not to have been fixed; consequently there is an uncertainty in the exact stimulus size and eccentricity to the fovea. Nevertheless, Henson and North\(^{58}\) reported excellent results using this instrument which were consistent with published results (see Section 5.4).

### 1.2.3 Goldmann Weekers Adaptometer

The Goldmann Weekers adaptometer (GWA) developed by Haag-Streit in the 1960’s\(^{95}\) and based on the Hecht-Schlaer\(^{90}\) specifications, is particularly important here as it was used to compare subject results obtained on the Concept Prototype and Automatic Dark Adaptometers. This adaptometer is an expensive, highly sophisticated and versatile instrument; that has attained the status of the benchmark instrument, by which other instruments past and present are compared and evaluated\(^{45,76,111,112,113,114}\).
Figure 1.2 Haag-Streit Goldmann-Weekers Dark Adaptometer.

The instrument shown in Figure 1.2 comprises an integrating sphere required for light adaptation, and a chin rest that fixes the viewing distance. With the subject's head resting on the chin rest a single circular 11° target stimulus is located centrally and directly in front of the subject's eyes. A red fixation light is traditionally presented at 11° → 15° to the fovea (6). Newer models of Goldmann-Weekers Adaptometer unit are available with a movable fixation light thus enabling examination of the full retina.

The recording of the threshold luminance values is made by the operator activating a lever on a recording arm connected to an indicating “pricker” that perforates a logarithmic paper chart that is mounted on a recording drum, rotating once per hour. Time is plotted on the abscissa in minutes while the luminance is plotted on the ordinate. Changes in stimulus luminance of both the target and fixation luminance are manually achieved. Up to 100 thresholds measurements are made until the threshold
stabilises, typically after 30 - 40 minutes; the test is then terminated. The paper chart is removed and the best fit curve subjectively drawn by the operator through the series of perforations thus yielding the adaptation curve.

A skilled and experienced operator must carry out the test in the dark along with the subject under examination throughout the test. A full description of the testing methodology is described by Russell\(^{(55)}\) et al.

1.2.4 Modified Field Analysers and Perimeters
Field Analysers may be used to obtain dark adaptation measurements\(^{(115)}\). For example, a modified Friedmann field analyser described by Bedwell\(^{(116)}\) has been used extensively to measure dark adaptation\(^{(53)}\). Neugebauer and Vernon\(^{(54)}\) developed a dark adaptometer based on the Lister perimeter. This instrument was successfully used by Rayner and Tyrrell\(^{(53)}\) to investigate nyctalopia in cystic fibrosis patients.

The disadvantage of using field screeners and perimeters is that the instrumentation is not specifically designed for dark adaptation measurements; consequently they are of limited use compared to dedicated instrumentation such as the Goldmann-Weekers device.

1.2.5 Dark Adaptometry and Prior Art Novelty Search
A novelty search was carried out at the Swedish Patents Office to establish the prior art specification and novelty in the area of dark adaptation testing and instrumentation\(^{(117)}\). Further examination was carried out by individual patent offices, the most rigorous being in the United States. A number of prior art specifications were identified, revealing a number of instruments and devices designed or capable of
measuring human dark adaptation, the details are included in the US patent application; these adaptometers are discussed in Appendix 3.

Prior to outlining the prerequisites design specifications required for the construction of an accurate quantitative and reliable dark adaptometer reviewed in section 1.4, it is necessary to briefly outline the anatomy, histology, physiology and biochemistry of the human visual system as they relate to adaptometry.

1.3 Anatomy, Histology and Physiology the Eye and Visual System

The human eye functions in essence as an optical instrument, refracting light at the cornea and focusing light rays with the assistance of the lens onto the fovea where a clear image of an object will be formed. A horizontal section through the human eye (Figure 1.3) shows the main anatomical features of the eye, comprising the tough, opaque white sclera membrane, and the transparent cornea which allows light enter the eyeball. Anterior to the crystalline lens is the pupil whose aperture is formed by the coloured iris, it is the variation in iris size that controls the amount of light entering the eye. Behind the lens is the posterior chamber which is filled with a clear jelly like fluid the vitreous humour which is separated from the retina by a
tough inner limiting membrane. The retina receives nourishment from the underlying choroids, a vascular membrane that is richly supplied with blood capillaries\textsuperscript{(121)} which is situated between the sclera and retina. The retina is the light sensing element of the eye, consisting of photo-sensitive neurons termed photoreceptors; it varies in thickness from approximately 0.1 mm to 0.5 mm, being thinnest around the fovea and thickest around the optic disc\textsuperscript{(122)}. The greatest visual acuity of the eye is in a small depression called the fovea centralis. The area surrounding the fovea and separating it from the peripheral retina is termed the macular lutea. Nerve impulses from the retina are transmitted to the brain via the optic nerve fibre.

There are two types principal photoreceptors in the retina, the rod and cone cells, which contain special light sensitive pigments termed visual pigments or photosensitive pigments\textsuperscript{(4)}. Colour vision and high visual acuity are provided by the cone cells during ordinary daylight (photopic vision). As a consequence of rod neural circuitry, the rod system exhibit poor visual acuity, however, enhances vision when the illumination is poor for example at night (scotopic vision). Rod cells are not colour sensitive.
Figure 1.4. Structure of the retina, showing the photoreceptors to the rear of the eye with the overlaying network of neurons. Note the passage of light as it passes through the neural layers to be absorbed by the photoreceptors. The axons of the photoreceptor cells synapse with many bipolar cells which in turn synapse with cells in the ganglion layer. The axons of the ganglion cells combine to form the optic nerve fibre. The image on the right is a light micrograph of a vertical section through the human retina. There are no large blood vessels present in the macular; while blood capillaries are absent in the fovea in order to enhance visual acuity. Modified from John Moran Eye Centre, University of Utah Web Site
When an image is focused onto the retina, visual pigments in the photoreceptors are altered or broken down, which generates a transduced electrical nerve impulses that are processed by interconnecting neurones in the retina. By the time the visual signal reaches the ganglion cells, considerable coding of information has occurred. To understand how this complex system works and how it applies to dark adaptation, requires an understanding of sensory nerve cells and their connectivity within the retina.

1.3.1 Photoreceptor Rod and Cone Nerve Sensory Cells

The photoreceptor neurones are specialised cells for transmitting electrical nerve impulses. A resting neurone is electrically polarised as a result of the concentrations of sodium (Na\(^+\)), calcium (Ca\(^{++}\)), Potassium (K\(^+\)) and Chlorine (Cl\(^-\)) ions across the cell membrane\(^{(123)}\). When a nerve impulse is triggered in a neurone, a depolarisation (Figure 1.5) wave spreads through the nerve as a consequence of Na\(^+\) ions flowing into the nerve cell; before further impulses can be transmitted the nerve must be repolarised. This change in voltage (depolarisation) across the membrane is known as the action potential\(^{(124,125)}\).

![Figure 1.5. Action potential generated by a typical nerve cell as an electrical nerve impulse is triggered by synapsing neurones. In its resting state, the neuron is negatively charged; when stimulated, Na\(^+\) ions sweep into the cell, reversing its polarity.](image)

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Projecting from one side of a neuron, is a short fine branching expansion, called dendrites, that carry nerve impulses into the cell. On the opposite side of the cell an axon emerges that terminates by dividing into several branches called teledendrons, which carries nerve impulses away from the cell body.

In the cone and rod cells, the teledendrons form synapses with bipolar cells in the outer plexifrom layer (Figure 1.4), while the dendrite consists of two distinct parts, the inner and outer segments, the latter part being sensitive to light when combined with photosensitive pigments, see Figure 1.6(126). Photoreceptor rods and cones are easy to distinguish with their names derived from the shape of the outer segment of both cells, namely rod and cone shaped outer segments(118). The outer rod segments are approximately 60 μm long and 2 μm thick while the outer cone segments are shorter than the rods at about 51 μm in length and ≈ 6μm wide(4,120,122).

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* dendrites - carries nerve impulses into the cell
* axon - a single long nerve fibre extending from the cell body
* teledendrons - carries nerve impulses away from the cell

Figure 1.6. Cone and rod sensory cells found in the human retina, showing the outer and inner segments. Modified from University of Pennsylvania Health System.
The outer segment of the rod cell comprises a series of discs each surrounded by a membrane within which the photosensitive pigments are present. At the base of the outer rod segment, rod discs are continuously being generated at the ciliary connection before migrating forward and being pinched off to form stacks of free floating discs\(^{120}\). The rod discs slowly move up the outer segment towards the retinal pigment epithelium (RPE) (see Section 1.3.2). Old spent discs are removed from the tip of the rod into the RPE, which ingests and destroys old discs during daylight. From generation to destruction of the disks takes 9 - 13 days in humans\(^{4}\).

Outer segment discs are separate independent sacs which number between 800 - 1100 discs in a single rod cell\(^{88}\) providing a large surface area containing visual pigment where light is absorbed. The outer segment of each human rod cell contains approximately \(4 \times 10^7\) visual pigment molecules\(^{123}\). In contrast outer segment cones disc membranes do not form independent disc structures and they are absorbed by the RPE at night\(^2\). Where there is an inability of the RPE to phagocytosis\(^*\) the shed rod disks, receptor debris accumulates leading to destruction of the retina, as observed in certain forms of retinitis pigmentosa which is characterised by impaired night vision\(^{127}\).

1.3.2 Neural Networks - Connectivity in the Human Retina

The human retina is composed of layers of neurones and synapses arranged in a complex neural network with a complex nomenclature. The layers closest to the choroid are termed the outer layers while those layers closest to the vitreous humour are termed inner layers. In-addition layers consisting of cell bodies, i.e. neurones, are termed inner or outer nuclear layers while those consisting of synapses between

\* phagocytosis - engulfment and digestion of bacteria or foreign body
neurones are termed inner or outer plexiform layers\textsuperscript{(120)} (see Figure 1.4). The complex interconnectivity of the neurons in the retina, forms a sophisticated neural network comprising the following cell types;

**Retinal Pigment Epithelium (RPE)**

The outer most layer of the neural retina, the retinal pigment epithelium is a single layer of cells important for the storage, renewal and transport of materials vital for retinal metabolism and vision\textsuperscript{(128)}. The outer surface of the RPE is attached to Bruch’s membrane while the inner surface has extensions that envelop the outer segment rod cells but not cone cells\textsuperscript{(129,130)}.

**Bipolar Cells**

The bipolar cells are situated in the inner nuclear layer and link the photoreceptor cells with the ganglion cells. The dendrites of the bipolar cells synapse with individual or several photoreceptors in the outer plexiform layer. One bipolar cell may be connected to up to 45 rod photoreceptors\textsuperscript{(4)}. The teledendrons of the bipolar cell may synapses with one or more ganglion cells in the inner plexiform layer.

**Horizontal and Amacrine Cells**

Horizontal cells are located in the outer plexiform layer, possessing dendritic and teledendroic extensions that synapse with groups of photoreceptors while amacrine cells are found in the inner plexiform layer and synapse with ganglion cells\textsuperscript{(123)}. The horizontal and amacrine cells are important in that they connect non-adjacent cells, laterally interconnecting non adjacent areas of the retina\textsuperscript{(120,129)}.

**Interplexiform Cells**

Interplexiform cells are located in the inner nuclear layer (see Figure 1.4), whose dendrites synapse with ganglion and bipolar cells while the teledendrons synapse with
photoreceptors in the outer plexiform layer. The direction of the electrical signal in these cells is from the ganglion cells to the bipolar and photoreceptor cells, thus these cells transmit information against the general flow in the retina (i.e. from the outer layer to the inner layers). These cells are involved in switching between photopic and scotopic vision and are thus important in the dark adaptation process\(^{(120)}\).

**Müller cells**

At the base of the inner segment of the photoreceptors are the glial cells, principally the Müller cells. These cells pass through the thickness of the retina and from the inner limiting membrane to the outer limiting membrane. These cells help support and stabilise the photoreceptors and assist in the retina's metabolism and significantly outnumber neurons.

**Ganglion Cells.**

The ganglion cells synapse with bipolar and interplexiform cells. The axons of the ganglion cells make up the nerve fibre layer that eventually forms the optic nerve. Activity in a photoreceptor cell is transmitted to the bipolar cell then on to the ganglion cells. The interactions of the cells comprising the neural network of the retina and central nervous system play an important role in dark adaptation\(^{(2)}\).

**1.3.3 Cone - Rod Histology and Distribution**

The human retina contains approximately 120 million rod cells and approximately 6 million cone cells distributed about the retina\(^{4,120,122}\) In order to understand dark adaptation and its determination, the functionality of the retina and the associated density variation of both photoreceptors must be considered.

The histology of the fovea and macular areas are considerably different from the peripheral retina. As can be seen from Figure 1.7 below, the distribution and density
of photoreceptor cone and rod cells are significantly different\(^{(131)}\). The fovea contains principally cone cells that reach a peak density of \(160,000 \text{ mm}^{-2}\).

The foveal cone cells are thinner than peripheral cones with the thinnest \(\approx 0.0015 \text{ mm}\) in diameter, numbering hundreds, located at the fovea centralis\(^{(120,132)}\), it is the minute distance between adjacent cones that provides high colour visual acuity\(^{(4)}\). The number of cone cells drops rapidly towards the periphery of the retina.

![Figure 1.7](https://via.placeholder.com/150)

**Figure 1.7.** Cone and rod densities across the horizontal meridian of the human retina showing the number of rod and cone cells per mm\(^2\). Note there is a complete absence of rod cells inside the fovea, where the concentration of cone cells is greatest. In the peripheral retina the numbers of rods gradually rises reaching a maximum at about 15° while the numbers of cone cells rapidly decreases outside the fovea. Modified from Osterberg.

The fovea is a rod free area and measures about 0.3 mm in diameter corresponding to an angle of approximately 1° which contains 17500 cone cells. The first rod cells appear at approximately 0.15 mm (0.5°) from the fovea and attains a maximum density of 150,000 mm\(^{-2}\) at approximately 5 mm (15° temporal and 20° nasal) before slowly decreasing towards the periphery.
1.3.4 Synaptology of Rod and Cone Cells.
There are about 1 million nerve fibres in the optic nerve that arise from the ganglion cells that synapse with the 120 million rod and 6 million cone photoreceptor cells, thus there is a considerable convergence or "downsizing" between receptors and optic nerve axons, resulting in considerable encoding of visual information in the retina as a consequence of the connectivity or hard wiring of the rod, cone, bipolar and ganglion cells within the plexiform layers\(^{(133)}\). Many aspects of visual function may be explained by the difference in photoreceptor cone and rod density in different regions of the retina which explains specialised functions particularly in relation to dark adaptation\(^{(133)}\).

As a consequence of the connectivity of bipolars and ganglions, a given receptor may activate many bipolar and ganglion cells so the effect of a light stimulus spreads horizontally as in moves vertically through the retina. Horizontal connectivity and signal spread are further enhanced by the horizontal and amacrine cells, which integrate signal transmission across the whole retina\(^{(4)}\).

1.3.5 Cone - Rod Synaptology and Dark Adaptation
Dark adaptation is strongly influenced by the synaptology of photoreceptor cells in the retina. Foveal cone receptors synapse directly with individual midget cone bipolar cells, which in turn synapse with single midget ganglion cells (see Figure 1.8). Central cone receptors transmit signals along individual pathways to their own private ganglion cells and hence to select sites in the brain. The cone system is consequently well suited for tasks requiring good spatial resolution (diffraction limited) such as visual acuity and contrast sensitivity at high spectral frequency. As mentioned the cones at the centre of the fovea are especially thin with axons that are very narrow,
resulting in fast conduction speed and response time\(^{(121)}\). Consequently the cone system has excellent spatial resolution and good temporal resolution. A single cone cell requires 5-10 photons of light to be absorbed in order to generate an action potential in a ganglion cell. In low illumination the probability of a single cone cell absorbing 5-10 photons is low; the probability of absorption increases as the illumination increases\(^{(2,130)}\).

In contrast, individual rod photoreceptors are more sensitive to light compared to cone receptors, as the rod outer segments are packed discs containing higher concentrations of the photoreceptor pigment, rhodopsin\(^{(2)}\) compared to the lower concentrations of the cone photopigments. The surface area of the rod cells are also greater than cone cells, hence they are more likely to absorb incident photons\(^{(130)}\). However, the primary reason the rod system is substantially more sensitive to light compared to the cone system is a consequence of its convergence.

In the peripheral retina up to 45 rods cells\(^{(130)}\) may be connected to a single bipolar cell and may receive signals from any one individual rod receptor, thus the rod system displays a high degree of convergence, in addition several rod bipolar cells synapse with a single ganglion cell, thus hundreds of photoreceptor rods may be connected to a single ganglion\(^{(134)}\). The high degree of convergence leads to spatial summation, as many rod receptors eventually synapse with a single ganglion cell.
The area of the retina that converges to a single ganglion is termed the receptive field. Light falling on one or more rod photoreceptors in a receptive field converge on one single ganglion cell and thus represent the summed or cumulative messages of a given location on the retina. Ganglion receptive fields synapsing with cone cells located in the fovea are small while peripheral receptive fields, consisting principally of rod cells, are large. Because of the high convergence, the rod system has poor spatial and temporal resolution compared to the cone system. In Figure 1.9, stimulation of one or more rod cells by either a large or small stimulus will activate a single ganglion cell, thus clearly demonstrating the poor spatial resolution of the peripheral retina (2) (see Section 1.4.7).

The larger ganglion cells that are connected to rod photoreceptors make up the magnocellular system. Individual ganglion cells must receive 5-10 nerve impulses from the photoreceptors via the bipolar cells cell in order for an action potential to be generated (2,130). As the receptive field is large, the probability of this occurring is high, even when the light level is low, thus the rod system is observed to be very sensitive to light (133).

1.3.6 Rhodopsin and Spectral Sensitivity of The Retina

There are four photoreceptor pigments in the outer layer of the human retina (excluding melanin); the three cones pigments, cyanolabe, chlorolabe, erythrolabe and the single rod pigment, rhodopsin (4). These four pigments are sensitive to EM
radiation with wavelength between 390 nm - 780 nm$^{(135)}$ corresponding to red and blue light with photon energies of between 1.6 eV to 3.2 eV ($2.5\times10^{-19}$ $5\times10^{-19}$ J.$s^{(136)}$). Cone pigments have maximum light absorption at 430 nm, 535 nm and 565 nm respectively$^{(4)}$ (see luminosity curve Figure 1.12). The rod pigment has maximum absorption at 510 nm. The reflected violet and red light gives rhodopsin its characteristic purple colour. Rhodopsin$^{(137)}$ is the name given to the light sensitive pigment visual purple first found by Boll$^{(138)}$ (1876) in the retinas of vertebrate animals (frogs); he noted the rich purple coloured pigment in the dark which rapidly faded as the light level increased, only to slowly reappear when the retina was in darkness once more$^{(136)}$.

The visual pigments found in vertebrates and human photoreceptors are formed when high molecular weight proteins, opsins, combine with light sensitive molecules known as chromophores$^{(139)}$. The chromophore is the actual light sensitive part of the photoreceptor pigment. The opsin is manufactured in the body while the rod chromophore (rhod-opsin) is obtained from the dietary intake of carotenoids$^{(133)}$. The rod chromophore found in vertebrates and man is 11-cis-retinal, an aldehyde, formed from the oxidation of vitamin A in the body$^{(139)}$. Vitamin A (retinol), first identified by E.V.McCollum (1913), is a fat soluble unsaturated alcohol ($C_{20}H_{30}O$) with five conjugated all-trans double bonds$^{(40)}$ (see Figure 1.10).
1 The structure of the all-trans vitamin A alcohol molecule (retinol) obtained directly or indirectly from the diet. All the methyl chain groups are located on the same side of the molecule. The CH$_2$OH at the end of the chain is the alcohol group.

2 Oxidation of all-trans vitamin A in the body yields an aldehyde of retinol called **ALL-TRANS-RETINAL**.

3 Rotation of carbon atom number 11 by the enzyme, isomerase, yields the chromophore, 11 cis - retinal, the light sensitive part of the photopigment. When combined with the rod opsin molecule the visual pigment rhodopsin is formed.

4 The action of light forms an unstable intermediary, meta-rhodopsin II that slowly dissociates to all-trans retinal and opsin.

5 Meta-rhodopsin-II rapidly decomposes into all-trans retinal and opsin.

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*Figure 1.10. Vitamin A is absorbed into the body and oxidised by the rods cells to all-trans retinal. It is converted to 11-cis retinal, before combining with opsin to form rhodopsin. Light causes rapid isomerisation to the trans isomer, forming an unstable intermediate meta-rhodopsin II, which slowly dissociates back into all-trans retinal within the outer disc segments; this destruction and renewal establishes the rhodopsin cycle responsible of dark adaptation. Original Illustration.*
1.3.7 Interaction of Light and Rhodopsin.

The primary photochemical event when light is absorbed by rhodopsin, is the isomerisation of 11-cis-retinal to all-trans retinal. The absorption of a single photon will split a single molecule of rhodopsin in picoseconds. The photochemical destruction (bleaching) of rhodopsin is rapid and efficient, whereas its regeneration in the dark is slow. The continued destruction and regeneration of rhodopsin forms the rhodopsin cycle where all-trans retinal is reformed into 11-cis-retinal and recycled in the photoreceptor outer segments.

The breakdown of rhodopsin generates the electrophysiological response in the rod photoreceptor cells that leads to vision. When the illumination is maintained at a high level, little regeneration of rhodopsin is possible thus the resulting photochemical response is weak, generating a weak visual response from the rod cells, thus the rod cells are insensitive to light. When the illumination is low, regeneration of rhodopsin occurs slowly with its concentration increasing with time. With increasing concentration the probability of quantal absorption increases, thereby increasing sensitivity and reducing the measured light threshold. The higher the rhodopsin concentration the greater is the photochemical effect produced when it decomposes. The greater the magnitude of the photochemical effect the greater is the visual response produced in the visual system and visa versa.

Reaction kinetics shows that 50% of bleached rhodopsin will revert to the un-bleached state within a five minute period, giving a the half life of 5 minutes given the retina is in black out conditions (see Figure 1.11).
Figure 1.11. Kinetics of rhodopsin regeneration in a normal eye at \( \lambda = 540 \) nm. There is almost a linear recovery following 100% bleach initially. Half the pigment is reformed in five minutes. The half life of cone pigments is about 90 seconds, thus cone pigments regenerate at a faster rate. Original Illustration.

Within approximately 10 minutes virtually all bleached rhodopsin should be reformed consequently, for a recovery time of five minutes the expected sensitivity should double in this period\(^{(141)}\). The sensitivity of the rod system is observed to increased to a maximum level within about 40 minutes when the eye is in complete darkness\(^{(130)}\) (depending on numerous factors see Section 1.4).

1.3.8 Luminous Efficiency
The scotopic luminosity curve (see Figure 1.12) shows that the maximum efficiency and peak sensitivity occurs at 510 nm (rod mediated vision), the effect of which is to produce a strong subjective visual response in the blue-green part of the spectrum. In contrast, the aggregate photopic luminosity curve identifies the peak sensitivity of cone mediated vision occurring at 555 nm, producing a strong subjective response in the yellow green spectrum\(^{(142)}\). This shift in spectral absorption, is called the Purkinje shift (1819)\(^{(143)}\) and has important consequences for dark adaptation.
Consequently, in the light adapted eye (cone mediated vision) stimuli of different colour but equal luminance are not equally perceived, thus the eyes are more sensitive to red light and less sensitive to blue (photopic vision). In contrast, scotopic vision in the dark adapted eye (rod mediated vision) gives coloured objects a colourless grey of varying brightness. However, from the luminosity curves, a blue object appears a brighter shade of grey than an equally illuminated red (or green) object when viewed under the same conditions. (see Section 1.4.6).

1.4 Adaptometers- Design Considerations & Parameters
The shape of the dark adaptation curve shown in Figure 1.1, is strongly influenced by the mode of its determination, thus knowledge of the anatomy and physiology of the retina; specifically the photoreceptor type, location, density, distribution and spectral sensitivity, are vital in order to develop a functional adaptometer. As previously stated, the prerequisite experimental methodology and specifications required for an accurate, quantitative and reproducible result were developed by Hecht-Schlaer and
Jean et al\textsuperscript{(90,101)}, identifying six specifications/conditions that must be considered in any attempt to develop a functional dark adaptometer. These include;

1. The intensity and duration of the pre-adaptation light or bleach
2. The intensity of the target light stimulus
3. The area and location of the test stimuli
4. The colour of the presented target stimulus
5. The use of a fixation source and its colour
6. Presentation time of the stimulus light

Consideration of these principles are prerequisite for quantitative dark adaptation testing and design\textsuperscript{(6,90,144)}.

1.4.1 Intensity and Duration of the Pre-adaptation Light
The dark adaptation performance of any two individuals would differ significantly if one were to begin a dark adaptation test after waiting in a dimly light room for some time and the second waited outside in bright sunshine. In order to quantitatively measure dark adaptation it is important to control the pre-test conditions such that the initial light threshold for all subjects is standardised/normalised; this is achieved by exposing the retina to a diffuse bright white light of known intensity for a fixed period of time\textsuperscript{(103,104,105,106)}. This process insures all subjects are light adapted to the same extent in advance of the formal test, a process termed pre-adaptation or bleaching. The rational is that identical concentrations of rhodopsin pigment are broken down.

In early instruments the bleach light occupied a 35° visual field\textsuperscript{(84,90,145)}, however, later instruments continue to use an integrating sphere that covers a greatly increased
visual field\(^{(95)}\). The integrating sphere reflects and diffuses white light giving a uniform light flux in all directions, a full discussion is provided by Longhurst\(^{(146)}\).

The intensity and duration of the bleach light markedly affects the course of dark adaptation in humans\(^{(90,109)}\). Following exposures to excessive or prolonged light intensities the appearance of the cone-rod break is significantly delayed, taking greater then 15 minutes, which is far too long for the average subject under test\(^{(7)}\). Decrease the brightness or duration of the bleach light and the cone-rod break appears in less then 60 seconds; below a critical bleach luminance it may be completely absent\(^{(7,90,147)}\). A dark adaptation curve lacking both cone and rod phases is of limited clinical use as it is difficult to determine the magnitude of the rod phase, see Figure 1.13 below.

![Figure 1.13. Dark adaptation curves following five different pre-adapting luminances (1-5), modified from Hecht et al\(^{(147)}\). The luminance thresholds on the ordinate are in μtrolands. Bleach time 3 minutes.](image-url)
In order to obtain well-defined curves subjects are typically exposed to the bleach light for 2-10 minutes at intensities ranging between 1,250-1,500mL (3,975-4,770cd/m²)\(^{(148,149)}\). For example, Hecht & Schlaer\(^{(90)}\) pre-adapted their subjects for 3 minutes at 1,500 mL (4,770 cd/m²); Russell et al\(^{(150)}\) bleached at 1,350 mL (4,293 cd/m²) for 10 minutes. A number of researchers have used extremes of intensities, for example Birren and Shock\(^{(104)}\) bleached at 500mL (1,590 cd/m²) for 3 minutes whereas Morrison et al\(^{(145)}\) bleached at a maximum light intensity of 2,100mL (6678 cd/m²) for 5 minutes. Light adaptation for 3 minutes at 1500mL (4,770cd/m²) is generally considered long enough to clearly identify the cone-rod transition\(^{(90,109,151)}\).

In both the Concept Prototype and Automatic Dark Adaptometers studies the bleach intensity was fixed at 2 minutes at 1500ml (4,770cd/m²), (see Chapter 4).

1.4.2 Control of Stimulus Intensity

Subject luminance thresholds are determined by the presentation a test stimulus whose “intensity” may be increased or decreased or both during a dark adaptation evaluation. In the former case, a slowly ascending light stimulus is presented until it just becomes visible to the subject, in the latter case, a descending target stimulus is decreased until the target is no longer visible to the subject. Traditional dark adaptometers use one or both these method-of-limits\(^{(90,144)}\) to establish the threshold luminance levels, however, the descending method is less accurate as it may interfere with the dark adaptation processes. Traditional adjustment of the stimulus intensity was achieved by neutral density filters. In both the CPA and ADA, the luminance is controlled digitally and a series of descending pre-set luminance levels presented to the subject in four symmetrical quadrants.
1.4.3 Test Stimulus Calibration

It is important that the output of the target stimulus is regularly checked, as the intensity of any light source may change with time; tungsten filaments are particularly affected, LED less so. Calibration of the output of the target stimulus is therefore critical; in Chapter 4, Section 4.4 calibration of the CPA and ADA is addressed.

1.4.4 Area and Location of the Test Stimuli

The size of the target stimulus greatly influences the test results in any dark adaptation examination. Large target size may mask or hide areas were the retina is abnormal\(^6\). A target size of 10° is preferred, making the stimulus clearly identifiable to the subject. The exact location on the retina where the stimulus is presented may be varied by changing the eccentricity by using a small red fixation light.

1.4.5 Fixation Target Source

The use of a fixation light is critical to the effective measurement of dark adaptation. The fixation target light fixes the attention of the subject under-test and critically it determines the location or eccentricity of the target stimulus with respect to the fovea. The fixation target helps ensure that the target is presented to the same area of the retina, as the test proceeds\(^6,90\); this point that is particularly important because of the large variation in sensitivity to light in different parts of the duplex retina (Section 1.3.2). Palmer and Blumberg\(^{102}\) showed that the lack of a fixation target resulted in inaccurate and unreliable dark adaptation data. Early instruments lacked a fixation target, later instruments used fixed and adjustable fixation targets that enabled different areas of the retina to be examined\(^{152,153}\). To avoid interference with the rod phase of adaptation, the fixation light intensity is presented just above the subject’s
luminance threshold and is typically coloured red, as red light does not break down rhodopsin (see Section 1.3.8), a red target was chosen for the CPA and ADA.

1.4.6 Colour of the Test Stimulus
Stimuli of different wavelengths vary in their ability to produce visual sensation. As previously discussed (see Section 1.3.8) the Purkinje shift in peak sensitivity from photopic vision (555 nm) to scotopic vision (510 nm) will have a significant impact on dark adaptation results. During the early part of dark adaptation (photopic phase), the cones are operational and are particularly sensitive to red light while the rods cells are relatively insensitive. As dark adaptation proceeds the cones become inactive while the rods are activated and are more sensitive in the blue end of the spectrum.

Figure 1.14. Dark adaptation curves using 5 different coloured test stimuli of wavelengths 680 nm, 635 nm, 573 nm, 520 nm and 485 nm, the grey curve represents white light. Subjects were pre-adapted at 2000 mL for 5 minutes; a 3° test stimulus was used, presented 7° nasally. Modified from Graham.¹¹
It can be seen in Figure 1.14 that using a red stimulus red, only a cone response is observed. When orange light is used a small rod component eventually appears. With decreasing wavelength, for example yellow and green, light the rod phase becomes progressively more prominent and appears earlier in the measurement\(^{(2)}\), see Section 4.7.2. Using a blue light stimulus to which the rod cells are particularly sensitive produces a well-defined rod phase.

A good approximation to the standard adaptation curve may be obtained by using green light, having an intermediate wavelength between red and violet, thus producing both cone and rod phases of adaptation.

Green light (Figure 1.14) is almost mid-way between the peak sensitivity for cone and rod vision; it may therefore be employed as a stimulus as it is a most efficient colour at evoking a visual response in both photopic and scotopic vision\(^{(148)}\) thus mimicking the effect of white light\(^{(6)}\); green LED’s were chosen for both the CPA and ADA. In Figure 1.14, there is a difference in the final threshold level after 30 minutes, thus dark adaptation data depend strongly on stimulus spectral bandwidth. This effect is due to the Purkinje shift which in turn reflects differences between the absorption spectra between rod and cones.

1.4.7 Duration of the Stimulus Light
In the CPA and ADA, the light intensity was adjusted by pulse width modulation of LED’s, thus the temporal aspects of vision need consideration, as the duration and intensity of the stimulus influences the perceived luminance\(^{(154)}\). A fundamental idea in photochemistry is the Bunsen-Roscoe law which shows how the reaction of any light sensitive pigment, including the visual pigments of the eye, is in general a linear function of the intensity of the light exposure and its duration\(^{(131)}\). Temporal
summation refers to the eye's ability to sum the effects of individual quanta of light over time. However, there are limits; temporal summation only occurs within a certain period of time, called the critical duration or critical period. According to Bloch's law of vision, within this critical duration, threshold is reached when the threshold luminous photoreceptor activation energy is achieved. Bloch's law states that in order to evoke a visual response, the total luminous energy should be constant, i.e., the product of the luminance threshold luminance \( L \) and stimulus duration \( t \) equals is constant. Bloch's Law is expressed as \( L \times t = k \).

Thus, when luminance is halved, a doubling in stimulus duration is required to reach threshold. When luminance is doubled, threshold can be reached in half the duration. When the duration is increased past a critical value (called critical duration), the threshold intensity becomes constant (see Figure 1.15).

Once steady state adaptation has been achieved, the critical duration is shorter for stimulus of high luminance and longer for stimulus of low luminance as a longer period of time is available to sum the quanta to reach threshold. Temporal summation ceases beyond the temporal integration time. Temporal summation is affected by other test variables such as background luminance and the size of the stimulus size.
and photoreceptor. Critical duration is shorter for dark backgrounds and larger test stimuli. Typically in rods cells, Bloch’s law levels off at about 100 ms-200 ms, and 50 ms for cones\(^{(155)}\).

Within the critical duration, if the number of quanta exceeds the detection threshold constant \(k\), the light will be seen, irrespective of how many flashes/pulses are presented, they will be seen as a single continuous light. In order that two flashes are resolved temporally, they must be separated in time by at least the critical duration\(^{(156)}\) for these reasons pulse duration was kept well below the critical duration in the CPA and ADA.

### 1.5 Summary

The anatomical, histological and physiological complexities of the duplex human retina, as they relate to dark adaptation\(^{(8,9,93,133,158,159)}\) have been considered in this Chapter. A total of 6 parameters affecting dark adaptation were discussed which lead to the establishment of criterion upon which the design principles used in the construction of the CPA and ADA were based. The design and construction specifications of the CPA are considered in the next Chapter.

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159 Von Kries, J. (1929) Zur theorie des tages und dammerungssehens Handbuch der normalen und pathologischen Physiologie. 13: 678pp
2. Description of the Concept Prototype Adaptometer

Apparatus

2.1 Introduction

Based on the prerequisite principles described in Chapter 1, a new Concept Prototype Adaptometer for the measurement of dark adaptometry was proposed, designed, constructed and evaluated. Herein a general outline is given of the instrument’s main features that provide a potentially improved apparatus for the application of dark adaptometry in both modern and third world contexts. The hardware circuit specifications are presented in Chapter 3.

While the dark adaptation data presented in this thesis was obtained using the integrating sphere of the GWA, it is accepted that alternative methods of light adaptation need to be further explored in order to make the CPA/ADA a fully portable instrument.

2.1.1 Description of the Concept Prototype Adaptometer

A detailed illustration of the new Concept Prototype Dark Adaptometer is presented in Figure 2.1. To aid recognition and to follow the text, each significant part/element is numbered, thus the Concept Prototype Adaptometer apparatus/instrument is indicated by the reference numeral 1 and so on. The apparatus comprises two distinct elements, (a) a test housing 2 includes the stimulus panel 8, that the subject under examination interacts with, (b) a control housing 3 that is used by the person administering the test. The test housing contains the majority of the instrument’s electronic circuitry and audible reinforcement devices. The stimulus panel comprises four green high efficiency
light emitting diode matrix arrays 11 that form the test stimuli. A plurality of test stimuli, namely, four test stimuli 11 are arranged around a centrally located red fixation light emitting diode (5mm diameter) 12 on the stimulus panel 8 for testing dark adaptation. The fixation light emitting diode 12 remains on throughout a test, however, at any one time, only one test stimulus 11 is switched on. The test housing is constructed of tough polyurethane structural foam for strength. A metallic frame A3 fixes the distance of the test housing and stimulus panel to the chin rest (adjustable) A2 and forehead rest A1.

The control housing 3 comprises an on/off main switch 23 that is mounted on the control panel 6. A start/reset push button 25 is provided on the control panel 6 for activating the apparatus in order to carry out a test or for resetting the test. Cable outlets 33 and 34 are provided in the test housing and control housing respectively for accommodating a cable connecting the circuitry of both enclosures. It is important that the two enclosures should be arranged so that the control panel 6 is not visible to a subject during a test. In practice, it was envisaged that during a test both housing 2 and 3 will be mounted remotely of each other in different rooms.

The operator initiates a test using the control panel 6 and monitors the subject's performance using the mimic LEDs. The stimulus presented to the subject is mimicked on the control panel by a set of four individual LED's that are spatial located in the identical positions as the four LED array stimuli. The subject response is mimicked on the control panel by a set of four red LED’s adjacent to the individual green LED’s. When a stimulus is selected and presented one of the four green LED’s on the control panel is illuminated, when the subject makes a choice the appropriate red LED is illuminated on the control panel, in this way the operator can monitor the progress of the test.
Figure 2.1. Illustration of the Concept Prototype dark adaptation apparatus, featuring the Test Housing and the Control Housing. The mimic LED's identify the stimulus chosen by the apparatus and the selection made by the subject. The subject sits in front of the stimulus panel in complete blackout. The control housing is situated outside the examination area. The two elements are connected using cabling.
2.1.2 Test Procedures using the CPA

Figure 2.2 illustrates the Instrument Test Protocol that establishes the protocol for administration of the dark adaptation test using the new instrument. As with all dark adaptation testing the test is carried out in a light-proof room (details of the instructions given to volunteer subjects are presented in Section 4.3). Following exposure to the pre-adaptation light which was provided by the GWA, not shown (see Section 1.4.1), a test is initiated by the operator; the circuitry randomly switches on one of the four test stimuli, mounted on the stimulus panel 8 at a pre-predetermined luminance. The stimulus is continuously presented until the subject has dark adapted at that luminance level/threshold. When the presence of the test stimulus has been detected or perceived the patient responds by indicating which stimulus has been illuminated. This is achieved by the subject depressing the chosen stimulus. Translucent acrylic covers 17 are mounted over each stimulus 11 that are themselves mounted on membrane switches to enable a subject to input the identity of a presented test stimulus. Each switch is operated by depressing the respective cover over the test stimulus. A comparing means is provided thereby the subject response and the presented stimulus is compared. A pair of alerting means, namely buzzers 20 and 21 are provided inside the test housing 2 to indicate to a subject if the test stimulus 11 is correctly identified or not. A correct choice is indicated by a single audible tone thereby functioning as a positive reinforcement to the subject.

Correct Subject Choice

Upon a correct selection by the subject, the elapsed time is recorded between the presentation of that threshold luminance and the time taken for the subject’s eye to adapt to that luminance or threshold level.
Figure 2.2. Block diagram shows the instrument test protocol procedures during a dark adaptation test. One of four LED array is randomly selected and presented to the subject at a predetermined luminance level. Positive and negative re-enforcement is provided on a correct or incorrect subject choice.
When a correct choice is made by the subject, the luminance level is reduced by a predetermined decrement and the stimulus presented once more at a randomly selected location. The ratio of the brightest to darkest luminance level presented by each stimulus is of the order of 32768:1 or 4.51 log units of light intensity, this allows a full dark adaptation curve to be obtained (see Section 1.2). LED matrix display arrays were chosen as the test stimuli, as they provide precise control of the threshold luminance when driven by a modulated input signal. In the CPA each luminance was exactly half that of the preceding one, this was achieved by reducing the pulse width of the input signal by a half. A total of 16 discrete thresholds were presented over the dynamic luminance range ($2^{15}$). The luminance of the red fixation LED was reduced once every fourth reduction of the level luminance. The arrays are robust and inexpensive providing good light stability and long life.

**Incorrect Subject Choice**

An incorrect subject choice is signalled by a double audible tone thereby acting as a negative reinforcement. The first incorrect choice by the subject results in the same stimulus being re-presented at the same location and at the same luminance level. A second incorrect choice would give the subject a 50:50 chance of giving a correct response (four stimuli). Consequently, there is a random re-selection of the four stimuli, one of which is chosen and is re-presented at the same luminance level. A third incorrect choices at the same luminance level automatically leads to a termination of the test and re-instruction. In this thesis termination and re-instruction were never required.

### 2.2 Test Housing Specification

The test stimuli in the CPA are located equi-distance from the fixation target. The size and position of the stimuli, together with the distance at which they are viewed was
chosen to stimulate appropriate regions of the retina for dark adaptation measurement, specifically the region of maximum rod density i.e. between $10^\circ$-$15^\circ$ from the fovea (see Section 1.3.3). A photograph showing a subject under test is presented in Chapter 7, section 7.2.

Figure 2.3. Test Housing 2 and stimulus panel 8 highlighting important angles and distance used in the CPA. The control panel is not shown. Not to scale.

The stimulus presentation angle is determined by the longitudinal and axial position the stimulus makes with the subject’s eye. In order to lock the axial position of the subject a chin rest was located fixed 30 cm for the stimulus panel. The height of the chin rest fixes the location of the average eye directly in front of the fixation stimulus.
thereby ensuring that the stimulus presented is imaged onto the desired area of the retina. In the CPA the eccentricity of the fixation stimulus and the centre of each test stimulus was set at $\beta = 10^\circ$ when viewed at 300 mm. When imaged on the retina each stimulus subtends an angle $\alpha = 10^\circ$, thus the area of the retina that is stimulated is located between $5^\circ - 15^\circ$, corresponding to maximum rod density. The fixation stimulus provides a means for enabling the subject to focus their eyes on the stimulus panel 8 during a dark adaptation test. In most cases the subject’s left eye is occluded with the examination of the right eye. The spatial arrangement of the LED arrays ensures that test stimuli are never imaged onto the blind spot of the eye. Each test stimulus 11 is numerical identified by the designation 11A, 11B, 11C and 11D.

**Figure 2.4.** Stimulus panel showing the four green LED arrays that act as the test stimuli. The centre of each stimulus subtends an angle of $10^\circ$ to fixation light when viewed at 300 mm. Each stimulus subtends a $10^\circ$ angle when viewed by the subject. The eccentricity of the fixation light and the centre of the test stimulus subtends an angle $\beta = 10^\circ$ to the subjects right eye. Each stimulus extends from $5^\circ - 15^\circ$. 

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2.2.1 Choice and Specifications of Test Stimuli used in CPA

Each test stimulus is formed by an array of green LED matrix arrays (TFB5X57A/C series - gallium nitride GaN) of peak wavelength $\lambda = 565$ nm with $\frac{1}{2}$ height bandwidth $\Delta \lambda = 30$ nm; see Appendix 4 for array specifications. Figure 2.6 shows the spectral output of these arrays. Green light was chosen to stimulate both cone and rod photoreceptors (Section 1.4.6). Calibration of the CPA is covered in detailed in (Section 44). The estimated time to failure for these LEDs is between $10^5 - 10^6$ hours or 11 - 22 years of continuous use, they are unaffected by frequent on-off cycling; the rise time is about 20 ns and fall time 30 ms which is within the critical period to which Block's Law applies.
Each test stimulus 11 present on the stimulus panel 8 is formed by discrete light emitting diodes 14 each of diameter 5 mm; Figure 2.7. The array consists of 5 rows by 5 columns 14, giving 25 discrete green light emitting diodes which give a distinctive pattern readily recognisable by the subject under test, thus aiding discrimination of the presented stimulus. The distance between the centre line of each row of diodes to the next row is a distance of 7.6 mm. Similarly each column of diodes is spaced 7.6 mm from adjacent columns. The area of the test stimulus comprises an area of 35 mm². In the CPA each row of the diode arrays was connected in parallel and driven by the circuitry shown in Figure 2.8 to be detailed presently.
Figure 2.7. The TFB5X57 series high efficiency light emitting diode matrix were chosen to act as the test stimuli display used in the CPA. The TFB5X57A/C series is a 5 X 7 LED X-Y matrix. Power dissipation per LED is 60mW. Viewing angle is $\approx 90^\circ$, peak emission wavelength $\lambda = 565$nm and spectral line half-width bandwidth $\Delta \lambda = 30$nm. In the CPA only 25 of the 35 LED's available were used providing a stimulus area of $35 \text{mm}^2$. The optical characteristic and terminal connections may be found in Appendix 4. The arrays were supplied by Three-Five Systems, Inc.

Figure 2.8. Row of 5 discrete light emitting diodes connected in parallel and modulated by a five volt input signal. The cathode of the last LED when connected to ground directly or via a transistor, illuminates the entire row of LEDs when the input signal is high. In the array all five rows are similarly connected. The array is disabled when a logical high is maintained on the cathode.
2.2.2 Fixation Light Specification

The fixation light emitting diode 12 was so chosen that the peak wavelength $\lambda$ of the light being emitted is 635 nm (red light), as previously stated the small/dim fixation light emitting diode 12 stimulates the cone photoreceptors preferentially, to avoid interference with the rod photoreceptors the fixation LED decreases in brilliance as the test proceeds. It was important that the fixation light was sufficiently dim to avoid interference with subject's ability to adapt to the test stimulus, however, it must be sufficiently bright to provide a viable fixation target.

2.2.3 Test Stimuli Translucent Covers

Hand made acrylic translucent covers 17 were mounted over the arrays of light emitting diodes and rest on membrane switches to enable a subject to input the identity of a presented test stimulus. Associated with each of the four test stimulus 11A, 11B, 11C and 11D are four corresponding switch networks A, B, C and D. Each switching network consisted of four individual membrane switches arranged about each test stimulus. The subject interacts with the apparatus by depressing the respective translucent cover over the illuminated stimulus which in turn will activate the switching circuit. Audio feedback is presented to the subject of a correct or incorrect choice. Each cover 17 comprises an area 37mm by 37mm and is located equi-distance from and around the central fixation light emitting diode 12, as are the LED arrays shown in Figure 2.8. Neutral density filters were used to attenuate the light luminance for calibration purposes as the initial light luminance was too high (see Section 4.4). The neutral density filters were located between the LED arrays and the translucent covers.
Figure 2.8. Illustration of the LED arrays 11A, 11B, 11C and 11D mounted on the CPA circuit board. Over each array is mounted a translucent acrylic cover. These covers are mounted on four switches on the circuit board of which only two (A, B) are shown. The neutral density filters are omitted.
2.3 Advantages of the Concept Prototype Adaptometer

There are several advantages of the Concept Prototype Adaptometer, sketched above, compared to conventional instrumentation, for example the test is self-administered by the subject who interacts with the apparatus by pressing the perceived illuminated stimulus when it is observed, thus the test is like a game, an important feature when assessing children. During the test the operator is free to externally monitor the subject's test performance as data may be displayed in real time as the test proceeds. Because multi-stimulus sources are used and randomly selected, cheating is eliminated and error rate determined (less than 5% of subjects): there is effectively no learning curve as is the case using a single stimulus presentation. Different test procedures may be easily implemented as four separate stimuli are used, thus it is possible to investigate at least four discrete localised areas on the retina for disease. At the end of a test the subject's particulars and test results can be download digitally for storage to a PC or laptop. Analysis of the data can carried out by comparison with standard curves for various age groups. In this way a large database can be built up over time of individual and group performances. Dark adaptation curves can be stored and printed out in various formats. As solid state electronic components were used in the CPA, the power requirement of the instrument is low; consequently a rechargeable dry cell battery could be used as a power source. When not in use the battery is recharged on a trickle charger (12 volt) through a transformer. This facility reduces the risk of electrocution to the operator or subject.

Chapter 3 will discuss the circuit specifications that implement the testing protocols and techniques described above.
3 Electronic Implementation of Test Protocol Blocks
and Associated Circuitry

3.1 Introduction

This chapter describes the electronic circuitry devised, to implement the instrument

3 test protocols block procedures, as previously described in Section 2.1.2, into a fully
working instrument. The instrument test protocol block is divided into a number of
smaller sub-blocks that outline and describe electronic circuitry required to carry out
particular functions. These blocks represent the implementation of particular features
novel to the Concept Prototype Adaptometer. Figure 3.1 identifies the critical circuit
blocks that were used to construct a working instrument; see below.

3.1.1 Circuit Blocks

(A) The Luminance Level Control/Array Driver Circuit describes the means for (i)
powering each test stimulus 11 and (ii) describes the means to control and select the
level of luminance at which the test stimulus is to be switched on. The luminance
level circuitry controls the luminance of each LED array and modulates individual
rows.

(B) The Test Stimulus Selector Circuit describes the means for randomly selecting a
sequence between 1 and 4, that randomly selects the test stimulus 11 to be switched
on. In the prototype unit this part of the circuit was also used to help control the
luminance level. The Test Stimulus Selector circuit randomly chooses one of the four matrix arrays to be illuminated.

(C) The **Subject Response Circuit/Comparing Means** provides (i) the input means for permitting the subject to input the identity of the test stimulus 11 which is perceived by the subject and (ii) a comparing means to identify if a subject has made a correct or incorrect choice. This element allows the subject to interact with the instrument, thereby, constituting the game element of the test.

When the instrument is activated, the Luminance Level Control/Array Driver circuit selects the starting luminance level, while the Test Stimulus Selector circuit selects the actual test stimulus 11 that is randomly to be switched on. When the subject responds by depressing one of the covers mounted over the arrays, the Subject Response Circuitry/Comparing Means determines the correctness of the subjects choice. A correct choice by the subject causes the luminance level control circuitry to reduce the level of luminance at which the next stimulus 11 is to be switched on by a predetermined decrement. An incorrect choice scenario causes the circuitry to randomly re-select a stimulus at the same luminance level.

(D) The **Fixation Control Circuit** controls the luminance level of the red fixation light emitting diode 12. A **Manual Reset Circuit** allows the test operator to intervene during a test procedure. A piezoelectric **Buzzer** device informs the subject of the correctness of the response/choice made. These circuit blocks are synchronised by a number of clocking circuits and input signals in the circuitry. The following sections will describe the implementation of each of the above circuit elements in detail.
Figure 3.1. Block circuit diagram showing the critical circuit elements for controlling the Concept Prototype Adapometer. These include (i) luminance level control and array driver circuit (ii) test stimulus selector circuit and (iii) subject response circuit and comparing means. The stimulus comprises arrays 1 to 4 and four response switches. An on/off switch, a fixation circuit and manual reset are provided.
3.2 Circuit Block - Luminance Level Control/Array Circuit

The luminance level control/array driver circuit has been designed to carry out the essentially function of accurately controlling the luminance level of the test stimuli and to do so with minimum power consumption. Figures 3.2 and 3.3 below, identify the organisation and circuitry elements required to construct the Luminance Level Control/Array Driver Circuit.

The precision of the Luminance Level Control/Array Driver circuitry required the output luminance to vary by a value not greater than ±1% over a dynamic range of 4.51 log units of luminance as previously stated. The light output from each LED array was controlled in two ways (i) by controlling the current; (luminance is linearly proportional to the forward current through the diode) and (ii) by rapid switching of the diode (modulation) with a variable duty cycle; both these methods were employed in the CPA. Colour tone remains precisely constant which would not be the case for a dimmed incandescent lamp. In the CPA control of the stimulus luminance was achieved by variation of the pulse width of an applied input signal used to drive the stimulus matrix arrays. Modulation of the pulse width controls the on time of each array, thus controlling the level of luminance of the test stimulus. As the pulse width signal increases the luminance level increases and visa versa; luminance varies linearly with pulse width.

In the Concept Prototype Adaptometer the stimulus luminance level is controlled by circuitry that compares an input trigger pulse provided by an external signal generator with the output of a retriggerable monostable multivibrator\(^{(1)}\). The variation in pulse width was provided by an adjustable logarithmic potentiometer.
Figure 3.2. Critical elements of the Luminance Level Control/Array Driver Circuit. The monostable multivibrator controls the pulse width of the driving signal which determines the brightness or luminance level of the test stimulus. In the prototype unit a manual adjustable logarithmic potentiometer was used.
Figure 3.3. Circuit diagram for the luminance level Control/Array Driver. The circuit features (i) the pulse width control (ii) display blanking (iii) row switching (iv) transistors row drivers and the stimulus panel. Important components are numbered and are referenced in the text.
3.2.1 Pulse Width and Luminance Threshold

It was found that a duty cycle greater than 65% tended to saturate the diodes, giving a small but measurable non-linearity between pulse width and luminance thus to ensure accuracy the maximum duty cycle was set at 50%. The smallest pulse width was limited by the switch on time of the arrays, thus care was taken to ensure that the pulse width exceeded the switch on (rise time – time taken to make a transition from one state to another, usually measured between 10% and 90% of the rise voltage) of the array in order to obtain a linear output from the arrays. Typical values for very high-performance LED’s and driver circuits would be 10 ns optical.

Investigations showed that a dynamic luminance range of only 128:1 was achievable, corresponding to 7 luminance decrements, well below that required. The solution to the problem required the use of a current control resistance that was switched into the circuit at the smallest pulse width. The luminance level with the smallest pulse width was made to equal to that with the largest pulse width with the trimming resistance in place. Thus the effectively dynamic range was doubled to 32768:1 which were presented over 16 luminance thresholds where the luminance is halved each time (see Section 3.3). With a fixed pulse width the light intensity is a linear function of pulse repetition rate\(^{(2,3)}\).

3.2.2 Pulse Width Control

Variation of the luminance level is by pulse width control circuit 76 (Figure 3.3). The pulse width control circuit 76 comprises a timer chip ICM7555 77 which is used as a retriggerable monostable multivibrator (A device that oscillates producing single square waves pulses on application of external trigger). A square wave input trigger signal was provided on line 85 by an external signal generator (Farnnell) at a frequency of 100Hz.
The input trigger applied through line 85 signal is connected to the trigger terminal (pin 2) of the timer chip 77. The output pin 3 of the timer chip 77 is connected to one pin of a quad 2 input NAND gate (CMOS 74LS00) 78. The input trigger on line 85 is connected to the second NAND input pin. Both signals are compared and modified by the NAND gate, whose output is the difference between the two signals. Appendix 5 provides data sheets on the main chips and transistors used.

The output signal on pin 3 of the timer chip 77 is controlled by an RC circuit which comprises a capacitor C1 of 100 pF, connected in series with a manually adjustable potentiometer 80 between the control voltage Vcc and ground. The trigger pin 2 of the timer chip 77 is connected between the capacitor C1 and the potentiometer 80. A PNP transistor (2N3906) T12 is connected across the capacitor C1.

A logical low applied to the base of the transistor T12 by either the threshold pin 6 of the timer pin 77 or the input trigger signal on the line 85, switches on the transistor T12, thus discharging or preventing the capacitor C1 from charging.

Initially, the capacitor C1 is held discharged by the timer chip 77. At the negative transition of the external trigger input on pin 2 of the timer chip 77, the capacitor C1 is prevented from charging and is thus discharged through the transistor T12, which keeps the capacitor C1 discharged until the trigger input on pin 2 of the timer chip 77 goes high. When the input trigger goes high capacitor C1 is then charged. When the voltage across the capacitor C1 reaches $\frac{2}{3}$ of the control voltage Vcc, the output on the threshold pin 6 of the timer chip 77 goes low and the capacitor C1 is discharged. The transistor T12 continuously discharges the capacitor C1 when the trigger input (pin 2) remains low, therefore the threshold output on pin 6 of the timer chip 77 stays high if the voltage across the capacitor C1 never reaches two-third of the voltage Vcc. The
timer chip 77 outputs a pulse on its output pin 3 which is longer than the input pulse. By varying the resistance of the RC network \( V_{out} = V_{cc}e^{-t/RC} \), specifically the potentiometer 80, the pulse width is varied. The logical waveforms are displayed, Figure 3.4.

In summary, as the resistance of the manual logarithmic potentiometer 80 increased, the output of the stimulus luminance increased in a linear fashion (and visa versa). A unit change in the pulse width produces a unit luminance output of the test stimulus arrays.

3.2.3 Power/Display Blanking

The circuits in Figure 3.3 were powered by standard laboratory power supplies in the CPA. The input supply voltage \( V_s \) applied on line 51 is connected to the voltage regulator (LM350) which provides a constant current to the circuitry. The output voltage from the regulator 50 is \( V_{CC} \) of 5 volts on the output line 52.

Another feature of this part of the circuit is the blanking of the arrays to conserve power. When the arrays are switched off, the power to the transistors driving each of the five rows of LED’s is interrupted; power is restored for the duration of the pulse width signal. This was achieved as follows.

The output of the timer chip 77 is inverted by the gate (74LS04) 81 and is applied to the display blanking circuit 38. The signal from gate (74LS04) 81 is connected to the base of a transistor NPN (2N2219) T14 via a 1k\( \Omega \) resistor R18. The transistor T14 and switches off the control voltage output \( V_{CC} \) on line 52 from the constant current power supply 50 during the space period of the square wave signal from the NAND gate 79, thus reducing the current and voltage to the driving transistors T5-T9. This saves power which is important for a battery operated portable instrument.
Figure 3.4. Logic waveforms obtained from the pulse width control circuitry using the monostable multivibrator. Waveforms not to scale. Below are the NAND and INVERTER logic tables for reference.

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>OUTPUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2</td>
<td>3</td>
</tr>
<tr>
<td>L L</td>
<td>H</td>
</tr>
<tr>
<td>L H</td>
<td>H</td>
</tr>
<tr>
<td>H L</td>
<td>H</td>
</tr>
<tr>
<td>H H</td>
<td>L</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>OUTPUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
</tr>
</tbody>
</table>
3.2.4 Transistor Row Drivers

Each of the five rows of LED's that comprise an array stimulus is powered by its own discrete switching and matched transistors. All four arrays that comprise the test stimuli are connected in parallel with these driving transistors see Figure 3.5. The output of the blanking circuit $V_{CC}$ on line 52 is applied to the supply voltage of the transistor drivers.

![Transistor Row Drivers](image)

*Figure 3.5. Each row of the arrays is powered by five discrete fast switching transistors.*

The rows of diodes (Figures 2.7 and 2.8) that comprise each test stimulus 11 are connected in parallel through the rows 54a, 54b, 54c, 54a and 54e. Each row of diodes was connected to the collectors of five PNP transistors (type ZTX 504) T5, T6, T7, T8 and T9. The transistors emitters were connected to the regulated five volt $V_{CC}$ on the output line 52 of the power supply 50 (blanking circuit). The bases of the transistors T5-T9 were connected via 6.8k$\Omega$ resistors R5 to R9 to the output pins 1 to 5 of a BCD-Decimal Decoder chip 73. The transistor bases are also connected to 1 k$\Omega$ pull up resistors R11 to R15 to the regulated control voltage $V_{CC}$. The choice of resistors ensured that the transistors are correctly biased and that no floating voltages are present on the decoder output terminals. The bases of the transistors T5 and T9 are normally held high and therefore the collector current is zero with the transistor switched off.

When a low appears on any of the output pins 1 to 5 of the decoder chip 73, the relevant
transistor will be switched on and the row of diodes illuminated. The diode rows 54a, 54b, 54c, 54d and 54e are sequentially switched, by transistors T5 - T9, for a duration predetermined by the output from the pulse width control circuit 76.

Adjustable trimmer resistors were used to make small adjustment to the current flowing in each row, so that the luminance of each diode row (in each array) were equally matched.

![Circuit Diagram](image)

Figure 3.6. Circuit to drive one row (of five) of an array. When the a logical low is applied to the base of the driver transistor, switching it on, current flows across the base and into the collector and through the row of five diodes to ground thus illuminating the row. A logical high applied to the base switches off the diodes. Each array comprises five rows of diodes driven by transistors T5-T9 with serial trimmer resistors. The variable resistance was used to match the luminance of all rows.

3.2.5 Sequential Row Switching Circuitry

Sequential switching of each of the five rows of diodes 14 is provided by a decade counter with asynchronous clear (type 74161A) 74 and a binary coded decimal (BCD) to Decimal Decoder/Driver (type 74145) 73. The (type 74161A) 74 binary asynchronous counter is a TTL pre-settable 4-bit binary fully programmable CMOS counter that is “clockable” to 25 MHz. The (74145) 73 is a monolithic binary to decimal decoder/driver.

It can be seen in Figure 3.3 that the output of the multivibrator circuitry (line 6) is used to switch on a binary counter (74161A) 74; which was programmed to count from 0 to 4 (binary from 0000, 0001, 0010, 0011, 0100), that is 0 to 4. The binary counter output
sequence is subsequently decoded to a decimal sequence by (74145) 73 which sequentially switches on transistors T5-T9 corresponding to diode rows 54a, 54b, 54c, 54d and 54e of the test stimulus.

The decoder chip (75145) 73 receives binary coded decimal signals on its inputs A, B, and C from the asynchronous clock counter chip (74161A) 74 which was clocked at 10 MHz. The decoder chip 73, gives a decimal output only when a logical zero is applied to input pin D from the pulse width control circuit 76 applied through line 6. When a logical high is applied the decoder 74, it is switched off. When working the decoder 73, decodes the input signal from the counter 74, thereby switching on the transistors T5 and T9 in rapid succession and allowing current to flow via the supply voltage Vcc. Clocking chip (74161A) 74 at 10 MHz, $\tau = 100$ ns, switches on each row virtually simultaneously, for the duration of the luminance as determined by the pulse width control 76. It can be seen in Figure 3.13 that the repetition rate is 100 Hz ($\tau = 10$ ms) (outside the critical flicker frequency) such that no flicker is perceptible. The maximum pulse width can vary between 5ms and 39μs.

![Logic waveform derived from the outputs of transistors T5 – T9. The pulse width is 5 ms; corresponding to Luminance Level 1. The pulse width for Luminance Level 8 is 39 μs.](image-url)
3.2.6 Counter and Decoder Operation

The asynchronous counter 74 was enabled by tying both enable inputs (P and T) permanently high. When the stimulus arrays are switched off by the pulse width control circuit 76 (output on line 6 is logical high) a logical zero is applied to the clear input of the counter 74 via the inverter (74LS04) 81A, which causes the J_K flip flop outputs of the counter to agree with the input data. The input data pins were all tied to ground; thus the 4 bit counter gives a count sequence starting at zero (0000), regardless of the state of the clock or load. When the stimulus arrays are switched on, the clear input goes logical high thereby initiating the counting sequence to commence.

The desired count, i.e. a binary count from 0 to 4, (corresponding to 5 rows of the stimulus) is accomplished using one external NAND gate 78A. The dual inputs to the NAND gate 78A are connected to \( O_A \) and \( O_C \) outputs on pins 14 and 12 of the counter 74. The output of the NAND 78A is connected to the load of the counter 74. When the count sequence has counted to 4, the next positive clock edge sets the counter outputs \( O_A \) and \( O_C \) high (i.e. a count of 5), the output of NAND 78A changes from high to low which disables the load input. This causes the output pins to agree with the input pins thus resetting the counter outputs to 0000 (LLLL) at the next positive clock edge and the counter sequence starts over. A high on the load does not affect the counter.

When the stimulus arrays are switched on, a logical low is applied to the input pin D of the decoder/driver 74 enabling the decoder and generating a binary output. When the input on pin D is logical high, the decoder is disabled and all the diodes rows are switched off.
The high speed (10 MHz) of the clock insured that each row of diodes were switched on for the duration of the pulse width derived from the pulse width circuit. In hindsight it would have been better to use a shift register here, as by clocking at 10 MHz, the equivalent result is achieved.

### Function Table of SN74161A 74 Counter

<table>
<thead>
<tr>
<th>Count</th>
<th>INPUTS DCBA</th>
<th>OUTPUTS OD OC OB OA</th>
<th>LOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0</td>
<td>L L L L</td>
<td>L L L L</td>
<td>H</td>
</tr>
<tr>
<td>1</td>
<td>L L L L</td>
<td>L L L H</td>
<td>H</td>
</tr>
<tr>
<td>2</td>
<td>L L L L</td>
<td>L L H L</td>
<td>H</td>
</tr>
<tr>
<td>3</td>
<td>L L L L</td>
<td>L L H H</td>
<td>H</td>
</tr>
<tr>
<td>4</td>
<td>L L L L</td>
<td>L H L L</td>
<td>H</td>
</tr>
<tr>
<td>5</td>
<td>L L L L</td>
<td>L H L H</td>
<td>L</td>
</tr>
</tbody>
</table>

### Function Table of SN74145 73 Decoder

<table>
<thead>
<tr>
<th>No.</th>
<th>INPUTS DCBA</th>
<th>OUTPUTS 0 1 2 3 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>L L L L</td>
<td>L H H H H</td>
</tr>
<tr>
<td>1</td>
<td>L L L H</td>
<td>H L H H H</td>
</tr>
<tr>
<td>2</td>
<td>L L H L</td>
<td>H H L H H</td>
</tr>
<tr>
<td>3</td>
<td>L L H H</td>
<td>H H H L H</td>
</tr>
<tr>
<td>4</td>
<td>L H L L</td>
<td>H H H H L</td>
</tr>
</tbody>
</table>

### Function Table of NAND 78A

<table>
<thead>
<tr>
<th>INPUTS OC OA</th>
<th>OUTPUTS 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>L L</td>
<td>H</td>
</tr>
<tr>
<td>L H</td>
<td>H</td>
</tr>
<tr>
<td>H L</td>
<td>H</td>
</tr>
<tr>
<td>H H</td>
<td>L</td>
</tr>
</tbody>
</table>

Figure 3.8. Function tables showing operation of the row counter. The counter chip starts counting in binary when a logical high is applied to the clear function when a signal is applied to the arrays. The count length was set from zero to four by using an external NAND gate. The counter output is applied to the decoder/driver, which decodes the binary input into a decimal output. When a logical high is applied to the decoder on pin D it is effectively switched off. Each output line of the decoder sequential goes low, thereby switching on rows of diodes.
3.3 Test Stimulus Selector Circuit

The block diagram Figures 3.9 below and circuit diagrams Figure 3.10, identify the critical elements of the Test Stimulus Selector Circuit. The circuit has three important functions: it provides (i) the means for illuminating an individual array stimulus, (ii) the means for randomly selecting which of the four LED arrays 11A, 11B, 11C or 11D is to be illuminated and (iii) the means to double the luminance range of the arrays by the addition of a switched trimmer resistance, a problem alluded to in Section 3.2.1. This part of the circuitry also allows for the subject response and presented stimulus to be mimicked on the operator control panel 6 by small discrete green LED’s.

3.3.1 Illuminating an Array

As outlined above the luminance level control circuit 76 on the anode side of each LED arrays (Figure 3.6) is connected to the lines 54 a to 54e; the cathode side of the of the test stimuli 11 is controlled by the Test Stimulus Selector circuit 37 to be described.

The cathodes of test stimulus 11a, 11b, 11c and 11e are connected in parallel on the common line 60, 61, 62 and 63 respectively. Transistors T1 to T4 are connected to the corresponding test stimuli 11A to 11D respectively via lines 60, 61, 62 and 63.

Initially all the stimulus arrays are reverse biased, consequently, all the arrays are switched off. Circuitry was designed to randomly forward bias one array thereby switching the selected array on. The circuitry is described below.
Figure 3.9 Block diagram showing the Test Stimulus Selector circuit protocol. This section of the design comprises a one in four selector that randomly chooses an array stimulus and the means for illuminating an array. A manual reset switch is included in the concept prototype unit. The stimulus presented to the subject is mimicked on the operator’s control panel 6.
Figure 3.10. Test Stimulus Selector Circuit that comprises a one in four selector, random number generator and cycle trimmer resistance.
Figure 3.11 The pulse width signal is applied to the diode rows S4a to S4e. The rows in each I1a to I1c are networked together on the cathode side. The output of the arrays on lines 60 to 63 are connected to discrete transistors T1 to T4. The arrays are initially reversed biased by the transistors, however, when one of the lines 60-63 is forward biased, it switches on the stimulus array.
For example, to switch on any of the test stimulus 11, the other side of the array must be grounded by the appropriate lines 60 to 63 through the switching means which comprises transistors PNP (ZTX 310) T1 to T4.

3.3.2 One Four Array Select

The counter (CD4017BC) 56 is a decade counter/divider with ten outputs. A logical high on the reset line 15 of the counter 56 resets the count output to zero. The counter 56 is enabled when the enable pin is logical low and advances on the positive edge of the clock signal. The desired count length i.e. a binary count from 0 to 3, (corresponding to a 1 in 4 selection of the four arrays) is accomplished using one external dual input (74C08) AND gate 58. The output of the AND gate 58 is connected to the reset pin 15 on the counter 56; while one of the two inputs is permanently tied the other is connected to Q4 (pin 10) on counter 56. When the counter has reached a count of 3 (from 0) in the count sequence the next bit causes the counter 56 output, on pin 10, to go logical high. The AND 58 output which is connected to the load of the counter 56 goes high. This resets the counter to zero and the count starts over. A logical low on the reset does not affect the counter. The counter 56, clocked by the timer clip (ICM7555) 55, was set at 1 MHz.

<table>
<thead>
<tr>
<th>Count</th>
<th>OUTPUTS</th>
<th>Count</th>
<th>OUTPUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>H L L L L</td>
<td>3</td>
<td>H L L</td>
</tr>
<tr>
<td>1</td>
<td>L H L L L</td>
<td>4</td>
<td>L L L H</td>
</tr>
<tr>
<td>2</td>
<td>L L H L L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>L L L H L</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Function Table of AND 58

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>OUTPUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2</td>
<td>3</td>
</tr>
<tr>
<td>L L</td>
<td>L</td>
</tr>
<tr>
<td>L H</td>
<td>L</td>
</tr>
<tr>
<td>H L</td>
<td>L</td>
</tr>
<tr>
<td>H H</td>
<td>H</td>
</tr>
</tbody>
</table>

Reset counter
The shift register (74LS194) 57 has the ability to store or transfer information bi-directionally, i.e. right or left of the serial inputs. The shift register 57 was configured for parallel input/output mode of operation. Synchronous parallel loading of the four bits of data from the decade counter 56 only occurred when the mode control input S₀ and S₁ were logical high. When both mode control inputs were low, clocking was inhibited and the state of output flip flops of the shift register was frozen with the last 4 bits loaded from the counter.

3.3.3 Operation of the one in four selector

When the subject makes a correct responds, a logical low on the input from the subject response circuitry applied on line 100 (for duration that the switch is depressed) enables the counter 56 (sequence from 0 to 3). The four bit output from the counter 56 was applied to the inputs of the shift register 57. The low from the subject response circuit applied on line 100 is inverted logical high by (74LS04) 58A and is applied to the mode control inputs of the shift register 57, thus the four bit inputs from the counter 56 are continually loaded into the shift register as the count proceeds. When the subject response signal 40 changes from low to high, (i.e. the switch is released) the last four bits loaded from the counter 56 are stored by the flip flops of the register, appearing on the output pins QA, QB, QC, and QD of the register.

The four bit output from the register 57 comprises three bits that are logical low and one logical high, and are applied directly to the base of four discrete PNP transistors (ZTX310) T₁, T₂, T₃ and T₄. The biasing on these transistors is such that when a logical high is applied to the base it shunts current supplied by the Luminance Level
Control Array Driver circuit to ground, thus switching on one of the stimulus arrays. Similarly a logical low applied to the base of the transistors switches them off, thus maintaining the supply \( V_{CC} \) on the collector and reverse biasing the transistor, thereby turning the transistor and the test stimuli off.

During the time it takes the subject to make a correct response by pressing the lens cover 16 over the appropriate test array stimulus 11, the counter starts and the shift register loads input data. Because the duration of the subject response is completely random and because the counter chip 56 is clocked at 1 MHz, stopping the counter 56 (subject releases depressed switch) results in a discrete pseudo-random output. Accordingly, the outputs appearing on the register 57 are randomly selected.

3.3.4 Switched trimmer resistance.

As previously mentioned (see Section 3.2.1), modulation of the pulse width gives a linear variation of the output intensity over a maximum to minimum luminance ratio range of 256:1 which corresponds to 2.4 \( \log_{10} \) units. Typically, dark adaptation in humans requires a variation of luminance with an order of magnitude of 4.5 - 5.0 \( \log_{10} \) units of intensity, therefore the linear response delivered by the arrays is half that required. Thus a problem arose as to how to increase the luminance range by a factor of two \( \log \) units. Investigation showed that it was possible to obtain the required dynamic range if both the pulse width modulation and current limiting methods were used.

The methodology employed to double the log luminance range utilised a number of trimmer resistances located on the lines 60, 61, 63 and 64 that were used to limit
current flowing through the arrays to ground (Figure 3.11). These resistances that were termed switched trimmer resistance's TRI, TR2, TR3 and TR4. In the CPA unit these resistors were manually switched into the circuit at the appropriate luminance level. The switched trimmer resistance's were calibrated so that when shunted into the circuit the resulting current reduction resulted in the display luminance been half that of the preceding luminance level. By careful calibration it was possible to match the luminance to within an accuracy of 1% using the United Detector Technology (UDT) Company's Optometer Model 40/X. (see Section 4.4).

Figure 3.12. Methodology employed to achieve required dynamic luminance range. The luminance is controlled by pulse width modulation and current control.
From Figure 3.13, the first part of the test gave eight luminance levels, called *phase one*, in which no resistance was used, this gave a ratio of luminance from maximum to minimum of 128:1. During phase two the same pulse widths were used, however, the switched trimmer resistance was shunted into the circuit, thus reducing the current flowing through the arrays and thereby reducing its luminance. By careful calibration, the minimum luminance produced by the minimum pulse width was equated with half
luminance produced by the maximum pulse width when the switched trimmer resistance was used. Using this method it was possible to get a further reduction in luminance corresponding to the first phase, over a further eight levels. The resulting maximum to minimum luminance using both phases yielded a ratio of $32768:1$ over $4.515 \log_{10}$ units which was sufficient to cover the required dark adaptation luminance range. The dynamic range so produced was sufficient to measure the response of the human eye to dim light which itself is logarithmic. In Table 4.2, detailed calibrated luminance details are provided.

The trimmer resistances were connected in series with a fixed resistance (Figure 3.14). The fixed resistance was chosen so that it provided off set luminance required while the trimmer resistance provided the small variation in luminance required for calibration purposes.

![Figure 3.14. The switched trimmer resistance network comprises a fixed 220k$\Omega$ and a 47k$\Omega$ preset or trimmer resistance in series. The resistance can be varied between a minimum of 220k$\Omega$ to 267M$\Omega$. The variable off set resistance allowed the luminance to be exactly set at half that required.](image)

The LED arrays used in the CPA were sourced from the same manufacturer with identical manufacture batch number to ensure matching optical performance. However, careful calibration showed a small variation of the luminance from each array when pulsed by the same signal. Thus 220k$\Omega$. trimmer resistance’s TR5, TR6, TR7 and TR8 were used in the circuit and adjusted to ensure that the output from each row were equally matched. The output of individual LEDs where found to be matched during the calibration phase.
3.3.5 Calibration

Calibration is discussed in detail in Section 4.4. However, it is worth stating that great care was taken to ensure that when the resistances (TR1-TR4) were switched into the circuit; the luminance of level 8 was exactly half that of luminance level 9. It should be remembered that the high precision in the control of the duty cycle results means all luminance levels are in strict proportional to the highest luminance level\(^{(4)}\).

3.4 Subject Response Circuit/Comparing Means

A subject response circuit 44 is described that allows the subject to interact with the test and input test data, by pressing the lens cover 16 of the perceived stimulus. A comparing circuit is also described that analyses and compares the correctness of the input response from the subject. A correct response causes the Test Stimulus Selector circuit to randomly re-select one of the four arrays to be illuminated at a new lower luminance level. An incorrect choice causes a re-selection of the stimulus presented but at the same luminance level. Figures 3.15 and 3.16 provide details of the protocol and circuitry. (Section 2.1.2)

The choice made by the subject is mimicked on the operator control panel 6 by small discrete red LED's. A correct choice is indicated by a single tone piezoelectric buzzer 20, an incorrect choice is indicated by a double tone buzzer 21. A manual reset is provided on the control panel 6 to prematurely end a test or change the test stimulus.
Figure 3.15. Block subject response circuitry. Once the test stimulus is perceived by the subject, the subject responds by activating one of the four translucent covers over each of the four arrays. The response is mimicked on the operator panel, the choice is compared with the actual stimulus presented. A correct identification activates a +ve reinforcement piezoelectric buzzer, the test continues at a new luminance level with one of the four stimuli randomly selected. An incorrect choice activates a −ve buzzer, the stimulus is re-presented to the subject. In the CPA unit a switch debounce was necessary.
Figure 3.16. Circuitry that compares the choice of the subject with the stimulus presented. Input lines 225-228 are connected to micro switches that are activated by the subject. The status of the arrays is identified on the input lines 60-63. When a stimulus is switched on one of the lines 60-63 is pulled low. When a subject responds the signal is applied on lines 225-228, the logic is such that one of the lines is pulled low when the switch network is depressed.

Figure 3.17. Fixation circuit for the target red LED used to focus the subjects attention on the stimulus panel which ensures each stimuli is imaged on the correct location on the retina.
3.4.1 Subject Response Circuit

The subject response circuit 44, Figures 3.15 and 3.16, provides the means for comparing the inputted response from the subject via the switches 18a, 18b, 18c and 18d with the status of the test stimuli 11a, 11b, 11c and 11d. The comparing means comprises four dual input NOR (74C02) gates 65 to 68. One input of each NOR gate is connected to the output of switch network 18a - 18d. While the second input of the NOR gates 65 to 68 are connected to lines 60 to 63 corresponding to test stimuli 11a, 11b, 11c and 11d respectively. The outputs from the NOR gates 65 to 68 are applied to the inputs of a quad input OR (4072BC) gate 69. The output of which is applied on line 100 to the counter 56 and shift register 57 of the Test Stimulus Selector circuit Figure 3.11.

Switches 18a - 18d were push to make type momentary action microswitches, connected to the control voltage 5V-Vcc, when depressed a switch is pulled to 0V; only when released by the subject is the switches pulled high once more. Thus, when any switch 18a-18d is open, a high is placed on the input pin 1 of the corresponding NOR gate 65 to 68. On any switch 18a-18d being closed, a low is placed on the input pin 1 to the corresponding NOR gate 65 to 68.

The lines 60 to 63 of the test stimuli 11 are normally high (reversed biased), thus putting a high on the input pins 2 of the corresponding NOR gates 65 to 68. When a test stimulus 11 is selected on by Test Stimulus selector circuit, the appropriate line 60 to 63 goes low, thereby placing a low on the input pin 2 of the corresponding NOR gate 65.
to 68. This combination of gates allows the determination of the correctness of the subject response.

For example, when the test stimulus 11a is selected, the line 60 goes low and the remaining lines 61 to 63 are held high. A low is placed on the input pin 1 of the NOR gate 65. While switches 18 are open, each of the pins 2 of the NOR gates 65 to 68 are high. Thus, in this state, the outputs of the NOR gates 66 to 68 are low. When the correct switch network is depressed/activated in this case switch 18a, the input pin 2 of the NOR gate 65 also goes low, thus two logical lows are applied to the input pins 1 and 2 of the NOR gate giving a logical high output. This is the only scenario for which the output of the NOR is high. Should any switch other than 18a be closed (or no choice made), the outputs of the NOR gates 66 to 68 will remain low, Figures 3.17 and 3.18. When a correct choice is made the output of the OR gate 69 goes high in all other cases the output remains low. An inverter (74C04) 70 applied on line 100 provides the required logic for the test stimulus selector circuit Figure 3.13.

![Function Table of NOR 65](image)

**Figure 3.18.** When array 11a is chosen by the test stimulus selector, the line 60 goes low, constituting one input to the NOR gate 65. If switch array 18a corresponding to this array is depressed, the line 225 is pulled low, the output of the NOR gate is logical high. If an incorrect choice by depressing switches 18b, 18c or 18d the output is logical low.

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>OUTPUTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>60a 18a</td>
<td></td>
</tr>
<tr>
<td>L L</td>
<td>H</td>
</tr>
<tr>
<td>L H</td>
<td>L</td>
</tr>
<tr>
<td>H L</td>
<td>L</td>
</tr>
<tr>
<td>H H</td>
<td>L</td>
</tr>
</tbody>
</table>

![Function Table of OR 69](image)

**Figure 3.19.** When a correct choice is made the output of the appropriate NOR gate goes high. Consequently, the output of the quad input OR gate 69 goes high. If no selection or an incorrect one is made the output of the OR gate 69 always remains logical low.
3.4.2 Switch Bounce

Ideally when any switch is closed the terminal contacts should snap sharply from one side (5V) to the other (0V) and back again providing for a clean square waveform recognisable to a variety of logic devices. In the course of testing the subject response circuitry, frequent errors in the test procedures suggested problems with the logic gates. After protracted investigation, the cause of the logic errors was eventually attributed to switch bounce. Examination by a Gould digital storage scope showed that when depressed the switches did not produce a clean waveform: short duration spikes (<0.25 µs) were observed and attributed to impact vibration or bouncing of the contact terminals (Figure 3.20). In the subject response circuit (Figure 3.16) switch bounce seriously affected logic gates with edge-triggered inputs. These unwanted spikes played havoc with the logic devices associated with the response circuit and had to be eliminated.

![Switch Bounce Diagram](image)

Figure 3.20. (a) An ideal switch output waveform. (b) Actual switch waveform with insert showing the voltage fluctuation observed in the original switch circuit. The duration of the spikes was typically < 0.25 µS. Trace obtained using a Gould Storage Digital Oscilloscope.
In the CPA prototype circuitry switches 18a to 18d, comprised four micro-switches mounted at the sides of each individual array matrix. These were push to make momentary action micro-switches, each normally connected high to 5Vcc. When depressed the switch is pulled low to 0V; only when released by the subject were the switches pulled high once more. Once the bounce problem was identified a debounce circuit was required for each array which was reverse engineered into the circuit.

3.4.3 Debounce Circuitry

The solution to the logical errors caused by switch bouncing involved an RC network, connected to a Schmitt trigger*, whose time constant greatly exceeded the worst-case bounce time (<0.25μs). The change in voltage across a capacitor as it discharges is related as

\[ V_{out} = V_{cc} \left( e^{-t/RC} \right) \]

The duration time constant \( \tau \) chosen was 33ms which required a 15kΩ resistance and 2.2μF capacitance. The time constant \( \tau = RC \) determined the rate at which the capacitor discharges and for the output voltage \( V_{out} \) to falls to 63% of \( V_{cc} \). While this choice of time constant smoothed the switch bounce, it resulted in very slow falling and rising switch voltage. Thus it was necessary to square up these slow rising and falling inputs, from the RC network, by using Schmitt triggers Figure 3.21.

---

* a comparator circuit with dual threshold action hysteresis that incorporates positive feedback.
The Schmitt trigger chosen was a hex Schmitt trigger (CD40106BC/4584) that provided a snap-action response with a hysteresis. The Schmitt trigger has open circuit inputs and two threshold or trip points $V_{t^-}$ and $V_{t^+}$ respectively. The lower trip point $V_{t^-}$ is triggered by the falling input voltage from the RC network, the upper trip voltage $V_{t^+}$ is triggered by the raising input voltage. The output voltage does not change for input voltages between $V_{t^-}$ and $V_{t^+}$ ($3.6 \text{ V} - 1.4 \text{ V}$), the so called dead band or hysteresis. In the case of the lower trip voltage $1.4 \text{ V}$ the time required for the capacitor voltage to drop to the Schmitt trigger voltage $V_{t^-}=1.4 \text{ V}$ (72\% of Vcc) is 42 ms* (Figure 3.21).

The upper trip voltage is $3.6 \text{ V}$ and is achieved once the subject releases the switch allowing the capacitor to charge.

\* $1.4V_{t^-}=5\text{Vcc} e^{-t/\tau_{RC}}$. Solution gives $t=42\text{ms}$
Figure 3.22. When a switch is activated, the RC circuit discharges slowly, the Schmitt trigger input voltage eventually falls reaching the threshold voltage $V_i$ (1.4V) causing the Schmitt trigger output voltage to go high, the output waveform has a well defined shape unlike the input waveform. When the switch is released the circuit charges until at $V_i^+$ (3.6) the Schmitt goes low. NOTE: the Schmitt trigger inverted the switch logic. See data sheet Appendix 5.

The circuit comprising the RC network and the Schmitt triggers completely solved the switch bounce problem (Figure 3.22). However, the Schmitt triggers 208-211 used in the circuit inverted the original signal logical, consequently inverters 212-215 were placed in series with the Schmitt triggers to obtain the correct logic. In Figure 3.23 it can be seen that each of the four micro-switches comprising switch 18a were connected to four individual inverters 212-215 forming the input to a four input AND gate 216 the output of which is applied on line 225. Activation of one or more micro-switches that comprises switch array 18a will apply the correct logic to the comparing circuit. This debounce circuitry presented in Figure 3.23 for switch 18a was duplicated on the remaining three switch arrays 18b, 18c and 18d.
Parallel switch network circuitry

A parallel switch network comprises four individual micro-switches connected in parallel. The schematic above shows the four LED arrays each with four micro-switches mounted on the sides of each array. Associated with array 1A is the switch network 1A comprising micro-switches A1, A2, A3, and A4. The switches are normally open with push to make contact. The layout (top right) is the schematic diagram of the hardwiring for 1A and is duplicated for the remaining arrays (not shown). When one or more micro-switches are activated by the subject, the switch is pulled to ground via the RC combination. Once all switches are released the switch is pulled high. The RC network and the Schmitt trigger act to minimize the switch bounce.
3.5 Fixation Circuit

The red fixation LED fixates the subject's vision under test (see Section 1.4.1). In the CPA unit the fixation LED 12 is attached to a three pole manual switch comprising a resistor chain that controls the luminance level of the fixation light emitting diode 12. It can be seen in Figure 3.17 each pole is connected to the supply voltage Vcc by resistance 1kΩ, 10kΩ and 50kΩ respectively with the luminance varying according to the power law \( P = I^2 R \) watts. During a dark adaptation examination the luminance of the fixation LED is reduced every fourth reduction of the pulse width.

3.5.1 Buzzer circuit

Figure 3.17 also shows the circuit for the positive buzzer reinforcements. When a correct choice is made by the subject the output of the OR gate 69 goes high, thus switching on the PNP transistor TBI ZTX212, causing current to flow in the collector and into the buzzer B1.

3.5.2 Reset Circuit

A manual push to make reset switch S10 is provided on the operator panel (Figure 3.17). This allows the operator to randomly change a test stimuli and intervene in a dark adaptation test procedure.

3.6 Conclusion

The circuits presented in this Chapter were constructed, tested and debugged prior to the commencement of clinical trials. In the next Chapter details are provided on the commissioning the Concept Prototype Adaptometer and Calibration considerations.


4. Commissioning of the Concept Prototype Adaptometer – Methodology, Protocols and First Dark Adaptation Results

4.1 Introduction

To assess the performance of the newly designed and constructed Concept Prototype Adaptometer (described in Chapters 2 & 3) a thorough evaluation on subjects with normal eyes was planned and implemented, the results of which are presented in this and subsequent chapters. Prior to the presentation and discussion of these results, the methodologies employed and followed in the evaluation phase must first be discussed, with details concerning testing procedures and methods, volunteer subject selection, and subject instructions. The testing procedures set out below were rigorously adhered to in all dark adaptation investigations throughout the evaluation process. The initial commissioning of the CPA is also discussed in this chapter, including calibration considerations and the very first dark adaptation results obtained using the new CPA.

4.2 Volunteer Subject Selection

A pool of test volunteers was established comprising individuals willing to act as test subjects and undergo night vision investigation using the CPA. These test subjects were sourced primarily from undergraduate and postgraduate students; secretarial staff; technical and academic staff within the Faculty of Science, Dublin Institute of
Technology. The most numerous and willing subjects tended to be undergraduate and postgraduate students; consequently, there is a disproportionate number of younger subjects reported in the evaluation process. Simple biographical data were recorded for each subject including name, gender, age, occupation, vision problems (if any) and a brief history of any diagnosed ocular diseases or health problems (see biographical questionnaire Appendix 8). Besides asking nominally healthy subjects to participate in the evaluation process, all subjects were otherwise unselected for testing on the CPA. It should be noted that a full ophthalmic examination was performed on a separate pool of volunteer subjects tested on the Automatic Dark Adaptometer - the ADA is a refined version of the CPA which is discussed later in (Chapter 7, 8 and 9). Permission for the evaluation of the CPA and ADA outlined above was obtained from the DIT Ethics Committee. All subjects gave written consent.

4.3 Testing Procedures and Instructions:

All dark adaptation examinations were managed and carried out by the author who was located outside the light proof examination room. Prior to the commencement of a dark adaptation examination, each volunteer subject was informed that the test was typically 35 minutes long, was non-invasive and would not cause any discomfort and was completely safe. The test procedure was explained in detail, including the fact that the test is carried out in complete darkness. The subject was informed that they would be exposed to a pre-adaptation bleaching light. Thereafter they were instructed to fixate on a small dimly lit red LED and wait until one of four test lights randomly became visible to them, at which point they were to gently depress the now visible light stimulus. Following this they were informed a new stimulus is randomly presented in 1 of 4 positions but at a reduced brightness: the subject was informed
that this process is repeated over 16 successively diminishing brightness levels. It was explained that a correct choice generates a positive audible sound (single beep), whereas an incorrect choice would illicit a negative (double beep). All subjects were informed that if they made two consecutive incorrect choices then the unit randomly selects a new array and that if a third incorrect choice is made then the examination would be terminated with the subject receiving additional instructions. The subject was instructed that it was not a competitive test and was advised to remain patient and not to guess. The importance of maintaining fixation continuously was also emphasized.

The operator subsequently performed a trial run through the test procedure in semi-darkness and once it was clear the subject understood what was required of them the actual test proceeded.

Each subject was seated and positioned comfortably in front of the pre-adapting integrating sphere. An integrating sphere pictured in Figure 1.2 is a hollow cavity whose interior is coated white for high diffuse reflectivity; multiple scattering reflections ensure a uniform distribution of light when viewed by a subject. The left eye was occluded using an ophthalmic eye patch so that the right eye was exposed to the bleach light and dark adaptation test; only the right eye of volunteers was examined. Kelsey and Arden\(^1\) reported that out of 2000 normal patients only two adults had unilateral loss of dark adaptation, consequently dark adaptation testing of either eye is valid as the vast majority of patient cases possess corresponding bilateral loss of adaptation.\(^1\), however, small inter ocular differences in dark adaptation may be more common.
It was the operator's function to ensure that each test subject did not close their eye during the pre-adaptation bleach and to ensure that their head was in the correct location by the appropriate use of the chin rest. At the end of the 2-minute pre-adaptation bleach period, the 1500mL bleach light was extinguished as were the lights in the investigation room and the procedure for measuring thresholds immediately commenced. At the end of the test, the operator stored all test and biographical data obtained on each subject.

4.4 Photo-detector Calibration

Stimulus intensities were measured throughout the evaluation phase of the study using a calibrated United Detector Technology, Model 40X integrating Opto-meter (UDT 40X) equipped with a photometric filter\(^2\), which gives a matched response of the eye to light as wavelength varies.

![Photo-detector Calibration Diagram](image)

*Figure 4.1. Silicon Photodetector with photometric filter which is connected to the 40X Opto-meter input.*

*Figure 4.2. The United Detector Technology, Model 40X Opto-meter\(^1\). Units Cdm\(^2\).*
The UDT 40X photometer gives excellent light precision over a wide luminance range with analogue readout. Doped silicon photodiodes are the most versatile and reliable sensors available comprising a P-layer material at the light sensitive surface and the N material at the substrate forming a P-N junction which operates as a photoelectric converter, generating a current that is proportional to the incident light. Silicon cells operate linearly over a ten decade dynamic range, and remain true to their original calibration longer than any other type of sensor\(^3\).

4.4.1 Calibration Methods

In both the CPA and ADA all test stimuli used were sourced directly from a single company, Three-Five Systems, Incorporated (USA), with the prerequisite that the manufacture batch numbers were the same to ensure operational uniformity in luminance output (see Appendix 4).

Test stimuli were calibrated in situ within the actual working circuitry over the full dynamic luminance range provided by the circuitry\(^4\). This was achieved using an ambient light suppression box, (painted matt black) which was constructed to snugly fit over each test stimulus and completely removed unwanted background light to allow only the desired LED light reach the detector. The photodetector head was fitted into an opening in the ambient suppression shade. The area of the light sensitive doped silicon of the photodetector was matched to the emitting area of the test stimulus by the use of a light mask placed over the LED array, thus ensuring equivalence in the respective emitting and detection areas - thereby efficiently coupling light into the detector (see Figure 4.3). Light from individual LEDs is emitted in the forward direction (Appendix 4) and does not significantly expand and will fall within the active area of the detector. The starting luminance of each of the
four test stimuli were carefully matched by making small adjustments to trimmer resistors (in the CPA) these were TR5, TR6, TR7 and TR8 (see Section 3.3.4) and by measuring the luminance using the UDT 40X Opto-meter.

In order to simplify the calibration process, the actual starting luminance, in both the CPA and ADA were set substantially above that desired; this was done for several reasons (i) at higher luminance the precision of the detector is optimised (ii) errors attributable to ambient light was reduced (iii) it was possible for the author to see the dynamic luminance and make appropriate adjustments/measurements (iv) adequate current (mA) was supplied to the LEDs over the whole required dynamic luminance range. Thus, it was necessary to reduce the starting luminance to that appropriate in dark adaptation measurements by using Neutral Density (ND) filters to attenuate the light. The ND filters were secured to each LED test stimulus.

Neutral density filters reduce the transmission light of all wavelengths equally and are rated using a logarithmic index; combinations of ND filters are thus additive Table 4.1.

<table>
<thead>
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<th>ND</th>
<th>Transmission Percent</th>
<th>Attenuation factor α</th>
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</thead>
<tbody>
<tr>
<td>0.1</td>
<td>80%</td>
<td>1.26</td>
</tr>
<tr>
<td>0.2</td>
<td>63%</td>
<td>1.58</td>
</tr>
<tr>
<td>0.3</td>
<td>50%</td>
<td>2.00</td>
</tr>
<tr>
<td>0.4</td>
<td>40%</td>
<td>2.51</td>
</tr>
<tr>
<td>0.5</td>
<td>32%</td>
<td>3.16</td>
</tr>
<tr>
<td>0.6</td>
<td>25%</td>
<td>4.00</td>
</tr>
<tr>
<td>1.0</td>
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<td>10</td>
</tr>
<tr>
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</tr>
<tr>
<td>3.0</td>
<td>0.1%</td>
<td>1000</td>
</tr>
</tbody>
</table>

*Table 4.1. Neutral Density Index and associated transmission and attenuation factor. Not allowing for reflection at each surface, Fresnel reflectance is approximately 2% (n = 1.5) at each surface. α = \text{antilog}_{10} ND ; t = (\text{antilog}_{10} ND)^4.*
In the CPA an ND = 2.5 was used which attenuated the light by a factor of 316.22 thus the light transmission was reduced to 0.316%, (while in the ADA an ND filter = 2.0 was used). Using these ND filters, the initial starting luminance presented by both the CPA and ADA was calculated $\log_{10} 4.8 \mu \text{cd.m}^{-2}$ which converts to $\log_{10} 7.3 \ \mu \text{L}$. A similar suitable luminance scale was also determined for the GWA. (Note: $1 \text{L} = \frac{10^4}{\pi} \ \text{cd.m}^{-2}$).

![Diagram](image)

Figure 4.3. Calibration procedure involved lowering the Ambient Light shade over the each LED test stimulus with the Light Mask in place. Once the desired starting luminance was achieved using circuit trimmer resistors, the shade and mask were removed and Neutral Density filters inserted and firmly attached to the LED array. Luminance was normalised for full array. See text.

The LED matrices were regularly checked throughout the evaluation period (months) and the calibration did not change more than an estimated 2% over that time.

### 4.5 Luminance Thresholds/Levels and Pre-adaptation Light

As described previously, the circuitry for the CPA provided for 16 discrete luminance levels with each level exactly half the preceding one, yielding a dynamic luminance range of $2^{15}$, representing a ratio of 32768:1 between the brightest and dimmest light.
levels; as a consequence, dark adaptation are normally plotted on a logarithmic scale, thus the luminance range presented by the CPA spans \(4.51 \log_{10}\) units of intensity. The maximum initial luminance is referred to here as level 16 which equates to \(\log_{10} 7.3 \mu\text{L}\) (\(\log_{10} 4.8 \mu\text{cd.m}^{-2}\)) while the dimmest is Level 1, equating to \(\log_{10} 2.8 \mu\text{L}\) (\(\log_{10} 2.8 \mu\text{cd.m}^{-2}\)). Starting at luminance level 16, the associated luminance is halving from one level to the next representing a 0.3 \(\log_{10}\) log brightness decrement between adjacent luminance thresholds. For example, decreasing the luminance level from 16 – 3 = 13 levels, which equals 13 \(\times\) 0.3 \(\log = 3.9\log\) or \(10^{3.9} = 7943\); thus the ratio of the luminance is reduced by a factor of 7943.

The calibrated luminance thresholds and levels presented to each subject are summarized in Table 4.2 which also shows the corresponding non-SI and SI luminance units, micro-micro-Lamberts (\(\mu\text{L}\)) and micro-candela (\(\mu\text{cd.m}^{-2}\)) respectively. Throughout this thesis the non-SI unit, \(\mu\text{Lambert}\), is used, the rationale being that it allows for an easier comparison between the CPA and landmark published results.

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>Threshold Luminance Log_{10} \mu\text{L}</th>
<th>Luminance Log_{10} \mu\text{cd.m}^{-2}</th>
<th>LEVEL</th>
<th>Threshold Luminance Log_{10} \mu\text{L}</th>
<th>Luminance Log_{10} \mu\text{cd.m}^{-2}</th>
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<td>2.7</td>
<td>1</td>
<td>2.8</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 4.2: Luminance threshold readings in SI and non-SI unit for each of the 16 luminance levels presented by the CPA. Level 16 is the brightest and Level 1 the dimmest.
The strength and duration of the pre-adaptation bleach light was an important consideration in this study, particularly when testing children; thus in order to help prevent boredom in children (and adults) a pre-adaptation luminance of 1500 mL (4774.6 cd m\(^{-2}\)) of 2-minutes duration was chosen, which minimized the time-taken to reach the cone-rod transition without interfering with resolution of the cone-rod break\(^{(5,6,7,8,9)}\); thus the appearance of the cone-rod break is expected to appear earlier in results than would otherwise be the case with higher luminances’ (see Section 1.4.1). During the initial commissioning of the CPA it was observed that subjects got bored and restless towards the end of the dark adaptation test consequently it was decided to terminate all tests at 30 minutes (~2000 seconds).

## 4.7 Commissioning of the CPA

A single healthy volunteer subject agreed to act as guinea pig in the commissioning of the CPA. The commissioning phase, it was hoped would elicit good adaptation curves and highlight any problems such as calibration errors or circuitry problems prior to the commencement of the clinical study phase.

It is worthwhile commenting at this point on the differences in the type of dark adaptation data obtained using traditional adaptometers (e.g. Goldmann Weeker adaptometer) and the CPA. In traditional adaptometers, luminance is the independent variable with time the fixed variable, in contrast, the reverse process is employed in the CPA, i.e. time is the independent variable and luminance the dependent variable. It is consequently problematic to directly compare the data from the CPA and published results. Thus in describing the results obtained using the CPA, comparisons will be required and made using variation in luminance (± mean luminance) and not just time (± mean time).
4.7.1 Commissioning Results - Subject 1

Subject 1 was a 28 year old healthy male whose dark adaptation was examined on 12 separate occasions spanning a three week period. The results obtained are shown in Figure 4.5 with the luminance threshold \((\log_{10} \mu \mu L \text{ and } \mu \text{cdm}^{-2})\) along the ordinate plotted against time (seconds) on the abscissa which is the standard method used to present dark adaptation data. Also shown on a separate axis to the right of the graph are 16 discrete luminance levels numbered 16 down to 1. The graph shows the 12 individual test results plotted as scatter points with specific colours (and particular identifying symbol, e.g. triangle) representing each individual examination. The mean time of the repeat tests for each luminance threshold was calculated and is plotted with associated standard deviation bars \(\sigma_x\) (error bars) for each luminance threshold. A spline curve, coloured red, is shown which draws the best fit line through the arithmetic mean times for each luminance level obtained for the 12 examinations. However, where feasible exponential curves are presented which give a very good approximation to the dark adaptation curves that would be expected from a skilled human interpretation of the test mean times. Both the spline and \(e^{-x}\) curves where calculated from Sigmaplot\(^{(10)}\) the graphing software used throughout this thesis. The spline function is calculated from a cubic polynomial interpolation to achieve the best fit curve to complex shapes.

Subject 1 was also examined once using the benchmark standard Goldmann Weeker Adaptometer under near identical testing conditions; the Goldmann Weekers Adaptometer test result are superimposed on Figure 4.5 and is coloured purple. The starting luminance of the GWA and CPA was adjusted to 7.3 \(\mu \mu L\). Double exponential curve fitting was used where spline fitting exhibits erratic behaviour in individual subject results.

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Figure 4.5. Dark Adaptation curve luminance/log₁₀ µL against time/sec. Repeat test results obtained over a 3 week period on Subject 1. The spline curve, coloured red is plotted through the mean times at each luminance level; ± one σₐ error bars (standard deviation) are shown. The purple line is the exponential dark adaptation curve obtained separately on this subject using the Goldmann Weekers adaptometer. Subject 1 attained luminance level 6 only once hence there is no corresponding error bar. As previously mentioned earlier, the y error is small at 2%. Starting luminance of the GWA and CPA were the identical.

The main finding or conclusion that may be drawn from the analysis of the data in Figure 4.5 is the clearly obvious elevation of thresholds throughout the rod phase of the dark adaptation curve obtained using the CPA, this is particularly evident when compared to the GWA curve; the CPA covers a luminance range of approximately log₁₀ 1.5 µL compared to log₁₀ 2.3 µL for the GWA. The shape of the dark adaptation curve obtained using the CPA does not correspond to the normal rod exponential decay curve that is to be expected. It is quite evident that from this simple comparison of the CPA and GWA test results that new adaptometer test results are not that expected. Upon investigation, the poor performance of the CPA was found to be attributable to an overlooked construction error, specifically the location of the
chin rest (and therefore viewing distance), which was found to be too long with the result that the eccentricity of the fixation and target stimuli were incorrect; thus the cones, as opposed to the rod photoreceptors, were being disproportionately stimulated as the incorrect location on the retina was examined. This problem was easily corrected with Subject 1 being retested with the correct viewing distance and corresponding fixation eccentricity.

4.7.2 Re-examination of Subject 1

The new sets of results obtained on Subject 1 using the CPA (complete with modifications) are tabularised in Table 4.3, which shows the adaptation times corresponding to each of the 16 luminance levels recorded over 8 repeated examinations made over a two week period; in addition the calculated mean threshold times and associated standard deviations are shown. Table 4.3 test results are graphed in Figure 4.6 which features a plot of luminance threshold (log_{10} \mu L) against time (seconds). Figure 4.6 shows (i) a scatter plot of the 8 examinations which are identified by a defining data point colour and shape, (ii) double decreasing exponential curves through the calculated threshold mean times (iii) ± standard deviations bars associated with the calculated mean times and (iv) superimposed result obtained on Subject 1 using the Goldmann Weekers adaptometer. Consideration of both the individual scatter plots shows that the dark adaptation curves more clearly matches GWA norms, for example the decreasing exponential cone phase has a depth of 1.0 log_{10} unit of luminance while the rod luminance depth extends over 2.5 log_{10} units: a marked improvement compared to Figure 4.5.
Subject 1 Test Results.

<table>
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<th>Mean -SD</th>
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</table>

Table 4.3. Tabulated results obtained on Subject I with modification to chin rest location. The Luminance Thresholds are shown along with the corresponding Luminance Levels. The recorded threshold times for each of the eight examinations are presented with the calculated mean times and standard deviations at each Luminance Threshold. The mean times plus and minus the standard deviation is shown. The count represents the observation frequency made by Subject I at each threshold.
Figure 4.6. Subject 1 was re-examined with modifications made to the CPA. Subject 1 was retested again 8 times over a two week period. The GWA curve is shown in purple. The mean times are shown in black with double decreasing exponential curves shown in blue. The error bars indicate ± one σ. The rod luminance depth is also highlighted. Starting luminance of the GWA and CPA were the identical.

The cone rod transition occurs at about 200 seconds (3½ mins) and is readily identifiable. The time course of the rod phase extends over a period of approximately 1000 seconds (17 mins) and has a decidedly decreasing exponential shape of the form \( L = e^{a+bt} + C \) (11), (where \( L \) is \( \log_{10} \mu\mu L \), where \( t \) is in minutes and \( C \) represents the final threshold time). Subject 1 adapted to luminance level 3 but not below during the repeat examinations.

Because the dark adaptation curve is asymptotic near absolute threshold, several hours could pass before luminance level 2 becomes visible, thus luminance level 3
while not necessarily representing the subject's absolute threshold, it is within 0.3 log units of it.

As previously stated, comparing the CPA with traditional adaptometers is problematic, thus in the course of presenting and discussing dark adaptation test results throughout this thesis, reference will be made not only to the variation in adaptation times but also to variations in luminance.

Figure 4.6 shows that the calculated mean times and standard deviations increases from about 210 seconds (3.5 mins) to 1200 seconds (20 mins) near absolute threshold is; there is a noticeable increased scatter of the data near final threshold which is to be expected. In terms of luminance variation (as opposed to time) the maximum/minimum luminance range is about 0.3 log units during the photopic phase, representing approximately ± 0.15 log units about (above and below) the mean. The luminance variation is about 0.8 log units throughout the scotopic phase or approximately ± 0.4 log units about the mean value at rod threshold.

Figure 4.7 below shows the comparison between the erroneous data from Figure 4.5 (First Data Set) and the correct modified data obtained by relocation of chin rest in Figure 4.6 (Second Data Set); it is obvious that the second data set represents a marked improvement in performance clearly identifying the cone-rod break and exponential decay to absolute threshold. Also superimposed in Figure 4.7 are two dark adaptation curves obtained on two individuals (plotted in orange and green ) that were reported by Hecht, Haig and Chase\(^{(12)}\) and obtained using the Hecht-Schlaer adaptometer (pre adaptation 1950mL for four minutes).
There are strong similarities between the second data set (Subject 1) obtained using the CPA and the two superimposed curves published by Hecht et al., (starting intensity about 7.2μL); particularly noticeable is the strong visual correlation between the 2nd data set and those reported by Hecht et al. The observed difference in the cone phase is as a direct consequence of differences in the duration and intensity of the pre-adaptation bleach intensity (see Section 1.4.6).
4.8 Conclusion

The test results obtained on Subject 1 suggest that the CPA possesses the accuracy and dynamic luminance range to successfully obtain reliable and reproducible dark adaptation curves. The following Chapters report more on detailed clinical evaluation of the CPA.


5. Evaluation of the Concept Prototype Adaptometer

5.1 Introduction

Following preliminary volunteer screening as described in Chapter 4, 21 healthy volunteer subjects were invited to participate in the clinical study devised to evaluate the performance of the Concept Prototype Adaptometer; where possible, all individuals were retested, under identical conditions, over a period of several months. The results presented and discussed in this Chapter provided details on the variability of single-subject dark adaptation performance and the variability in performance between unrelated subjects.

Several important questions needed to be addressed and answered by this study, specifically (i) can the CPA obtain consistent and reproducible test results (ii) does the observed normal day to day single-subject performance agree with established norms (iii) does the observed multi-subject performance among unrelated individuals agree with established norms (iv) what is the Pearson correlation and significance level between the CPA test results and published individual/group test results (v) what is the repeatability and precision using Bland and Altman analysis and (vi) is it possible to identify age related changes in dark adaptation performance. These questions will be addressed presently.

The testing procedures outlined in this Chapter were adhered to in the subsequent clinical investigations that are reported in later Chapters unless stated otherwise.
5.2 Subject Details

In this study, the CPA performed 60 individual dark adaptation tests on 21 volunteer individuals, of which 14 were male and 7 female. Of the 21 healthy individuals, 8 individuals volunteered once for examination before absconding, while 13 individuals agreed to up to five repeat examinations over an eleven month period. The age range of subjects extended from 8 years to 49 years. The testing methods and protocols were previously described in Chapter 4.

5.3 Repeat Examinations Results

In this section, dark adaptation test data is presented and discussed on individual subjects that were examined several times over a period of months. Those subjects that were examined only once are considered in Section 5.4. Two case studies are presented below that are typical of the 13 subjects that undertook multiple dark adaptation examinations; the inclusion of Subjects 10 and Subject 3 here is an arbitrary choice, as both subjects are representative of the study group; the 11 other multi test subjects and their results are presented in Section 5.3.1.

Case Study 1
Subject 10 was a healthy 22 year old male subject, with no prior dark adaptation testing experience who was examined 5 times over a two month period under identical test conditions. The dark adaptation curve in Figure 5.1 below shows a scatter plot of the 5 tests examinations alongside the calculated mean times with exponential DA curve and standard deviations error bars. The close grouping of retest data (in terms of time) as indicated by the small standard deviation about the mean
time suggest a close correlation between the 5 examinations over the 2 months testing period.

A number of observations may be made in relation to Subject 10: the transition between photopic and scotopic vision is evident at about 200 seconds (3.3 mins) for all 5 tests. The rod luminance depth phase is estimated at 2 log units of luminance. The variation in luminance between 400 seconds (6.6 mins) and 600 seconds (10 mins) is about 0.6 log units of luminance or ± 0.3 log units about the mean; beyond 600 seconds (10 mins) the variation in luminance decreases towards absolute rod threshold. It should be noted that as absolute threshold is approached, it is observed that the standard deviations (time) increases to a maximum at luminance level 6. This wide variance is attributed to the subject nearing the asymptote of the decay curve. A smaller variance is observed at the lower luminance level 5, which is explained by the fact that the subject reached this lower luminance on only two of the five repeat examinations.
The degree to which Subject 10's retest dark adaptation thresholds were reproducible was determined by calculating the inter-correlations between retest data, using Pearson's correlation coefficient, which yielded a 5 by 5 correlation matrix. To illustrate, the test data obtained on the 1st examination was plotted against the data set for the 2nd examination (for all determined luminance thresholds) and the Pearson correlation found. The first examination was then correlated with the third examination and so on.

You can see the relevant graph in Figure 5.2 below showing a plot of the test times obtained in the 1st examination against the 5th examination test times (arbitrary...
choice) which shows the resulting regression line and 95% confidence limits. The number of discrete threshold points in Figure 5.2 was $N = 11$ which yielded a Pearson correlation coefficient $r = 0.98$ with significance level $\alpha < 0.05\%$. A summary of the inter-correlations are presented in Table 5.1, which shows the 5 by 5 correlation matrix and significance levels for all five test examinations obtained on Subject 10.

The strong reproducibility of the test results obtained using the CPA is demonstrated in Table 5.1 which shows that each examination is closely correlated with the other 4, for example, the lowest correlation is 0.89 ($\alpha < 0.05\%, N=11$) while the highest is 0.98 ($\alpha < 0.05\%, N=11$). The average of all the correlations in Table 5.1 were found yielding, $<r_t> = 0.95$ (where $<r_t>$ = an author defined number which is generated by finding the average of all 10 Pearson correlations) this parameter, "$<r_t>$" will be used to compare the results obtained on Subjects 10 with all other volunteer test results. A more detailed analysis on Subject 10 and 3 using Bland Altman is provided later.
Figure 5.2. Regression line with 95% confidence limits, showing the adaptation threshold times obtained using the Concept Adaptometer for the first and fifth examinations obtained on Subject 10. The difference in luminance between adjacent data points is 0.3 log units. The single data point outside the 95% confidence limit at 255 seconds (x axis) corresponds to the cone-rod break. The Pearson correlation is $r = 0.98$ with $\alpha < 0.05\%$, and $N = 11$.

Table 5.1. Inter-correlation matrix ($5 \times 5$) showing Pearson correlations $r$ and number $N$ (brackets) obtained on 5 repeat examinations; in all cases the $\alpha < 0.05\%$. The Pearson's correlations were determined using SigmaPlot software. The numerical average of all the correlations was $<r> = 0.95$. The data point in Column 5 - Row 1 is coloured red as it is the Pearson Correlation determined in Figure 5.2 above. The sum of $N = 125$. 

<table>
<thead>
<tr>
<th>TEST</th>
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<th>4</th>
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<td>$r$ (N)</td>
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<td>$&lt;r&gt; = 0.95$</td>
</tr>
</tbody>
</table>

The data point in Column 5 - Row 1 is coloured red as it is the Pearson Correlation determined in Figure 5.2 above. The sum of $N = 125$. 

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To obtain a quantitative assessment of the entirety of all 10 correlations presented in Table 5.1 and to arrive at some gross "average" single correlation figure for Subject 10, a parameter termed "<r~>" was used; where <r~> is the average Pearson correlation that was generated by analysis of all 10 possible inter-correlations (at each luminance level). The <r~> group correlation figure will be used to compare the totality of test results obtained on Subject 10, with all other multi-test subjects in order to assist in assessing the reproducibility of the CPA.

Recall in Figure 5.2 that examination 1 was plotted against examination 5, now the <r~> was calculated by including all examinations in a single graph; for example examination 1 is plotted against examinations 2, 3, 4; then examination 2 against examinations 3, 4, 5 and so on. In this way a single unifying picture emerges that provides a single snap-shot of the totality of Subject 10's overall/gross performance. Such analysis on Subject 10 is presented in Figure 5.3. The single Pearson correlations for N = 125 points was calculated, <r~> = 0.86, a <0.05%. It should be noted that Figure 5.3 is presented as a log/log plot to help in the discrimination of the data.
Figure 5.3. Inter-relationship between all examination data obtained on Subject 10. The log/log plot is used simply to aid discrimination of the times data. The correlation was determined using non-log data calculations. $<r_0> = 0.86$, $\alpha < 0.05\%$, $N=125$.

The dark adaptation curves and high correlations $r$, $<r>$ and $<r_0>$ and significance levels presented here indicate the CPA has the ability to reproduce consistent and reliable dark adaptation curves measured over a 2 month period as demonstrated by Subject 10.

$r$ = single correlation value (Figure 5.2) with significance level
$<r>$ = numerical average of correlation matrix table (see Table 5.1). No significance level
$<r_0>$ = group inter correlation number for all discrete data points (Figure 5.3) with significance level
Case Study 2
Presented in Figure 5.4 below are the results obtained on Subject 3, a 40 year old male in good health, who was tested four times over a 5 month interval with CPA and once with the GWA. (Calibration of the GWA is discussed in Section 9.1.2). A classic dark adaptation is evident from the scatter plots and exponential curve of the mean times.

Figure 5.4. Subject 3 was retested 4 times over a five month period. The 4 examinations are plotted as scatter plot, the means times and standard deviations and exponential curve are presented. Note the classic dark adaptation and cone rod break. The continuous purple line is the dark adaptation curve obtained using the Goldmann Weekers Adaptometer; the GWA data was normalised and superimposed onto the CPA data. The starting luminance of the GWA and CPA were identical.

From Figure 5.4 it is evident that all four tests show an asymptotic cone phase which identifies the cone-rod break at about 400 seconds (6.6 mins). The rapid onset of the rod phase is characterized by a decreasing decay curve that takes about 800 seconds (about 13 mins) to reach final threshold. The rod luminance depth extends over a luminance range of about 2.2 log units of luminance.
It can be seen that variation in time to reach cone-rod break on the CPA is equivalent to the variation in luminance of 0.6 log units of luminance or ± 0.3 log units about the mean. Toward the final rod threshold the variation decreases to ± 0.15 log units (it should be recalled that the luminance standard deviation in time increases approaching the asymptote of the decay). Subject 3 was also tested using the Goldmann Weekers Adaptometer (GWA) under the same test conditions with the same initial starting luminance; the GWA test data was normalized/rescaled and superimposed on Figure 5.4 as a continuous purple curve. While the final rod thresholds are identical using both instruments, it is interesting to note that in this instance the CPA data provides a more clearly identifiable cone-rod break which is absent in GWA curve.

Figure 5.5 below shows a plot of the 3rd and 4th examination times (arbitrary choice) with the regression line and 95% confidence limits. The number of discrete threshold data points presented in Figure 5.5 was N = 12 which yielded a Pearson correlation coefficient \( r = 0.99 \) with significance level \( \alpha < 0.05\% \). The 4 by 4 correlation matrix in Table 5.2, shows correlation “r” values for all 4 examinations which yielded \( \alpha < 0.05\% \) in all cases: the lowest correlation was 0.95, \( \alpha < 0.05\% \), N=11 while the highest was 0.99, \( \alpha < 0.05\% \), N=12. The average of the 6 correlations were calculated, yielding \( \langle r \rangle = 0.97 \), which indicates significant reproducibility of the set data measured over a 5 month period on this subject.
Figure 5.5. Adaptation threshold times obtained using the CPA showing the third and fourth examinations obtained on Subject 3. The difference in luminance between adjacent data points is 0.3 log units for each of the 12 data points. The interval between 60 and 410 seconds corresponds to the cone-rod break: $r = 0.99$ with $\alpha < 0.05\%$, $N=12$.

<table>
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<td>$r$ (N)</td>
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</tr>
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<td>0.96 (11)</td>
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</tr>
<tr>
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<td>0.99 (12)</td>
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<tr>
<td>3</td>
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<td>0.99 (12)</td>
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</tr>
<tr>
<td>4</td>
<td></td>
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</tr>
</tbody>
</table>

$\langle r \rangle = 0.97$

Table 5.2. Subject 3 inter-correlation matrix (4x4) obtained on 4 repeat examinations. In all cases $\alpha < 0.05\%$. The Pearson's correlations were determined using Signaplot. The average of the correlations was $\langle r \rangle = 0.97$. Column 4 Row 3 is coloured red as it is the Pearson correlation determined in Figure 5.5 above. The sum of $N = 69$. 

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The group inter-correlation $<r_\phi>$ was also determined as before on Subject 10. Analysis shows that for Subject 3, $N = 69$, $<r_\phi> = 0.91$, $\alpha < 0.05\%$. These correlations are highly significant and indicate the similarity in repeated dark adaptation times; a similarity that was unlikely to have occurred by chance. The $r$, $<r_\gamma>$ and $<r_\phi>$ correlations determined on Subject 3 suggests significant reproducibility of the result data which was obtained over many months using the CPA. These results agree with the findings reported earlier on Subject 10.

**Bland Altman Analysis**

High correlation and significance levels (e.g. $r = .98$, $\alpha < 0.05\%$) as previously discussed in Case 1 (Subject 10) and 2 (Subject 3) indicate a reasonability probability that the test/retest results are indeed related, however, this does not necessarily mean that the results are in agreement and repeatable. Thus high correlations do not automatically imply a good agreement between test/repeat results or good agreement between two test methods; Bland and Altman state “a high correlation for any two test methods designed to measure the same property in itself may be just a sign that one has chosen a wide spread sample”(1).

An improved method to assessment the agreement between CPA test/retest results, may be found using a Bland and Altman plot(2), where a scatter graph is used to display the differences in two measurement against (ordinate) plotted against the averages (abscissa ) of the two measurements. In addition to the scatter plot, horizontal lines are drawn to identify the mean difference and the limits of agreement, which is defined as the mean difference plus and minus 1.96 times the standard deviation of the differences (95 % confidence limits).
Assuming the mean difference is zero or near zero, it is expected that 95% of differences will be less than two standard deviations of the mean difference, which is the definition of the repeatability used by the British Standards Institution. Thus an assessment of the repeatability of CPA may be found using the Coefficient of Repeatability (CR) which is calculated as 1.96 (or 2) times the standard deviations of the differences between the two measurements ($d_2$ and $d_1$). Thus good repeatability is demonstrated when then the majority of scatter points in a Bland Altman plot lie within the 95% confidence limits.

An assessment of the repeatability of the CPA on Subject 10 and Subject 3 using Bland Altman methods is described below. Subject 10 under went 5 examinations giving 10 data points for compassion at each luminance level. A Bland Altman plot of Subject 10's test/retest results is shown in Figure 5.5.1; the difference in the test/retest times obtained at luminance level 8 is plotted against the mean times.

It can be seen from Figure 5.5.1 that all test/retest data points all lie within 95% confidence limits; that is all data lies between +105 and -72 seconds, as the coefficient of repeatability $CR = 94$ is seconds. Thus there is good agreement between test and retest results. It is evident that at luminance level 8 there is a mean difference or bias of 20 second which may be accounted for by the subtleties of psychophysical dark adaptation measurement; for example unexpected differences in the degree of light adaptation between tests. The observed bias is shown to vary at other luminance levels also, as can be seen in Table 5.2.1; the bias is observed to increase at the cone rod break and towards final rod threshold which is to be expected. The distribution of data in Figure 5.5.1 shows that random errors are well distributed about the mean with no data outliers beyond the 95% confidence limits.
Subject 10, Luminance Level 8

Figure 5.5.1. Bland Altman plot at luminance level 8, showing the difference in test/retest times against the mean of the times obtained on Subject 10. The mean difference or bias is 20 seconds and is identified by the blue line; the 95% and 65% confidence limits are shown in red and green respectively. Between the red lines, i.e. between $\bar{x} \pm 2\sigma$, 95% of the differences will lie within these limits for a normal distribution and indicate good repeatability of test data.

The coefficient of repeatability on both Subject 10 and 3 was calculated for all luminance levels and is shown in Table 5.2.1; it was found that for all luminance levels test/retest results lie within the 95% confidence limits thus demonstrating good agreement between test/retest data. It should be mentioned that the expectation is that the mean difference should approach zero as the number test/retest results increases.

Subject 3 underwent 4 examinations giving 6 data points for compassion at each luminance level. A Bland Altman plot on this subject is shown in Figure 5.5.2 at luminance level 8. It can be seen that all test retest data points all lie within 95%
confidence limits, with the coefficient of repeatability $CV = 70$ seconds. Thus all data lie between $+70$ and $-72$ seconds, demonstrating good agreement between test and retest results. The mean difference or bias in test retest data was found to be $-2.5$ seconds. The distribution of data in Figure 5.5.2 shows that the majority of the data lie within one standard deviation (or less) of the mean difference with no outliers beyond the 95% confidence limits.

![Bland Altman plot at luminance level 8](image)

*Figure 5.5.2. Bland Altman plot at luminance level 8, the difference in test retest times are plotted against the mean of the times obtained on Subject 3. The mean difference or bias is 2.5 seconds and is identified by the blue line; the 95% and 65% confidence limits are shown in red and green respectively. Between the red lines, i.e. between $\bar{x} \pm 2\sigma$, 95% of the differences will lie within these limits for a normal distribution. Excellent repeatability is demonstrated by this subject.*

From Table 5.2.1 below, it is evident that Subject 3’s test/retest results demonstrate excellent repeatability of test data obtained on this subject compared to Subject 10; which confirms our earlier analysis using correlation and significance levels. Both these subjects demonstrate good repeatability of test data obtained on the CPA.
Table 5.2.1. The sum of the mean differences at each luminance level is shown for Subject 10 and Subject 3. The Bland Altman plot shown in Figures 5.5.1 and 5.5.2 were obtained at luminance level 8, which is highlighted in red. These results indicate good repeatability of the test data on both subjects.

Repeated dark adaptation curves on the remaining 11 multi-test subjects are presented in the following pages; included is a brief description of the important observations that can be made on each subject. The results were sorted so that younger subjects are presented first. The Figures presented include; (i) scatter plots of test results, (ii) mean times, spline and e\(^x\) curves, (iii) standard deviation, (iv) Pearson correlation values \(<r_c>\) and \(<r_p>\) and significance values, (vi) superimposed Goldmann Weekers Adaptometer curves where determined. The inclusion of all these retest results, highlights the observed functionality of the CPA on multiple subjects each with repeated testing.
5.3.1 Individual Retest Graphs

Figure 5.6. Subject 9 was tested 5 times over a 4 month period. Despite a relatively wide variance in the data about the mean time, the data shows an individual with excellent dark adaptation, this subject attained Luminance Level 3 on 4 out of 5 examinations, the depth of rod adaptation is estimated at over 2.5 log unit of luminance. The variation in luminance throughout the rod phase is about 0.6 log or ± 0.3 log unit of luminance about the mean. The standard deviation in time increases slightly towards absolute threshold. A single dark adaptation curve obtained using the GWA obtained under identical conditions, compared well with the averaged times obtained with the CPA data.

$<r_t> = 0.91; \quad <r_d> = 0.90, \quad \alpha < 0.05\%, \quad N = 125.$

Figure 5.7. Subject 11 was tested 3 times over a 3 day interval. The cone-rod break occurs about 300 seconds (5 mins) at which the variation in luminance is 0.7 log units or ± 0.35 log units about the mean. The rod adaptation depth is about 2.0 log units. A single result obtained on the GWA is shown as a purple curve and closely correlates with the averaged times obtained with the CPA data.

$<r_t> = 0.93; \quad <r_d> = 0.84, \quad \alpha < 0.05\%, \quad N = 42.$
Figure 5.8. Subject 12 was tested 4 times over a 4 month period, and displays a nice consistent set of results with a small variation at each Luminance Level with corresponding small standard deviations in time, save Level 4 near the curve asymptote. The cone-rod break is just discernable at 400 seconds (6.6 mins), with the rod luminance depth of about 2.2 log units. The luminance variation at the commencement of the rod phase is about 0.5 log units or ± 0.25 log units above the mean; this variation decreases to about 0.3 log units or ± 0.15 log units approaching absolute threshold. Luminance Level 3 number was the lowest achieved.

\(<\bar{c}_t> = 0.96; \ <\bar{c}_q> = 0.88, \alpha < 0.05\%, \ N = 79.\)

Figure 5.9. Subject 14 was tested twice over a six month interval and shows excellent correlation, 0.99, between the two sets of data. A single result from the GWA is highly correlated with the CPA data throughout the test spanning about 1200 seconds. The only noteworthy variance is that the GWA indicates the cone-rod break at just over 200 seconds (3.3 mins), no unequivocal break can be established using the CPA.

\(<\bar{c}_t> = 0.99; \ <\bar{c}_q> = 0.99, \alpha < 0.05\%, \ N = 11.\)
Figure 5.10. Subject 7 was tested 3 times over a 5 month period. The classic dark adaptation curve is evident: a fast cone phase is followed by the cone-rod break at about 380 seconds (6.3 mins) and rapid rod phase. The rod luminance depth is about 2.5 log unit. The luminance variation at the start of the rod phase is 0.3 log units or ± 0.15 log unit of luminance about the mean. The time standard deviation is correspondingly small at initiation of rod adaptation and increases towards final threshold. During the second examination (green data points) the subject reached Luminance Level 3, whereas in the 2 other tests the thresholds are elevated. This data indicates that as the asymptotic region is approached additional smaller luminance decrements could increase data resolution.

$<r_t> = 0.94, \quad <r_p> = 0.91, \quad \alpha < 0.05\%, \quad N = 67$.

Figure 5.11. Subject 6 was tested twice over a 3 day period. An excellent DA curve is evident, showing a clear cone-rod break at 400 seconds (6.6 mins). The depth of the rod phase is about 2.0 logs units of luminance. The mean luminance variation was 0.7 log unit or ± 0.35 log units about the mean throughout the rod phase.

$<r_t> = 0.93, \quad <r_p> = 0.87, \quad \alpha < 0.05\%, \quad N = 33$. 
Figure 5.12. Subject 4 was retested 4 times over a five month period. The cone rod break occurs at about 400 seconds (6.6 mins). The rod phase is fast, reaching final threshold in less than 1200 seconds (20 mins). The luminance variation throughout the rod phase is 0.9 log units of luminance or ± 0.45 log units about the mean. The time standard deviation increases from about 800 seconds (13.3 mins). One possible explanation for the large variation in test-retest times is that an aberrant set of data is present; for instance either examination 1 OR 2 is erroneous because of poor bleach or concentration by the subject. Removing one of these would markedly improve the result.

<\bar{t}_r> = 0.89; \ <\bar{t}_q> = 0.77, \ \alpha < 0.05\%, \ N = 70.

Figure 5.13. Subject 2 was retested 3 times over a five month period. The cone rod break is clearly identifiable. The rapid cone phase is followed by an initially rapid rod phase that decays to absolute threshold. The rod luminance depth covers 2 log units of intensity. At about 400 seconds (6.6 mins) the luminance variation is 0.6 log units or ± 0.3 log units about the mean. The standard deviations in the time increase to a maximum near asymptote at Luminance Level 5. During one test, Luminance Level 3 was attained. The continuous purple line is the Goldmann Weekers Adaptometer (GWA) data which provides a visual comparison between both instruments.

<\bar{t}_r> = 0.93; \ <\bar{t}_q> = 0.92, \ \alpha < 0.05\%, \ N = 37.
Figure 5.14. Subject 8 was tested twice over a 15 day interval. The cone-rod break occurs at 300 seconds (5 mins) with a rod luminance depth of about 1.8 log units. The data is noteworthy in that there is a very small variation in time for all Luminance Levels, except the last, Luminance Level 6, which is to be expected at the end of the decay asymptote. The spline curve and mean times of the data show classic dark adaptation characteristics.

$\langle t_r \rangle = 0.94; \quad \langle t_q \rangle = 0.94, \quad \alpha < 0.05\%, \quad N = 11.$

Figure 5.15. Subject 13 was tested 3 times over an 11 month period and shows very consistent test-retest results. The cone-rod break occurs at about 200 seconds (3.3 mins). The variation in luminance is about 0.7 log units or ± 0.35 log units about the mean at the start of the rod phase, which decreases towards final threshold. The subject increases in light sensitivity to Luminance Level 7 yielding a depth of rod adaptation of about 1.4 log units. Comparing to the younger Subject 9, in Figure 5.6, it is evident that the difference in absolute light sensitivity is 1.2 log units, in other words Subject 13 requires, at absolute threshold, a light stimulus to be 16 times as bright as Subject 9.

$\langle t_r \rangle = 0.95; \quad \langle t_q \rangle = 0.94, \quad \alpha < 0.05\%, \quad N = 30.$
Figure 5.16. Subject 5 was one of the older volunteers tested and was tested 6 times over an 11 months period. What is interesting here is that despite a wide spread in threshold times, the mean times and spline curve shows a clear dark adaptation curve with the cone-rod break occurs at around 400 seconds (6.6 mins). The depth of the rod phase is about 2 logs units of luminance. The relatively large standard deviation in time can be attributed to an aberrated test result in either examination 1 or 2 which skews the results. However, Subject 5 does exhibit large luminance variations of just over 1.0 log unit or ± 0.5 log units about the mean, which was one of the largest found: the variation decreased to 0.6 log units approaching final threshold. 

$<r_1> = 0.81; \quad <r_2> = 0.74, \quad \alpha < 0.05%, \quad N = 189.$

Figure 5.17. A total of 8 subjects were tested just once, the results of which are presented in Section 5.4, however, the inclusion of this single result is worthy because Subject 15 was an 8 years old female. The cone-rod break is at 400 seconds (6.6 mins) with about a 2 log range of rod adaptation. The final threshold achieved was Luminance Level 3. This curve clearly suggests that children at least as young as eight possess the faculties to successfully use the CPA.
5.3.2 Observations – Individual Retest Examinations

Individual retest graphs presented in Figures 5.1, 5.4 and 5.6 - 5.17 highlight dark adaptation differences which are manifested in the terms of (i) cone rod-breaks times (ii) duration of cone and rod phases (iii) luminance depth of cone and rod phases (iv) rate of adaptation and (v) age changes. For example Subject 9 (Figure 5.6) demonstrates the greatest light sensitivity; reaching luminance level 3 on repeated occasions compared to Subject 13 (Figure 5.15) whose best result was a relatively bright luminance level 7. The fastest rod adaptation rate was exhibited by Subject 11 (Figure 5.7), who reached luminance level 8 in just 400 seconds (6.6 mins), whereas Subject 13 (Figure 5.15), who was the slowest, took over 1000 seconds (16.6 mins), to adapt to the same level.

Subjects 10, 12, and 7 (Figures 5.1, 5.8, 5.10), showed very consistent performance over several months with close inter-correlation of the retest data and small standard deviations. Subject 12 (Figure 5.8) exhibited the smallest variation in the mean luminance with a variation of ± 0.25 log units observed over 4 repeat examinations. In contrast some subjects, most notably Subjects 4 and 5 (Figures 5.12, 5.16) exhibited large variations in the test-retest performance. Such erratic variability in performance is not unexpected. Mote\(^{(3)}\) reported that subject performance can without explanation depart by up to 0.3 log units from previously well established thresholds established over several weeks, the subject “may suddenly have an “off” day for no apparent reason” or as a result of poor fixation.

Another important finding from this study is that, children as young as 8 years can carry out the test (Figure 5.17), without difficulty.
Perusal of all 13 subjects results presented here clearly suggested an elevation of final rod threshold with advancing years as demonstrated by Subjects’ 8 and 13 (Figure 5.14, 5.15). When compared to younger volunteers these two individuals exhibit well defined elevated final thresholds, for example the rod luminance depth approximated 1.4 log units in these older subjects compared to just under 3 log units of intensity observed in younger subjects. These observed age related changes are discussed further in Chapter 6.

5.3.3 Comparison with Published Results

Hecht and Mandelbaum⁴ made pioneering investigations into assessing individual variability of dark adaptation by making by repeated measurements on 6 subjects (age 15 - 45 years) over a four week period and reported that at final rod threshold individual standard deviations varied by $\pm 0.3$ log units about the mean luminance. Hunt and Hayden⁵ made 8 individual dark adaptation measurements on 50 subject (indeterminate age) and found individual standard deviations averaged $\pm 0.2$ log units at final rod threshold; with well-experienced subjects and operators, the variation at final threshold may be as low as $\pm 0.1$ log units⁶.⁷. Sheard⁸ observed that on a day to day basis, individual (25 - 45 years) standard deviation data can scatter by as much as $\pm 0.3$ log unit at final threshold. Sloan⁹ measured 101 subjects (indeterminate age) and found the largest standard deviation in the luminance averaged $\pm 0.15$ log units at 12 minutes into the test which reduced to a minimum of $\pm 0.12$ log units at the absolute rod threshold.

To evaluate individual (single subject) dark adaptation variability using the CPA, a detailed investigation was performed that compared test results obtained on the CPA to a meticulous paper by Mote⁶. Mote determined individual day to day variability by recording 24 dark adaptation measurements on 3 subjects (age 20’s) over an 11
month period. The results reported by Mote show that all 3 subjects (called M01, M02, and M03) had virtually identical adaptation curves and associated variability; the range between maximum and minimum luminance averaged ± 0.5 log unit at the cone-rod break (start of rod decay) and ± 0.2 log unit at final rod threshold; while the luminance standard deviation averaged ± 0.2 log units at the start of the rod phase and decreased to ± 0.1 log units at final threshold. Mote used the Hecht and Schlaer adaptometer (10) with a violet test stimuli, subtending 5° at eccentricity 7° from the fovea; no artificial pupil was used; pre-adaptation bleach light was 1250ml.

**Case Study 3**
Subject 12, previously presented in Figure 5.8, exhibited the most consistent set of repeat results when retested four times over a four month period; yielding an average Pearson correlation value \( r_4 = 0.96, \alpha < 0.05\%\), N=79. For this reason Subject 12’s results where chosen so as to allow a direct comparison with Subject M02, one of the three subjects’ result reported by Mote (all three subjects dark adaptation results were indistinguishable as stated). Figure 5.18 below shows the mean threshold times ± standard deviation (average of 4 examinations) obtained on Subject 12 using the CPA; superimposed on this figure is the mean luminance ± standard deviation dark adaptation envelope, coloured red, which was accurately redrawn and normalized from Subject M02-(Mote).

It is useful to remember that the standard deviations obtained on the CPA are time based (abscissa) while the standard deviations reported by Mote are luminance based (ordinate) consequently, comparisons are difficult between both data sets, as there exists a reciprocity in standard deviations for both the independent and dependent variables.
It is clear from Figure 5.18 that the results obtained on the CPA are closely correlated with those obtained by Mote. The standard deviations overlap throughout the dark adaptation curve (less so at the cone rod-break), in addition the magnitude of the standard deviations are virtually indistinguishable from each other, thereby suggesting that the CPA exhibits similar variability and precision as that reported by Mote. In order to obtain an accurate quantitative comparison between Subject 12’s performance and Subject M02-(Mote), it was firstly necessary to manually extract time measurements directly from Subject M02’s continuous curve presented in Figure 5.18 at each luminance level and then compare these times with Subject 12’s times.

Figure 5.18. Subject 12 (4 examinations) previously presented in Figure 5.8. The mean times and standard deviation error bars (x-axis) obtained using the Concept Prototype Adaptometer are coloured black (individual test results which are not shown). Test results obtained on Subject M02-(Mote) have been normalised and redrawn showing mean luminance points and ± standard deviations (σx and σy) which are drawn as red solid envelope (starting luminance log10 7 µL): Mote obtained this data on a single individual retested 24 times under identical conditions. Subject 12 (CPA) and Subject M02 (Mote) were chosen as they are both demonstrated typical and consistent retetest dark adaptation performances.
The estimated accuracy of the extraction procedure was ± 5 seconds. For example in Figure 5.18 at luminance level 11, the green dotted line equates to 330 seconds on Subject M02 curve while the corresponding time for Subject 12 was 249 seconds on CPA; a comparison for all the luminance levels is summarized in Table 5.3 below. A plot of Subject 12's mean time and the extracted times from Subject M02-(Mote) is shown in Figure 5.19, the comparison is made over 12 discrete thresholds.

<table>
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<th>Hecht and Schlaer Adaptometer</th>
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Table 5.3. Subject 12's mean threshold times obtained using Concept Adaptometer at each luminance level and the corresponding mean times, extracted from Subject M02-(Mote). The luminance decrement for each level is 0.3 log units over 12 discrete thresholds.

*Extracted Data - Uncertainty ± 5 sec
Interestingly, the slope of the graph in Figure 5.19 is \( m = 0.99 \) highlighting a virtual one-one correspondence in times between the \( x \) and \( y \) parameters. The number of data points presented in Table 5.3 and plotted Figure 5.19 is \( N = 12 \), \( DF = 11 \). The Pearson correlation coefficient was calculated, \( r = 0.99 \) and \( \alpha < 0.05\% \), \( N=12 \), a highly significant result over a dynamics luminance range of \( 2^{12} \) (4096:1) which indicates that there is a highly significant relationship between Subject 12’s performance obtained on the CPA and that reported by Mote using the Hecht-Schlaer Adaptometer.

The CPA results obtained on Subject 12 were also compared to Subject M02-(Mote) using Bland Altman methods.

Figure 5.19. Regression line showing 95% confidence limits, showing the mean adaptation threshold times obtained using the CPA (Subject 12, age 21) and Subject M02-(Mote) test results (single subject age 20’s) obtained using the Hecht and Schlaer adaptometer; these are mean times and were extracted from Figure 5.18. The difference in luminance between adjacent datum points is 0.3 log units.
The difference in times at each luminance level (16 to 4) was plotted against the mean of the times using results in Table 5.3 above.

![Bland Altman Plot](image)

Figure 5.19.1. Bland Altman plot of the difference in test times plotted against the mean of the times which were obtained on Subject 12 using the CPA and Subject M02-(Mote) obtained using the Hecht Schlaer adaptometer. The mean difference or bias is -25 seconds and is identified by the blue line; the 95% confidence limits is shown in red. Between the red lines, i.e. between $\bar{x} \pm 2\sigma$, 95% of the differences will lie within these limits for a normal distribution. The result shows good agreement between both adaptometers.

Figure 5.19.1 is the Bland Altman plot of this data and shows that all the data points are within the 95% confidence limits with no outliers; the coefficient of repeatability was found to be 55 seconds which is excellent over the course of a dark adaptation examination and demonstrates good agreement between the CPA and the Hecht Schlaer adaptometer albeit with a 25 second bias indicating that the CPA generated a time that was generally shorter than that observed using the Hecht Schlaer adaptometer. The Bland Altman results agree with those obtained using correlation coefficients methods presented earlier on this subject.
Case Study 4
A significant (85%) of the retest results already presented in Figures 5.1, 5.4 and 5.6 -5.17 show high average Pearson correlations ($r_\phi$ is greater than >0.80); analysis of these subjects gave similar findings to those presented and discussed in Case Study 3 above. However, two subjects had noticeably wide variations upon repeat testing compared other subjects; possessing significantly lower Pearson correlation ($r_\phi$ <0.80). For example, Subject 4, age 28, (Figure 5.12) possessed a low average Pearson correlation, $r_\phi = 0.77$, $\alpha < 0.05\%$, N=70 and exhibited a relatively wide variation in dark adaptation performance upon repeat testing. Thus Subject 4 was selected for identical comparison as in Case Study 3, however, with a different subject reported by Mote, namely Subject M03-(Mote). See Figure 5.20 below.

Figure 5.20. Subject 4 (4 examinations) previously presented Figure 5.12. The mean times and standard deviation error bars obtained using the CPA are coloured black (individual test results which are not shown). Test results obtained on Subject M03-(Mote) have been normalised and redrawn showing mean luminance points and ± standard deviations which are shown as red solid envelope (starting luminance log_{10} 7μL): the Mote data was obtained on a single individual retested 24 times under identical conditions. The maximum/minimum luminance is also shown as a broken envelope.
It can be seen that there is an excellent correlation between the two subjects presented, the only noteworthy difference is the larger standard deviation determined on the Subject 4 compared to Subject M03-(Mote). As before the correlation was found by plotting the mean test times obtained on Subject 4, against the Subject M03-(Mote) mean times, see Figure 5.21.

![Figure 5.21](image_url)

Figure 5.21. Regression line showing 95% confidence limits, showing the mean adaptation threshold times obtained using the Concept Adaptometer (Subject 4, age 28) and Subject M03-(Mote) test results (single subject age 20's) obtained using the Hecht and Schlaer adaptometer; these are mean times and were extracted from Figure 5.20. The difference in luminance between adjacent datum points is 0.3 log units.

The slope of the graph in Figure 5.21 is \( m = 0.997 \) again highlighting a virtual one-one correspondence in times between the \( x \) and \( y \) axes. The Pearson correlation coefficient was calculated, \( r = 0.99 \) and \( \alpha < 0.05\% \), \( N=12 \), showing a strong relation between the mean times obtained on both subjects in Figure 5.20. A Bland Altman analysis was completed on Case study 4 which demonstrated good agreement between the CPA and Hecht Schlaer adaptometer for Subject 4 and M03-(Mote).
5.4 Single Examinations Results

Of the 21 volunteer subjects participating in this evaluation, 13 repeat test subjects were discussed in previous Sections 5.3, thus it is necessary to present results on the 7 individual remaining single test subjects. It can be seen in Figure 5.22 below, representative dark adaptation curves obtained on four of these subjects: all measurements are single reading and first performances.

Figure 5.22. Montage of four dark adaptation curves obtained on four of the seven individual subjects (ages 23-33 years) that were examined once before absconding. Where appropriate an exponential fit was used.
The significance of these first performance curves is that they simply and clearly demonstrate the CPA's ability to determine dark adaptation curves. In order to quantify single test performance it was decided make comparisons with appropriate published results.

**Case Study 5**
Subject 21 was a healthy 34 years old female (not shown overleaf), with no prior dark adaptation experience whose individual dark adaptation curve is shown in Figure 5.23 below (as a solid black line). It can be seen that this subject exhibits a fast cone phase followed by the cone-rod break at about 270 seconds (4.5 mins). The rod phase decays slowly to absolute threshold at luminance level 3 in 1150 seconds (19.2 mins). The rod luminance depth is about 2.3 log units.

Data from Subject 21 was used to make comparisons with those from 2 other studies (i) Mote using the Hecht-Schlaer adaptometer (full details in Sections 5.3.3) and (ii) Henson-Allen\(^{11,12}\) adaptometer (obtained on two subjects called DH and SR – age unknown ). The Henson-Allen (H-A) adaptometer used a single green LED test stimulus (\(\lambda = 565\text{nm}\)) presented at 20° eccentricity: the pre-adaptation light was a diffused 60W incandescent light bulb. Thus in Figure 5.23 four dark adaptation curves are presented comprising (i) Subject 21 - CPA (ii) Subject DH and SR – Henson-Allen adaptometer and (iii) Subject M02-(Mote) Hecht-Schlaer Adaptometry: all published test results were redrawn and rescaled as appropriate, paying particular attention to starting luminance thresholds.

It is evident from Figure 5.23, that there is a very close correlation between the four test results, for example the characteristic dark adaptation shapes of all four curves are remarkably similar throughout with a typical ± 0.15 log spread in luminance at each
threshold. The absolute rod threshold for all four curves occurs at approximately log 3.4 µL (log 0.9µcd.m²). The time to reach absolute threshold is earliest with the CPA, which is to be expected near asymptote because of the relatively large 0.3 log luminance decrement in threshold between luminance levels: given sufficient time, it is reasonable to suggest luminance level 2 would have been attained by this subject.

![Graph](image)

**Figure 5.23.** Subject 21's dark adaptation curve is coloured black. Subjects DH and SR reported by Henson (data was redrawn and normalised) are highlighted Orange and Green respectively. Subject M02-(Mote) is presented in Red. The DH and SR starting luminance were log 7.5 µL (3.0µcd.m²) while M02-Mote was 7µL (4.5µcd.m²)

A quantitative comparison between these curves was made as before by plotting CPA times against the times extracted from the Henson-Allen and Hecht-Schlaer adaptometer times (Subjects DH, SR and M02-(Mote)), the results of which are shown in Figure 5.24 below.
The slopes of the graph in Figure 5.24 are all close to unity, indicating a close correspondence in times between the $x$ and $y$ parameters. The Pearson correlation coefficients and significance values were calculated and are summarized below.

<table>
<thead>
<tr>
<th></th>
<th>H-A Adaptometer</th>
<th>H-A Adaptometer</th>
<th>Hecht-Schlaer Adaptometer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subject DH</td>
<td>Subject SR</td>
<td>Subject M02-Mote</td>
</tr>
<tr>
<td>Correlation $r$</td>
<td>0.994</td>
<td>0.989</td>
<td>0.953</td>
</tr>
<tr>
<td>Significance $\alpha$</td>
<td>$&lt; 0.05%$,</td>
<td>$&lt; 0.05%$,</td>
<td>$&lt; 0.05%$,</td>
</tr>
<tr>
<td>Slope $m$</td>
<td>1.126</td>
<td>0.989</td>
<td>0.953</td>
</tr>
</tbody>
</table>

Table 5.4. Pearson correlations obtained when Subject 21's test results obtained using the CPA is compared with H-A adaptometer (Subjects DH and SR) and Hecht-Schlaer (Subject M02-(Mote)).
Table 5.4 clearly demonstrates that over the dynamics luminance range of $2^{12}$ (4096:1) presented in Figure 5.4, Subjects 12's performance determined using the CPA is closely related to the results obtained on the Henson-Allen adaptometer and Hecht-Schlaer adaptometers over the approximate identical luminance range (between luminance level 15 and 3). The question that clearly arises is how do all the results obtained using the CPA, not just Subject 12, compare with the normal variability observed in the general population?

5.5 Variability between Subjects - Comparison & Published Results

The maximum/minimum luminance variation AND the standard deviation variations are important parameters measured throughout the course of dark adaptation which will be used here to compare the performance of the CPA with published results.

The normal variability of human dark adaptation among unrelated individuals has been investigated since the 1930's. For example Hecht and Mandelbaum\(^4\) measured the thresholds of 110 normal individuals (age 15 - 45 years) and reported that at the cone final threshold the maximum/minimum luminance variation of about ± 0.5 log about the mean value; at final rod threshold, subjects having the lowest and highest absolute thresholds were separated by about 1 log unit or ± 0.5 log about the mean.

The largest scatter between subjects was reported to be about 1.0 log or ± 0.5 log, occurring between 10 - 15 minutes, which corresponds to the rapid increase in rod sensitivity soon after the cone-rod break. Sheard\(^8\) examined 45 subjects (25 - 45 years) and found a maximum/minimum luminance variation of ± 0.3 log units at final
rod threshold. The comparison between the performance of the CPA with these referenced papers is discussed below.

5.5.1 Variability in Maximum/Minimum Luminance - All Subjects
Of the 21 volunteer subjects (8-49 years) examined in this study, a total of 60 unique adaptation curves were recorded and are shown in Figure 5.25 as multiple scatter plots. The highest and lowest threshold envelope was determined subjectively by the author, has been drawn on this figure in an attempt to highlights the variability of the test data. It is evident that the cone luminance depth is about 1.5 log units and terminates at about 370 seconds (6.2 mins); the maximum/minimum luminance scatter at the cone final threshold is approximately ±0.25, (which agrees with Hecht and Mandelbaum). The luminance scatter at the start of the rod phase is 0.8 log or ±0.4 log about the mean, which increases to 1.2 log scatter or ±0.6 log at final rod threshold. It can be seen in Figure 5.25 that some subjects exhibited relatively elevated final rod thresholds compared to others, for example the smallest rod luminance depths is around 1.5 log while the largest is significantly deeper depths at 2.7 log; the average of these gave a rod luminance depth of about 2.1 log unit.

While the overall form of Figure 5.25 possesses the characteristic of appearance of the two phase dark adaptation curve\(^{(13)}\), the observed large 1.2 log maximum/minimum luminance scatter in the final rod threshold luminance suggests other factors are influencing the spread in final rod thresholds; specifically age effects may be contributing to the large scatter in final rod threshold which will addressed presently.
Figure 5.25 shows a scatter plot of all test data obtained on all 21 subjects, both male and female, which comprises 60 unique examinations. Single test and retest subject data results are included. The best approximate Upper and Lower luminance threshold envelopes are shown. The standard deviation envelope is shown in blue. The luminance variation is indicated by the red arrows.

From Figure 5.25 it is possible to quantify the maximum/minimum variation in luminance throughout the test, for example at 200 seconds maximum/minimum variation in luminance is about 0.5 log or ± 0.25 log about the mean: variation at increments of 200 seconds are summarised in Table 5.5 below, which clearly demonstrates that as the dark adaptation test proceeds the luminance variation steadily increases towards the final rod threshold.

<table>
<thead>
<tr>
<th>Time/seconds</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminance Variation(log₁₀)</td>
<td>± 0.25</td>
<td>± 0.4</td>
<td>± 0.6</td>
<td>± 0.6</td>
<td>± 0.6</td>
<td>± 0.6</td>
</tr>
</tbody>
</table>

*Table 5.5. Luminance variation at 200 second increments obtained from Figure 5.25 all subjects.*
A more detailed investigation into spread of dark adaptation results at each threshold luminance may be achieved by analysing the standard deviations.

5.5.2 Variability in Standard Deviation – all Subjects

The calculate positive standard deviations obtained on all 21 subjects for each of the 16 luminance levels are presented in Figure 5.26 below.

![Standard Deviation against Luminance Level](image)

It is evident from Figure 5.26 that the standard deviation is smallest throughout the cone phase of adaptation and increases steadily approaching the cone-rod break. During the subsequent rod phase the standard deviation decreases slightly, before again increasing to a maximum approaching final rod threshold; this increase is to be expected approaching the asymptote of the adaptation decay curve; the subject taking progressively longer times to adapt to the lower luminance threshold. Several points
are worth noting here: (i) the form of the Figure 5.26 is analogous to dark adaptation curves with the cone-rod break occurring between luminance level 12 – 11, (ii) the standard deviation at luminance level 3 is smaller than those directly preceding it possibly reflecting that significantly fewer subjects attain this lower luminance, (iii) these standard deviations of time values are reciprocal to the results obtained using luminance based studies.

5.5.3 Summary of CPA Performance – all Subjects

The CPA’s test results obtained on all subjects may be readably compared with Hecht and Mandelbaum and Sheard, (as discussed above) as the age profile presented in these papers are similar.

To facilitate the comparison of the CPA with dark adaptation studies obtained using Hecht-Schlaer and Henson-Allen adaptometers, a list of the critical instrument features is presented below in Table 5.6.

<table>
<thead>
<tr>
<th>Adaptometer</th>
<th>Hecht and Schlaer</th>
<th>Henson and Allen</th>
<th>GWA</th>
<th>CPA</th>
<th>ADA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimulus Colour</td>
<td>λ</td>
<td>Violet</td>
<td>565 nm</td>
<td>540nm</td>
<td>565nm</td>
</tr>
<tr>
<td>Stimulus Size</td>
<td>α</td>
<td>5°</td>
<td>7.15 cm²</td>
<td>10°</td>
<td>10°</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>β</td>
<td>7°</td>
<td>20°</td>
<td>10°</td>
<td>10°</td>
</tr>
</tbody>
</table>

*Table 5.6. Summary of the Adaptometers referred to in this thesis with important instrument parameters. The parameters α and β are explained in Figure 2.3.*

Tables 5.7 and 5.8 below, summarise the maximum/minimum variation in luminance and standard deviation variation in luminance compared to papers by Hecht & Mandelbaum and Sheard at (i) final cone threshold (ii) start of the rod phase (iii) final rod threshold: the rod luminance depth also included.
Maximum/Minimum

<table>
<thead>
<tr>
<th></th>
<th>Hecht and Mandelbaum</th>
<th>Sheard</th>
<th>CPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject Numbers.</td>
<td>110</td>
<td>45</td>
<td>21</td>
</tr>
<tr>
<td>AGE</td>
<td>15–45</td>
<td>25–45</td>
<td>8–49</td>
</tr>
<tr>
<td>Max/Min Luminance</td>
<td>Max/Min Luminance</td>
<td>Max/Min Luminance</td>
<td></td>
</tr>
<tr>
<td>µL Log Units</td>
<td>µL Log Units</td>
<td>µL Log Units</td>
<td></td>
</tr>
<tr>
<td>Start Luminance</td>
<td>7.5</td>
<td>7.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Final Cone</td>
<td>5.5 ± 0.25</td>
<td>6.8 ± 0.7</td>
<td>6.1 ± 0.25</td>
</tr>
<tr>
<td>Threshold</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start Rod Phase</td>
<td>± 0.5</td>
<td>±0.7</td>
<td>±0.4</td>
</tr>
<tr>
<td>Final Rod</td>
<td>3.0 ± 0.5</td>
<td>5.2 ± 0.6</td>
<td>4.0 ± 0.6</td>
</tr>
<tr>
<td>Threshold</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rod Luminance</td>
<td>2.5</td>
<td>1.6</td>
<td>2.1</td>
</tr>
<tr>
<td>Depth</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7. Comparison of reported maximum/minimum variation in luminance at (i) the final cone threshold, (ii) commencement of the rod phase of adaptation, (iii) final rod threshold and (iv) rod luminance depth for similar age distributions.

By comparing and contrasting the 3 studies in Table 5.7 it is justifiable to suggest that the CPA demonstrates a functionality similar to Hecht and Mandelbaum study (using the Hecht-Schlaer adaptometer) in terms of the luminance variation throughout the time course of human dark adaptation. In addition, the CPA appears to demonstrate a comparable functionality compared to the Sheard study (using the Hecht-Schlaer adaptometer). A better comparison between these studies was achieved by making a comparison using the standard deviations which minimises the significance of aberrant adaptation curves. See Table 5.8.
Standard Deviation

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Hecht and Mandelbaum</th>
<th>Sheard</th>
<th>CPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 – 45</td>
<td>110</td>
<td>45</td>
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<tr>
<td>25 – 45</td>
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<td>8</td>
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<td>8 – 49</td>
<td>8</td>
<td>8</td>
<td>49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Start Luminance</th>
<th>Standard Deviation µmL Log Units</th>
<th>Final Cone Threshold</th>
<th>Standard Deviation µmL Log Units</th>
<th>CPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>5.5 ± 0.2</td>
<td>± 0.4</td>
<td>6.8 ± 0.2</td>
<td>± 0.3</td>
</tr>
<tr>
<td>7.5</td>
<td></td>
<td></td>
<td>6.1 ± 0.25</td>
<td>± 0.3</td>
</tr>
</tbody>
</table>

Table 5.8: Comparison of reported standard deviation variation at (i) the final cone threshold (ii) commencement of the rod phase of adaptation (iii) final rod threshold and (iv) rod luminance depth for similar age distributions.

Table 5.8 demonstrates that by considering only standard deviations then the three studies show similar variations in performance. The results indicates that the CPA exhibits a performance very close to that reported by Hecht and Mandelbaum, save for the numerical difference at final rod threshold and the magnitude of the rod luminance depth both which may be partially explained by (i) the use of violet stimuli used in the Hecht-Schlaer adaptometer, as opposed to green used in the CPA(ii) the large 0.3 log decrement between luminance thresholds (CPA) and (iii) the possible influence of age on the quoted published results. These results also indicate a slightly better performance compared to the Sheard study. Finally, a more detailed consideration of the CPA’s performance is required as Age effects have been overlooked up to this point and must be addressed.

5.5.4 Variability in Standard Deviation 20 – 29 age Category

In order to obtain a clearer insight into the CPA’s test results it was deemed necessary to eliminate age effects from the results; this was done by including data from the 20 – 29 age category only and rejecting older subjects. The 20 – 29 age cohort comprised
12 individuals that were examined on 33 separate occasions (single and multi test). It can be seen in Figure 5.27 below a scatter plot with maximum/minimum and standard deviation envelopes.

The contrast between Figure 5.25 and Figure 5.27 clearly suggests that in the younger age group (i) there is smaller maximum/minimum and standard deviation variation about the mean throughout the test (ii) the luminance variation at final rod threshold is smaller (iii) the rod luminance depth is larger and (iv) there is a greater sensitivity to light.

From Figure 5.27 it is evident that there is very close similarity between all 12 subject in the 20 – 29 age cohort, the consistency of the data was determined by calculating the Pearson’s correlation coefficient, which yielded a 12 by 12 correlation matrix. For
those subjects that were examined more than once, then the mean time was used. The results presented in Table 5.8, shows the 12 by 12 correlation matrix and significance levels for all subjects in the 20 – 29 age group.

The significance levels for all Pearson’s correlations presented in Table 5.9 were all \( \alpha < 0.05\% \). The lowest correlation was \( r = 0.92 \) and highest was 0.99, the average value, \( r = 0.97 \pm 0.012 \). The high correlations and significance values demonstrated in this age group, strongly indicate the CPA possesses the accuracy and precision to obtain reliably and reproducible dark adaptation curves over many multi-test and single test scenarios.

**CPA Inter-subject matrix correlation:**

20 – 29 age range. \( \alpha < 0.05\% \) for all values of \( r \), \( 15 \leq N \geq 10 \)

<table>
<thead>
<tr>
<th>Subject</th>
<th>4</th>
<th>6</th>
<th>7</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>17</th>
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</thead>
<tbody>
<tr>
<td>r</td>
<td>0</td>
<td>0.99</td>
<td>0.94</td>
<td>0.99</td>
<td>0.98</td>
<td>0.96</td>
<td>0.98</td>
<td>0.96</td>
<td>0.96</td>
<td>0.99</td>
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</tr>
<tr>
<td>r</td>
<td>0</td>
<td>0.96</td>
<td>0.98</td>
<td>0.98</td>
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<td>0.99</td>
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<td>0.99</td>
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<tr>
<td>r</td>
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</tr>
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<td>0.98</td>
<td>0.98</td>
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<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>r</td>
<td>0</td>
<td>0.94</td>
<td>0.97</td>
<td>0.97</td>
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<td>0.97</td>
<td>0.97</td>
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<tr>
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</tr>
<tr>
<td>r</td>
<td>0</td>
<td>0.99</td>
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<td>0.99</td>
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<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
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<td>0.99</td>
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<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>r</td>
<td>0</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
<td>0.96</td>
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<tr>
<td>Average</td>
<td>0.99</td>
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<td>0.96</td>
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<td>0.97</td>
<td>0.96</td>
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<td>0.98</td>
<td>0.98</td>
<td>0.98</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Table 5.9. Inter-subject 12 x 12 correlation matrix obtained on 12 volunteer subjects in the range 20 – 29 years. For example by plotting the dark adaptation times for Subject 4, against Subject 9 yields a correlation of 0.99 and so on. Where a subject was examined repeatedly, the mean times were used to evaluate the correlation values. In all cases \( \alpha < 0.05\% \); correlation range \( r = 0.92 – 0.99 \); \( 15 \leq N \geq 10 \).
In addition to the correlation coefficient matrix previously discussed the test results obtained on the CPA were analysed using Bland Altman methods to establish the agreement between dark adaptation data obtained on the subjects in the 20-29 age group.

The performance of the CPA at luminance level 8 is presented in detail in Figure 5.27.1. There is an excellent distribution of data about the mean difference which showed a 0.5 seconds bias. The coefficient of repeatability of was calculated at 190 seconds corresponding to the 95% confidence limits. All the results lie with the 95% confidence limits demonstrating very good agreement among test data obtained on the CPA. Again, these results agree with those determined using correlation coefficients.

![Bland Altman Plot](image)

**Figure 5.27.1.** Bland Altman plot on 12 subjects using the CPA at luminance level 8. The mean difference or bias is 0.5 seconds and is identified by the blue line; the 95% confidence limits are shown in red. Between the red lines, i.e. between $\bar{x} \pm 2\sigma$, 95% of the differences will lie within these limits for a normal distribution. The result shows very good agreement between subjects tested on the CPA at this luminance.
In addition to luminance level 8, the mean of the differences and the coefficients of repeatability were calculated for all luminance levels and are summarised in Table 5.9.1 below.

<table>
<thead>
<tr>
<th>Luminance Level</th>
<th>20 – 29 Age Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sum of Mean Difference</td>
</tr>
<tr>
<td></td>
<td>Sec</td>
</tr>
<tr>
<td>16</td>
<td>-0.19</td>
</tr>
<tr>
<td>15</td>
<td>-0.28</td>
</tr>
<tr>
<td>14</td>
<td>-0.22</td>
</tr>
<tr>
<td>13</td>
<td>0.00</td>
</tr>
<tr>
<td>12</td>
<td>-4.16</td>
</tr>
<tr>
<td>11</td>
<td>-1.19</td>
</tr>
<tr>
<td>10</td>
<td>2.50</td>
</tr>
<tr>
<td>9</td>
<td>0.53</td>
</tr>
<tr>
<td>8</td>
<td>-0.81</td>
</tr>
<tr>
<td>7</td>
<td>-0.44</td>
</tr>
<tr>
<td>6</td>
<td>-5.75</td>
</tr>
<tr>
<td>5</td>
<td>26.39</td>
</tr>
<tr>
<td>4</td>
<td>13.08</td>
</tr>
<tr>
<td>3</td>
<td>-41.33</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.9.1. The sum of the mean differences at each luminance level is shown on 12 subjects in the 20 – 29 age group using the CPA. A Bland Altman plot shown in Figures 5.27.1 was generated from data obtained at luminance level 8, highlighted in red above.

It is evident from Table 5.9.1 that the sum of the mean differences at each luminance level approaches zero in most cases except at the cone rod break and near final rod threshold. An analysis identical to that described for Figure 5.25.1, showed good agreement and repeatability between all individuals over several luminance levels.
5.6 Conclusions
In this Chapter the results of the clinical study into the evaluation of the newly constructed proto-type CPA were described. This involved a total of 21 volunteer subjects, age 8 – 49 years that underwent lengthy detailed dark adaptation examinations, which culminated in 60 unique profiles been amassed over an 48 week period. Detailed information was provided that outlined the investigation and evaluation process.

Dark adaptation test results obtained using the CPA were presented with accompanying figures that provided evidence that the CPA can accurately characterise and quantify the photopic and scotopic phases of dark adaptation. Analysis of test data showed strong agreement using both correlation and Bland Altman methods which was obtained on individual volunteers examined on multiple occasions on these subjects; the results presented proved to be consistent and repeatability over many months. Further evidence as to the successful performance of the proto-type was provided by the use of appropriate case studies which investigated and scrutinized several individual performances in minute detail.

All 60 test results determined in the clinical study were compared with landmark papers by Hecht and Mandelbaum; Mote and Sheard using the Hecht-Schlaer adaptometer and also by Henson and Allen with their adaptometer; several investigations were also made using the Goldmann Weekers Adaptometer. This analysis demonstrated that the CPA can accurately determine dark adaptation measurements for single and group measurements that are consistent with expected limits observed within in the general population.
The detailed analysis presented using correlation and Bland Altman methods showed a statistically strong basis for concluding that the dark adaptation results presented here using the CPA device are, while not identical, are comparable to those obtained with other instruments.

Several examples have been highlighted in this Chapter that suggest that age is an adverse influencing factor in dark adaptation performance; specifically, test data indicates there is an observed elevation in final rod threshold with advancing years. These age changes will be investigated in more detail in the next Chapter.

6. Dark Adaptation and Age related Changes

Observed using the Concept Prototype Adaptometer

6.1 Introduction

The previous two Chapters dealt with the commissioning and test-retest results obtained during the evaluation of CPA. At the end of the last Chapter, the results hinted that CPA test data could successfully identified age related changes in dark adaptation. In this Chapter, data is presented that the CPA has the accuracy and precision to identify age dependent effects. In this study it is accepted that the number of older subjects here is low compared to younger subjects, ideally it would have been preferred to exam 10 individual from each decade of human life in order to establish baseline data from a wider age range. However, an age effect was clearly identified.

6.2 Age Related Changes in Dark Adaptation

Hecht and Mandelbaum\(^{(1)}\) first reported elevated cone thresholds with advancing years. Many researchers subsequently demonstrated that both final cone and rod thresholds are closely correlated with age. This is partly because with advancing years more and more light is required to perceive a light stimulus: the rate of dark adaptation is also observed to decrease\(^{(2,3,4,5)}\). The final rod threshold for an 80 year old is approximately 2.2 log units higher than a 20 year old\(^{(6)}\), (a 158 reduction in sensitivity). Figure 6.1 shows that every 13 years, the intensity of light, must be doubled on average, for an object to be seen by the fully adapted eye\(^{(7)}\).
However, over the age of 60, there is a progressive increased deterioration in sensitivity compared to the observed loss in younger age groups\textsuperscript{(8,9)}.

With increasing age the elevation of mean cone and rod thresholds is clearly observed, however, the maximum/minimum luminance range and standard deviations of these results remain relatively unaffected when compared to younger age groups\textsuperscript{(6,8,10,11)}.

Figure 6.2 shows a scatter plot by McFarland-Fisher\textsuperscript{(6)} showing the final rod luminance thresholds against age for normal individuals, which shows a very close relationship between both these variables, the reported Pearson correlation coefficient was $r = 0.895$, which is highly significant\textsuperscript{(6)}. It can be seen from Figures 6.1 and 6.2 that with advancing years, luminance thresholds are elevated compared to younger subjects; the age effect appears to accelerate in subjects over 60 years.

![Figure 6.1. Plot of dark adaptation curves as a function of age obtained from 240 subjects. Note the elevation of the final rod thresholds with age and its acceleration in the over 60’s. From McFarland-Domey\textsuperscript{(7)}.](image)

![Figure 6.2. Scatter plot obtained on 188 subjects showing the final log threshold with age. A strong correlation (0.895) between the two variables was reported. From McFarland-Fisher\textsuperscript{(6)}.](image)
6.2.1 Age Factors Controlling Dark Adaptation
Many causal factors adversely influence dark adaptation including senile miosis*, crystalline lens and neural changes in the retina all of which are a consequence of the natural aging process. Abnormal dark adaptation is observed as a consequence of ocular dystrophy's and many others conditions including vitamin A deficiency. A full discussion of these disorders is given in the Appendices.

6.2.2 Senile Miosis - Age Changes in Pupil Size
Changes in pupil size help control the amount of light entering the eye and reaching the retina; these changes are involuntarily\(^\text{12}\). In the dark the pupil of younger adults increases in size from approximately 2 mm to approximately 8 mm very rapidly as the surrounding light level falls\(^\text{13,14}\). Pupil dilation plays a limited but important role in dark adaptation which is influenced by other factors\(^\text{2,8,15}\).

Senile miosis is a significant casual condition contributing to poor dark adaptation with increasing age, the reduced of pupil reflex, observed in the elderly, has an adverse effect on dark adaptation\(^\text{6}\). Of particular importance in dark adaptation testing is that the maximum pupil diameter is observed to decrease in size throughout life\(^\text{16,17}\) thus the number of quanta reaching the retina will be reduced as retinal luminance is directly proportional the area\(^\text{13,18}\).

Birren, Roland and Casperson\(^\text{19}\) measured pupil sizes in 222 subjects and showed the pupil decreases in size with age during dark adaptation: the difference in pupil diameter at ages 20-29 and 80-89 is 2.6 mm representing a difference in area of 25 mm\(^2\). Thus the effective maximum pupil area (after 90 seconds) for ages 20 – 29 was 43.65 mm\(^2\), compared to 18.62 mm\(^2\) for ages 80 – 89; thereby effectively more than

\* miosis - construction of pupil caused by the action of light
halving the pupil area: with a consequent reduction in light sensitivity in the older group. Dark adaptation will consequently be affected as a result of the decrease in light entering the eye as a consequence of the pupil constriction in the aged. Estimates on pupil constriction suggest there is a consequent elevation in the final rod threshold of 0.6 log units for individuals over 70 years \(^{20}\).

Many researchers have attempted to exclude the pupillary age changes in order to minimise age differences between subjects by controlling the amount of light entering the eye and thus eliminate age differences. A number of techniques are used to control pupil size and thus standardise dark adaptation data; (i) pupils may be dilated with a mydriatic, for example 5% euphthalmine administered twice prior to testing, which increases the pupil size to > than 5mm diameter \(^{11}\) or (ii) an artificial standard pupil may be placed in front of the eyes \(^{6}\), however, the use of an artificial pupil is problematic in that elderly subjects have difficulty in keeping their eye centered on such an aperture \(^{11}\).

Dilation of pupils is the preferred method in most cases \(^{6,8,11,21}\). Dilation of the pupil with a mydriatic in the age group over 40 will increase the pupil size to greater than 5 mm \(^{8}\). Importantly, but surprisingly the effect of pupil size over 5 mm on dark adaptation is negligible \(^{3}\). Consequently younger subject pupil’s (<40 years) need not be dilated as their pupils dilate sufficiently \(^{22}\). Controlling pupil size has the effect of reducing age differences between subjects. Interestingly, the literature indicates that many researchers do not dilate pupils or fail completely to mention it as a influencing factor \(^{23,24,25,26,27}\).
6.2.3 Increased Density of Crystalline Lens

It has been estimated that the retina of a 60 year old receives one third the amount of light compared to a 20 year old as a consequence of increased absorption (attenuation) of light by the crystalline lens regardless of the level of adaptation\(^28\). This increase in absorption may be explained by increased ocular lens density in the elderly and particularly in patients with cataract and corneal opacities\(^29\). The attenuation of light increases with shorter wavelength, affecting colour perception and rod adaptation\(^30\).

6.3 Observed Age Changes using CPA

Test data obtained using the CPA on the 21 Subjects described previously (Chapter 5), were analysed to establish if any age related changes could be identified. The 21 subjects were divided into 6 age bins comprising 20-24; 25-29; 30-34; 35-39; 40-44; 45-49 age cohorts which are summarized in Table 6.1 along with the associated test frequencies.

<table>
<thead>
<tr>
<th>Age</th>
<th>Number of Subjects</th>
<th>Number of Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-9*</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>20-24</td>
<td>7</td>
<td>27</td>
</tr>
<tr>
<td>25-29</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>30-34</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>35-39</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>40-44</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>45-49</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>21</td>
<td>60</td>
</tr>
</tbody>
</table>

* Not included in age analysis

*Table 6.1. Age cohorts with number of subjects tested and the number of repeat examinations.

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The dark adaptation results obtained by the CPA were analysed in order to identify if age changes were evident. The results of this analysis are presented in Figure 6.3, which plots the mean luminance threshold against average time for each of the 6, half decade age groups, 20-24 through to 45-49. It should be noted an artificial pupil was not used in this study.

![Figure 6.3](image)

*Figure 6.3. Dark adaptation curves showing the mean times corresponding to specific age categories. Note significant grouping is observed in the first 600 seconds, however, as the test proceeds there is a noticeable elevation in luminance thresholds and the elongation of time towards final rod threshold.*

It can be seen in Figure 6.3 that there is no discernable age effect in the early part of the dark adaptation curves, particularly in the first 600 seconds (10 mins), however, as the test proceeds and the luminance is reduced, the data suggest that the CPA can discern changes in older subjects; there is an increase in the time required to reach a particular luminance level, compared to younger subjects. Thus, age effects become
increasing evident with time, with older subjects, (i) taking proportionately longer
time to achieve each threshold and (ii) showing elevated thresholds which are evident
from luminance level 9 through to level 3. It can be seen in Figure 6.3 that the 20-24
age group will reach luminance level 7 in about 600 seconds (10 mins) whereas older
age groups take progressively longer times. Analysis of the data showed that the time
to reach luminance level 7 was closely correlated with age $r = 0.52$, $N = 60$, $\alpha <$
0.05%. Similar results were found for luminance levels to 9 - 3. Assuming a linear fit
in younger subjects (under 60), Figure 6.4 shows the mean times and standard
deviations at luminance level 7 for each age group.

Figure 6.4. Linear regression plot (95% confidence limits) of the means times with standard
deviation bars for each age cohort recorded at luminance level 7: $r = 0.52$, $N = 60$ and $\alpha < 0.05%$. 
6.3.1 Age Changes – Comparison with Published Results
An improved assessment of the relationship between dark adaptation performance and age was achieved by investigating the relationship between final rod luminance thresholds with age, these details are presented in a scatter bubble graph with linear regression line and 95% confidence limits in Figure 6.5; all 60 dark adaptation examinations are included. It should be noted that the area of each bubble point is directly proportional to the frequency of its occurrence.

![Final Rod Luminance vs Age](image)

**Figure 6.5** Bubble plot of the estimated final rod threshold luminance versus age obtained on 21 subjects examined 60 times using the Concept Adaptometer. Each bubble area represents the repetition frequency at a given Luminance Threshold as a function of age. The regression line and 95% confidence line is shown.

For example, at age 20 years, 7 individuals tests attained luminance threshold 3.4 log \( \mu \text{L} \) (luminance level 3) thus the area of the large orange “bubble” is 7 times that for a single individual.
Analysis of the numerical data presented in Figure 6.5 yields $N = 60$, and $r = 0.51$ and $\alpha < 0.05\%$. The slope of the regression line, $m = 0.0232$; thus for every year above 20, the thresholds increases in proportion to 0.0232. Calculation from the regression line shows that the final rod threshold is elevated by 0.3 log every 12.9 years; the landmark paper by McFarland-Fisher\(^6\) reported 0.3 log elevation every 13 years. In this study McFarland-Fisher\(^6\) used the Hecht-Schlaer adaptometer to study 188 males in 20-47 age group using a pupil, 1500mL pre-adapting light for 3 minutes; those over 40 pupils were dilated with a mydriatic.

The slope of this graph was also used to predict the thresholds for older age groups. For example, calculation predicts that the final threshold for the 85-89 age is estimated at of $5.6 \pm 0.35$ log $\mu$L to a 95% confidence limit; which corresponds to a final rod luminance elevation of about 2.0 log units of intensity, when compared to the 20 – 24 age group; McFarland-Domey\(^7\) found a virtually identical elevation of 2.1 log units over the same age range.

In order to make further comparisons with McFarland-Fisher, the age data presented in Figure 6.5 was reorganized and grouped into 6 cohort age bins, and re-plotted as the mean final rod luminance threshold against Age Bins with associated error bars representing ± standard deviation, see Figure 6.6 below. By plotting the data in this way the degree of scatter has been substantially reduced. The Pearson correlation of all the data in Figure 6.6 shows, $r = 0.52$, $N = 60$, $\alpha < 0.05\%$.

Final rod luminance threshold measurements determined by McFarland-Fisher\(^6\) (Figure 6.2) were normalized (base-line adjusted by $+0.98\log_{10} \mu$Ls see Figure 6.7.1)
and superimposed the CPA test results in Figure 6.6 for comparative purpose which shows there is a strong relationship between the two studies.

![Final Rod Threshold](image)

**Figure 6.6.** Grouped mean final luminance threshold (and standard deviations) as a function of half decade age groupings. Regression 95% confidence interval is also shown. N = 60, r = 0.52, \( \alpha < 0.05\%. \) The McFarland-Fisher test results with blue data points was modified from Figure 6.2 and superimposed: these results were obtained on the Hecht-Schlaer adaptometer. The elevation of absolute rod threshold with age is evident.

It can be seen from Figure 6.6 that the grouped data obtained on the CPA, that over the 3 decades there is an elevation in final threshold from 3.60 \( \pm \) 0.3 log \( \mu \text{L} \) units to 4.37 \( \pm \) 0.3 log \( \mu \text{L} \), a variation of 0.77 log units which corresponds to an elevation of 0.33 log \( \mu \text{L} \) per 13 years, which is in close agreement to McFarland-Fisher\(^6\) as already stated.
The final rod threshold results presented in Figure 6.6 are summarized in Table 6.5 below along with the actual tabularised published results reported by McFarland-Fisher\(^{(6)}\); the bin sizes were identical.

<table>
<thead>
<tr>
<th>Age</th>
<th>CPA Absolute Threshold Luminance</th>
<th>McFarland and Fisher Hecht-Schlaer adaptometer Absolute Threshold Luminance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>log µL SD</td>
<td>Log µL SD</td>
</tr>
<tr>
<td>20-24</td>
<td>3.6  0.386</td>
<td>2.75  0.060</td>
</tr>
<tr>
<td>25-29</td>
<td>3.75  0.258</td>
<td>2.82  0.080</td>
</tr>
<tr>
<td>30-34</td>
<td>3.86  0.272</td>
<td>2.87  0.090</td>
</tr>
<tr>
<td>35-39</td>
<td>4.09  0.142</td>
<td>3.02  0.090</td>
</tr>
<tr>
<td>40-44</td>
<td>4.22  0.328</td>
<td>3.15  0.120</td>
</tr>
<tr>
<td>45-49</td>
<td>4.39  0.376</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 6.5. Final Luminance Thresholds as a function of age obtained on the Concept Adaptometer and published Thresholds reported by McFarland & Fisher using the Hecht-Schlaer adaptometer.

It is evident from Table 6.5, there is a base-line difference in starting luminance between the two studies, the average difference was found to be 0.95 ± 0.08 log units. The difference may be explained as a consequence of calibration errors or the fact the Hecht-Schlaer adaptometer differs in several ways (stimulus size, colour, eccentricity etc) from the CPA (see Table 5.6).

Using the CPA's time based measurement, it is difficult to determine when the decaying rod asymptotic curve has finally plateaued. Thus there is a small uncertainty in the time recorded at final threshold, however despite this the CPA results are in accordance with results obtained on luminance based measurement instruments such as the Hecht-Schlaer Adaptometer.
Figure 6.7 below is a plot of the data in Table 6.5. Now although a mere 5 points are plotted, these points represent the mean of measurements completed by McFarland-Fisher on 188 test volunteers and 60 volunteers on CPA dark adaptation examinations (loaded into age bins).

![Comparison with Published Data](image)

**Figure 6.7.** Plot of McFarland & Fisher (Hecht-Schlaer adaptometer) against CPA using Table 5.5, demonstrates a close correlation 0.98 between both sets of data. The regression line and 95% confidence lines are shown along side standard deviations in x and y.

Analysis of Figure 6.7, show $N = 5$, $r = 0.979$, $\alpha < 0.05\%$, results which strongly suggests that the CPA has the precision to identify dark adaptation age changes, despite the limited number of older volunteers.

The relationship between the CPA and the McFarland & Fisher (Hecht-Schlaer adaptometer) data was also investigated using Bland Altman methods.
Figure 6.7.1. Bland Altman plot of test data obtained on the CPA which is compared to McFarland & Fisher (Hecht-Schlaer adaptometer) at final rod threshold. These results were calculated from Table 6.5. All data lies within the 95% confidence limits. The bias was calculated at $0.98 \, \log_{10} \mu\text{L}$.

Figure 6.7.1 demonstrates good agreement between the CPA data and those reported by McFarland & Fisher using the Hecht-Schlaer adaptometer. The coefficient of repeatability was $0.18 \, \log_{10} \mu\text{L}$ with all results falling within the 95% confidence limits. There is an observed bias of $0.98 \, \log_{10} \mu\text{L}$, thus the final rod threshold recorded by the CPA is elevated by $0.98 \, \log_{10} \mu\text{L}$ compared to the McFarland & Fisher data. Thus age differences identified by the CPA agree with those published by McFarland & Fisher.
6.3.2 Threshold Variation within a given Age Cohort

To obtain an overall sense of the age variations measured by the CPA, analysis of the percentage of subjects adapting to the various luminance levels as a function of age was performed and is presented as a 3D plot in Figure 6.8.

![Figure 6.8. Plot showing the relationships between (i) Age (ii) luminance level and (iii) percentage at each luminance level. All subjects adapted to luminance level 9, those above this figure are not shown.](image)

This figure shows a marked loss of sensitivity in older subjects, it also indicates a natural spread in sensitivity within a given age cohort as determined by the CPA. It is evident in Figure 6.8 that all subjects (100%) tested on the CPA adapted to luminance level 8 (and above) for all age groups. At luminance level 6, 100% of subjects under 40 years of age adapted to the light, in contrast to the 40 – 50 age group. At luminance level 5, there is a dramatic almost linear drop in sensitivity with age. At level 3, only
the youngest subjects perceive any light. Figure 6.8 also indicates that within a given age group, there is a natural spread in performance; for example in the 25-29 age group, where 100% of subjects reached luminance level 4; only about 50% of these subjects reached level 3.

6.4 Conclusions:

This Chapter has presented evidence that the CPA possess the sensitivity to observe age changes in the study group as witnessed by a consistent decline in sensitivity of the dark adapted eye. The loss of sensitivity could have been the result of reduced pupillary function, lens opacities or neural changes in older volunteers. The final rod luminance thresholds showed significant correlations when compared to published results.

These results were sufficiently encouraging that a second more advanced adaptometer was planned, constructed and tested. The second device was called the Automatic Dark Adaptometer (ADA) which was microprocessor controlled and included several changes to the CPA. Based on the clinical studies presented here, additional luminance levels were included to improve data resolution particularly during the rod phase of adaptation. The design details are discussed in the next Chapter.


7. Automatic Dark Adaptometer

7.1 Introduction

Following the successful evaluation of the Concept Prototype Adaptometer, the author proceeded to develop a fully working microprocessor based instrument. The principles and expertise developed in the construction and evaluation of the CPA were incorporated into its advanced successor. The microprocessor unit was completely based on the design and circuitry devised for the CPA presented in earlier Chapters of this thesis.

In order to achieve the highest level of performance from this new advanced instrument it was realized that the input from third parties would be required to fabricate the housing and circuitry. The objective was to engage outside expertise to assist in the design of a fully independent instrument that incorporated the novel features used in the CPA, with several improvements which are discussed below.

It must be emphasised that at all times, work carried out by third parties, was supervised and directed the author, Dr. P. Davison and Dr. Thomas Grennan, such input is readily acknowledged where appropriate, as per declaration on page vii.

A full evaluation of the new Automatic Dark Adaptometer (ADA) was completed and is reported in full in the next Chapter.
7.1.1 New Improved Features

Besides the advantages of the CPA listed previously, the microprocessor based unit include the following features;

- An **Erasable Programmable Read-Only Memory** (EPROM) was employed which facilitates great flexibility in the test methods and procedures; for example the ADA can be programmed to alter/modify the test protocols to that desired. (The testing procedures and methods used to evaluate the ADA were identical to those already describes in Chapter 4, except that the number of luminance levels increased from 16 to 37 in order to improve curve resolution. (see Tables 4.2 and 8.1 respectively).

- The ADA was power by a rechargeable battery and can run for several days on a single charge, depending on use.

- A low battery detect alert is provided.

- Sleep mode activation 60 seconds: 9V supply switched off.

- The test is fully automatic and does not require the direct input from the clinician, who is free to observe the data via a laptop. (The operator control housing 3, described in Chapter 2, Figure 2.1 was no longer required.)

- Variable baud rate. Default 9600.

- Maximum permitted time out default 3200 seconds

- Correct choice: 1 beep Duration: 0.4 seconds

- Incorrect choice: 2 beeps Duration: 0.4 seconds

- Comms is via an RS232 link. Data is stored on computer hardisk for subsequent analysis and comparison.

- A PC or similar sends test instructions to the ADA and receives data from it. The information received by the PC includes (i) presented luminance levels and (ii) subject response times. As a test proceeds subject data may be displayed in tabular or graphic format.

- Automatic luminance control of fixation light
7.1.2 ADA Design and Construction
The ergonomic design of the ADA was of the utmost importance, particularly in
regard for use with children; award winning designer, Oliver Hood was contracted to
assist in the design of the instrument (see Figures 7.1 and 7.2) using funds awarded by
DIT and others; see acknowledgements. Schematics of the instrument are reproduced
in Appendix 6.

The detailed microprocessor design was contracted to the National MicroElectronics
Application Centre (MAC), University of Limerick; the circuit design used in the
CPA was used as the template for the microprocessor based unit. The design brief
given to MAC required that a single printed circuit board be designed with
appropriate functionality as outlined above. The author worked with the team MAC
over a 6 month period. See Figures 7.3 – 7.11 below.
Gwent Tool (Wales) was contracted to manufacture the mould tool and ten injection
moulded units made from high impact resistance polyurethane.

The printed circuit board design layout and the production of ten printed circuit
boards was completed by Irish Printed Circuit Boards Limited; a company that
specialises in small production runs see Appendix 7.

The assembly, stuffing and testing of the ten units was completed by the author and
colleagues within the Dublin Institute of Technology. Each unit required the soldering
of over 1000 individual hand solders. Photographs of the ADA enclosure, printed
circuit board and component are shown in Figures 7.12 and 7.13.

The evaluation of the ADA is presented in Chapter 8.
7.2 Design Automatic Dark Adaptometer

Figure 7.1. Automatic Dark Adaptometer, showing red fixation and green test stimulus. The matt black colour was chosen to minimise reflections under test conditions. Circuit board with electronics and battery are housed within the housing.
Figure 7.2. Subject under test depressing visible test stimulus. Chin rest and forehead restraint ensure that the test stimulus is presented at the appropriate location on the retina as determined by the fixation light.
7.3 Circuit Specifications

Figure 7.3. Architecture of the ADA, showing the microprocessor, Array 1; Arrays A2 – A4; Tone Sounder, Power Supply Unit; Array Select and Flash (the pre-adaptation light). These elements were established in the CPA, described in Chapter 3. All circuits designed by author to my specification.
Figure 7.4. Main microprocessor elements comprising the ADA.
Figure 7.5. Modification of circuits used in the CPA (Figure 3.3 and 3.10). Row scan and the high/low current control by shunting trimmer resistance for array 1.
Figure 7.6. Modification of circuits used in the CPA (Figure 3.3, 3.10 and 3.11). High/low current control by shunting trimmer resistance arrays 2-4.
Figure 7.7. Modification of circuits used in the CPA (Figure 3.17, 3.10 & 3.11). High/low current control by shunting trimmer resistance arrays 2-4. Fixation luminance control circuit.
Figure 7.8. Low battery detect; supply voltage with on/off switch and reset.
Figure 7.9. Six switch contacts for each array. Refer to Figure 3.23. Six membrane switches were used for each array.
Figure 7.10. Photo-flash pre-adaptation circuit with relay and 12V power supply.
Figure 7.11. Ferrite beads (passive electric components) used to suppress high frequency noise generated by the flash circuit.
Figure 7.12. Enclosure and Printed Circuit Board with components.
Figure 7.13. Printed circuit board with components
8. Commissioning and Evaluation of the Automatic Dark Adaptometer (ADA)

8.1 Introduction

The successor to the Concept Prototype Adaptometer took approximately 24 months to design and construct. The first task was to evaluate its precision, reliability and functionality as a fully working instrument. The commissioning of the ADA, described in this Chapter, involved the examination of 15 individual in the 20-29 age group using the ADA. A comparison was subsequently made between the ADA and CPA for this age group. The reproducibility of the data was also investigated.

Some of the questions that were to be addressed included: (i) can the ADA obtain normal or near normal dark adaptation threshold data among unrelated individuals, (ii) is individual subject dark adaptation data reproducible and consistent, (iii) how does individual and group test data compare with that obtained on the CPA, (iv) does the ADA deliver an improved test performance and accuracy compared to the CPA, (v) what have been the effects of the inclusion of extra luminance thresholds and (vii) how does the performance of the ADA compare to the GWA.

8.1.1 Luminance Light Levels and Calibration

Before proceeding further it is worth reiterating that the original CPA had 16 discrete levels covering a luminance range of 32768:1 (log₁₀ 7.3 μL - log₁₀ 2.78 μL); identical to the ADA's luminance range. However, as previously discussed, the
number of discrete level was increased from 16 to 37 discrete luminance thresholds.

Where previously the luminance decrement was fixed at 0.3 log_{10} units in the concept unit: after luminance level 8 in the ADA, the luminance decrements change from 0.3 log_{10} units to 0.075 log_{10} units. The luminance thresholds are presented in Table 8.1.

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<th>Luminance ( \log_{10} \mu \text{cdm}^{-2} )</th>
<th>LEVEL</th>
<th>Luminance ( \log_{10} \mu \text{L} )</th>
<th>Luminance ( \log_{10} \mu \text{cdm}^{-2} )</th>
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*Table 8.1. The luminance variation for each of the 37 discrete thresholds presented to the subject. The luminance thresholds are presented in \( \mu \text{L} \) and the S.I. unit of luminance \( \mu \text{cdm}^{-2} \).*

The UDT Optometer Model 40X photodetector was used to set the initial starting threshold of the ADA at log_{10} 7.3 \( \mu \text{L} \)/4.8 \( \mu \text{cdm}^{-2} \) (see Section 4.4).

### 8.2 Individual Test Results

The testing protocols, methodologies and testing instructions used here were identical to those described previously in Sections 5.1 and 5.1.1. In this study 15 volunteer subjects were examined; 5 of whom were female and 10 male. All individuals were healthy with good vision and free from eye disease to their knowledge. All volunteer
subjects were exposed to a bleach light of 1500mL for 2 minutes prior to testing using the GWA. As before only the right eye was examined (no high myopes).

8.2.1 Case Studies
Two case studies are presented below and are typical of the 15 subjects examined and dark adaptation results obtained; the inclusion of Subjects 30 and 38 here is an arbitrary choice, as any of remaining subjects, excepting Subject 41, would have been representative of the group.

Case Study 1.
Subject 30 was a 23 year old male with no prior experience of this type of test.

![Graph showing dark adaptation curve](image)

Figure 8.1. Single dark adaptation curve obtained using the ADA on Subject 30, a 23 year old healthy male. Spline curve generated by Sigma plot.
Figure 8.1 shows a near classic dark adaptation curve, the fast cone phase covers approximately 1 log\textsubscript{10} unit of luminance and is rapid. The cone-rod break is clear at about 309 seconds (5.1 min) at 5.796 \mu\text{L}, thereafter there is a sharp and noticeable increase in sensitivity towards the final rod threshold, the rod luminance depth has a depth of 2.6 log units of luminance, commencing at 400 seconds (6.6 min) and terminating around 1069 seconds (17.8 min) at 3.164 \mu\text{L}. Despite running the test for an additional 10 minutes, Subject 30 did not reach the next threshold at 3.089 \mu\text{L}. A much improved rod profile is evident from about 500 seconds (8.3 min) onwards; the improved smoother profile is directly attributable to the extra luminance threshold levels provided by the ADA.

**Case Study 2.**
Subject 38, was a 28 year old male that demonstrated another classically shaped adaptation curve in Figure 8.2; for example a very clear cone rod break is identifiable at 297 seconds (5 min). The initiation of the rod phase is abrupt and exhibits a rapid increase in rod sensitivity. The rod luminance depth is 2.6 log\textsubscript{10} units and the final rod threshold occurring after 1011 seconds (16.8 min) at 3.164\mu\text{L}.

Again it is evident that the extra luminance levels markedly improve the resolution and definition of the rod adaptation curve. It is thus easier to accurately determine absolute rod threshold as a consequence.
Figure 8.2. Dark adaptation curve obtained using the ADA on Subject 38, a 28 year old male. Double decreasing exponential curve shown in grey.

A montage of another six adaptation typical curves obtained on Subjects 31, 32, 33, 34 36 and 43, all in the 20 -29 age group (male and female) is shown in Figure 8.3: these curves demonstrate that the extra threshold levels have achieved the desired result in that the shape of the rod phase of the dark adaptation has improved markedly compared to curves obtained on CPA; it is clear there is excellent resolution in both the cone and rod phases threshold times, rod luminance depth and decay times.

A detailed analysis of the results obtained on all 15 subjects follows.
Figure 8.3 Montage of several decreasing exponential dark adaptation curves, calculated using Sigmaplot, on 6 individual subjects all within the 20-29 age group. Remaining adaptation curves
8.2.2 Inter Subject Variation

A total of 15 normal volunteers in the 20-29 age cohort were examined to determine the range and spread of dark adaptation performance within this population group, the results of which are compared with published data. A scatter plot of the data obtained on all normal 15 subjects in the 20 -29 age group is shown in Figure 8.3 including outlying maximum and minimum subjective curve data envelope.

![Scatter Plot 15 Subjects 15 Examinations 20-29 Age Group](image)

*Figure 8.3 Plot of all 15 subjects in the 20 – 29 age group showing the scatter of all data points obtained on the ADA. The envelope of the scatter points highlights the maximum and minimum range/envelop of the data set*

The envelope of the data points in Figure 8.3 indicates a cone depth of about 1.2 log units and rod luminance depth in excess of 2.5 log units of luminance. The cone-rod break occurs at about between 200 and 300 seconds (3.3 – 5 min). The cone and rod phases are well differentiated and pronounced. The rod phase is rapid, eventually
decaying to the asymptote of the curve. The additional luminance levels used by the ADA are evident after 250 seconds (4.2 min).

8.2.3 Correlation and Significance Levels
To establish the inter-subject correlation of the scatter data in Figure 8.3, dark adaptation data for each of the 15 subjects was correlated with all others yielding a 15 × 15 correlation matrix which shown in Table 8.2. It was found that all inter-subject correlations values (r) were in the range 0.84 to 0.99, all of which were statically significant at \( \alpha < 0.05\% \), \( 37 < N > 27 \). The average of all correlations in Table 8.2 was \( \langle r \rangle = 0.97 \pm 0.01 \) which shows a high level of consistency between all subjects. The correlation matrix in Table 8.2 closely agrees with the matrix reported Domey and McFarland\(^{(1)}\) using the GWA.
ADA Inter-subject matrix correlation (r): 20 – 29 age range. 37 < N >27, α < 0.05% for all values of r

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| Average | 0.99| 0.97| 0.98| 0.97| 0.97| 0.97| 0.98| 0.97| 0.97| 0.97| 0.97| 0.97| 0.97| 0.97| 0.97|

Table 8.2. ADA Inter-subject 15 × 15 correlation matrix obtained on 15 volunteer subject in the range 20 – 29 years. For example by plotting the dark adaptation times for Subject 30, against Subject 31 yields a correlation of 0.95, α < 0.05%, N = 34 and so on. Each subject was tested up to a maximum of 37 luminance thresholds. For α < 0.05%.
**Bland Altman Analysis**

Bland Altman analysis on the 15 volunteers in the 20-29 age cohort showed that the results showed excellent repeatability at all luminance levels. For example, a typical result is shown in Figure 8.3.1, which was determined at luminance level 5A (3.915μL/1.416μcd.m⁻² found Table 8.1). The coefficient of repeatability was calculated at ±270 seconds, it can be seen that all results lie within the 95% confidence limits, thus demonstrating good repeatability of the test data. A small bias of 3 seconds was observed.

**Bland Altman Plot**

**20 - 29 Age Group. Luminance Level 5A**

Figure 8.3.1. Bland Altman plot obtained on 15 subjects using the ADA at luminance level 5A which corresponds to 3.915μL/1.416μcd.m⁻² found in Table 8.1. The mean difference or bias is 3 seconds and is identified by the blue line; the 95% confidence limits are shown in red. Between the red lines, i.e. between $\bar{x} \pm 2\sigma$, 95% of the differences will lie within these limits for a normal distribution. The result shows very good agreement between subjects tested on the ADA at this luminance.
While there is good agreement in that test data at luminance level 5A above, it is reasonable to inquire as to the agreement for the other luminance levels. The agreement for the remaining luminance levels was investigated and is summarised below in Table 8.2.1. It can be seen that of the 25 luminance levels, it was found that all data points lay within the 95% confidence for 17 luminance levels limits, thus demonstrating good repeatability of the results; of the remaining 7 luminance levels falling outside these limits, it was established that just one data point or outlier was responsible. For example at luminance level 8C in Figure 8.3.2 all the data points all lie within the 95% confidence limits except one data outlier.

![Bland Altman Plot](image)

Figure 8.3.2. Bland Altman plot obtained on 15 subjects using the ADA at luminance level 8C which corresponds to 4.667uL (2.169uL/m²) found in Table 8.1. The mean difference or bias is 11 seconds and is identified by the blue line; the 95% confidence limits are shown in red. Between the red lines, i.e. between μ ± 2σ, 95% of the differences will lie within these limits for a normal distribution. The result shows very good agreement between subjects tested on the ADA at this luminance, except for the single outlier.
Upon investigation it was determined that a single subject (Subject 40, Appendix 7) was responsible for the majority of outliers identified at the different luminance levels. Removing this subject reduced the outliers to two, one at luminance level 12 and 10 at the cone rod break.

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*Table 8.2.1.* The table summarises the analysis of data on 15 subjects (20-29 age cohort) obtained on the ADA, using Bland Altman methods. At each luminance levels the sum of the mean difference is presented along with the associated correlation of repeatability. For data points lying within the 95% confidence limits, a true is recorded, if outside a false is recorded. The number of outlier data points are shown. Luminance levels 8C and 5A are coloured red as they are used in Figures 8.3.1 and 8.3.2.

These results suggest that there is good agreement between the data collected on the 15 individuals in this age group which suggests good repeatability of the ADA.
8.2.4 Mean and Standard Deviation in the 20-29 age range

To further assess the ADA's performance, the 20-29 age cohort was examined further by finding the mean times and standard deviations presented in the scatter plot Figure 8.3 and comparing them to the results reported in a landmark paper by Hecht and Mandelbaum\textsuperscript{(2)}, who obtained dark adaptation data on 110 normal individuals, with the Hecht-Schlaer Adaptometer\textsuperscript{(3)} (which comprised a test violet test stimulus subtending a 3° visual field which was viewed 7° nasally with the right eye). The results of the Hecht and Mandelbaum study are superimposed on the ADA data in Figure 8.4, the former being displaced 200 seconds in order to superimpose the cone-rod break. The ADA data demonstrates classic dark adaptation shape features with differentiated cone, cone-rod break and rod phases with the smallest standard deviation (time) occurs at the cone-rod break and increases to a maximum at final rod threshold.

It is clearly evident that the results obtained on the ADA and those reported by Hecht and Mandelbaum are similar. For example, (i) the rod phases are virtually identical - there is a near perfect match between both data sets starting at the cone-rod break and progressing to absolute threshold (ii) the estimated rod luminance depth is within the expected range 2.5 ~ 3.0 log units\textsuperscript{(1,3,5,4)} (iii) the rod final threshold is about 3 µµL units for both data sets (iv) the region containing 68% sample population (± σ) obtained on the ADA (blue envelop) is strongly matched to the region containing 80% sample population reported by Hecht and Mandelbaum (grey dotted envelop).
Figure 8.4. The mean times and double decreasing exponential dark adaptation curves (cyan) and standard deviation error bars (red) with error bar envelop (blue) obtained on the ADA. A normalised overlay of the Hecht and Mandelbaum data is superimposed showing the lowest and highest threshold envelop (solid grey line). The dotted grey line contains 80% of the sampled normal population reported by Hecht and Mandelbaum. The Hecht and Mandelbaum starting luminance was 7.8 μL.

The difference in cone phase evident (4 mins) between both studies, may be explained by (i) the longer bleach time employed by Hecht and Mandelbaum (3 minutes) compared to the ADA (2 minutes) and (ii) the intensity of the bleach light: Hecht and Mandelbaum state the bleach light was "about" 1900 mL whereas in the ADA the bleach light was 1500 mL: the bleach duration and intensity strongly influence the time appearance of the cone-rod transition, without unduly influencing the rod phase of adaptation\(^{(5,6,7,8)}\).

A similar comparison to that described above was completed which compared the ADA results to a paper by Hecht, Haig and Chase\(^{(7)}\) using the Hecht-Schlaer
The results obtained on two individuals (pre-adaptation 2 minutes at 1950 mL for two minutes) are superimposed as before in Figure 8.5.

Once again the similarities between the published data and the ADA results are striking throughout the rod phase indicating a strong correlation between the two sets of results. The difference in bleach intensity can account for the difference in the cone duration.

Figure 8.5. ADA mean times and decreasing exponential curve (cyan) and standard deviation envelop (blue). Two superimposed curves from Hecht, Haig and Chase obtained on two subjects (highlighted in orange and green) that were light adapted for two minutes at 1950 mL. The Hecht, Haig and Chase starting luminance was 7.2 μL.
8.2.5 Contribution of Additional ADA Luminance Levels

The effect of the 21 additional luminance thresholds (decrement 0.075μL per level) on the test results was found to be beneficial. Reviewing all individual test results (Figure 8.3) demonstrates that the additional thresholds produced a significant improvement in the profile of the dark adaptation curve. The spline profile/exponential is smoother in the rod phase compared to the CPA (luminance decrement 0.3μL per level). The ability of the ADA to discriminate and resolve data provides for a more accurate determination of each subject's final rod threshold. Figure 8.6 below shows that the additional thresholds have improved curve resolution without interfering with adaptation results. Another beneficial effect of the additional luminance thresholds was that the calculated standard deviation was reduced throughout the test compared to the CPA. Figure 8.7 shows the average time at each threshold datum for all 15 subjects in the 20 - 29 age cohort with the associated standard deviations. It should be remembered that the initial 8 discrete thresholds the decrement luminance was 0.3 log steps, which are followed by 29 thresholds of 0.075 log decrements. The additional luminance levels in addition to improving resolution also improved the quality of the data as the time between the perception of one threshold stimulus and the next was substantially reduced compared to the CPA, thus the subject was more involved in the test as they had less time sitting bored in the dark. Waiting a shorter time for the next stimulus apparently improved their concentration.
Threshold Changes approaching Final Rod Threshold
20 - 29 Age Group - All Subjects

Figure 8.6. The percentage of subjects attaining a particular threshold is shown for the ADA (15 subjects) and CPA (12 subjects) as the luminance is reducing. Clearly the ADA’s resolution is superior to the CPA. The higher luminance thresholds are not shown for obvious reasons.
Figure 8.7. Mean threshold times obtained on all 15 subjects in the 20–29 age group with standard deviation. It can be seen that the standard deviation increases to the cone-rod break and remains relatively constant before increasing towards a maximum at final rod threshold.
8.3 ADA Test/Retest Analysis and Comparison with CPA

Two individuals were tested twice on the ADA to investigate the repeatability of test data obtained on the instrument. Of the two, one individual had been examined on the CPA 24 months previously, thus it was possible to directly compare their performance on both the ADA and the CPA.

Case Study 3. Subject 35 was a 23 year old male and was examined twice on the ADA, over a period of two weeks Figure 8.8. The correlation between both examinations was \( r = 0.98, \alpha < 0.05\%, N = 31 \) indicating excellent retest performance by the ADA.

The curves in Figure 8.8 show that the cone-rod break in both tests occurring at 197 seconds (3.2 min) and 236 seconds (3.9 min) respectively. The luminance depth of the
rod phase is 2.26 log units. The data from both tests are almost indistinguishable from each other.

**Case Study 4.**

Subject 7A was a 23 year old male and is interesting because he was also tested on the CPA, 2 years previously; the letter “A” indicates this subject was tested on both CPA and ADA. Figure 8.9 below shows the two dark adaptation curves obtained on the ADA; the retest interval was two weeks.

![Figure 8.9](image)

*Figure 8.9. Subject 7A was tested twice on the ADA, the correlation $r = 0.97$, $\alpha < 0.05\%$, $N = 23$ between both tests. Dark adaptation curve found using spline curve.*

A strong correlation ($r = 0.97$, $\alpha < 0.05\%$, $N = 23$) is present between both data sets although each luminance level was reached later on the second examination. The cone rod break occurs at 6.097 $\mu$J/L in 238 and 312 seconds (3.9 and 5.2 min). The final rod threshold occurs at 3.764 $\mu$J/L in 1040 and 1111 seconds (17.3 and 18.5 min). The
rod luminance depth is 2.33 log units for both curves. The maximum variation in luminance between the two curves occurs at about 460 seconds, (7.6 min) corresponding to 0.4 log units; which is well within the expected test-retest variability of normal populations discussed extensively in Chapter 5. The curves in Figures 8.8 and 8.9 illustrate good test reproducibility by the ADA.

8.3.1 Comparison with CPA

Of particular importance to the author was that the ADA should replicate the performance of the CPA, irrespective of the improvements in its design, thus Subject 7A provided the perfect opportunity for comparison purposes. The dark adaptation curves obtained on Subject 7A using both the ADA and CPA are presented in Figure 8.10. The mean times and standard of four repeat examinations recorded using the CPA are plotted together with the mean times and standard deviations of the two repeat test obtained using the ADA (Figure 8.9 just mentioned above). The cone-rod break in Figure 8.10 occurs at 5.796 μL on both instruments at 275 (ADA) and 374 (CPA) seconds (4.6 and 6.2 min), while the final rod threshold is 3.387 μL (ADA) and 3.464 μL (CPA). What is evident from Figure 8.10 is that both curves are remarkably similar the correlation between the mean times on both units calculated to be \( r = 0.98, \alpha < 0.05\% \), \( N = 13 \), indicating a significant similarity in the results obtained using both the CPA and its successor. The smaller standard deviation error bars evident in the ADA data suggest that the control of the luminance is superior to the CPA. The results presented in Figure 8.10 suggested that although the ADA/CPA correlation is high, an off-set luminance calibration error estimated at 0.3 μL is present; thus the data was normalized and is presented Figure 8.11 which shows a striking similarity in the data obtained on Subject 7A using both instruments.
Male - Right Eye 23 Years
Subject 7A

![Figure 8.10. Mean and standard deviations obtained on Subject 7A obtained using the CPA and ADA. Subject 7A was tested twice on the ADA and 4 times on the CPA. The dark adaptation curves were calculated using Sigmaplot. Note the reduced ADA standard deviation compared to the CPA. The correlation in the mean times is 0.98.](image)

![Figure 8.11. Normalised data obtained on both ADA and CPA exhibit exceptional similarity in test-retest performance by Subject 7A, r = 0.98, α < 0.05, N = 12. Spline fit used here.](image)
8.3.2 20-29 Age Group Comparison: ADA and CPA.

The performance of all subjects in the 20 – 29 age group using both instruments was assessed and compared. Within this age group 12 subjects underwent 35 dark adaptation examinations using the CPA while 15 subjects were examined 17 times on the ADA. The resulting mean times and standard deviations across all subjects and all examinations are presented in Figure 8.12 which demonstrates the similarity in test results as each curve closely tracks the other.

It is evident that the ADA curve has markedly improved profile in that the rod phase is monotonic and that error bars are smaller compared to its predecessor. The ADA cone-rod break occurs at 5.79 μL in 184 seconds (3 min) whereas the break was indeterminate using the CPA. The final rod threshold occurs at 3 μL in both data sets. The correlation coefficient between both curves was calculated $r = 0.94$, $\alpha < 0.01\%$, $N = 15$, indicating that the probability that the two curves are unrelated is small, though as in Figure 8.10 thresholds were reached more quickly with the ADA.

When the data was normalized as before (see Section 8.3.2) assuming a zero error of 0.3 μL then the similarity between the results obtained on both instruments is pronounced Figure 8.13.
Mean Time & Standard Deviations 20-29 age group
CPA - 12 Subjects 35 Examinations
ADA - 15 subjects 17 Examinations

\[ r = 0.94 \]
\[ \alpha < 0.01\% \]
\[ N = 15 \]

Figure 8.12. Dark Adaptation for all subjects tested on the CPA and the ADA. Note a double decreasing exponential dark adaptation is shown for the ADA results (cyan), however, the CPA results do not yield such a curve, thus a spline fit was used (blue).

Concept Unit - 12 Subjects 35 Examinations
ADA - 15 subjects 17 Examinations

\[ r = 0.94 \]
\[ \alpha < 0.01\% \]
\[ N = 14 \]

Figure 8.13. Normalised Dark Adaptation presented in Figure 8.12 for all subjects tested on CPA and the ADA.
The ADA's performance was shown to be closely correlated to the dark adaptation data obtained on the CPA though with improvements as noted above. Thus it is reasonable to hypothesis and infer that the ADA should possesses the ability to discriminate age related dark adaptation changes as demonstrated by the CPA in Chapter 5; it was not feasible to investigate such older age groups at the time of writing.

8.4 Conclusion

This Chapter reported on the results that were obtained on 15 healthy subjects using the ADA. These results showed that the ADA performed well when compared published results. Test/retest results where also shown to be consistent indicating excellent reproducibility. The ADA performed well compared to the CPA, and provided improved data resolution with a corresponding reduction in standard deviation sizes.

The next Chapter will present results that were obtained when the ADA was directly compared to the Goldmann Weekers Adaptometer.

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8 Chase, A (1961) The course of rod adaptation as influenced by the intensity and duration to pre-adaptation light. J. Gen Physiol. 735 -751
9. Comparison between the ADA and the GWA

9.1 Introduction

In order to further evaluate the ADA, a detailed clinical study was performed that directly compared subject performance using the Automatic Dark Adaptometer (ADA) and the Goldmann Weckers Adaptometer (GWA) under matching experimental conditions. All volunteer subjects in this study were required to take a rigorous ophthalmic examination before inclusion into the study. The Optometry Department within the Dublin Institute Technology, Ireland, provided assistance in selecting/screening suitable candidates for inclusion into the study. The testing procedures have already been described in Section 4.3.

9.1.1 Volunteer Subject Screening

To establish a homogenous set of normal subjects it was necessary to query and examine all potential subjects for disorders that cause defective dark adaptation (Chapters 1) and exclude where appropriate. The ocular examination was carried out with the assistance of, 3 supervised 4th year Optometry undergraduate students, as part of their final year research thesis. The clinical supervision of these students was carried out by Dr. Veronica O'Dwyer, a qualified Optometrist and senior lecturer within the Optometry Department DIT: the author supervising training and testing procedures on the ADA and GWA.
As part of their research thesis, each ophthalmic undergraduate student was required to complete a detailed questionnaire on all potential subjects which recorded subject’s personnel details including test date, investigator name, subject name, sex, age, occupation and hobbies, (activities that expose the retina to ultra-violet radiation, such as sailing, fishing, sunbathing or tanning saloons, lengthen dark adaptation times; consequently such persons were excluded (Section 1.3). Each potential subject’s ocular history was ascertained and recorded to ensure that they never had strabismus (squint) nor undergone surgery for squint correction (which can result in eccentric fixation) nor had history of infection or injury to the eye which may affect visual field. Potential subjects were questioned about their general health, including details of prescribed medications, if any.

Subjects diagnosed or identified with cataract, vitamin A mal-absorption, vitamin A deficiency, diabetes, retinitis pigmentosa, gastrointestinal or liver disease, cystic fibrosis, or dystrophies of the retinal pigment epithelium were deemed inadmissible to the study. Medicated depressive individuals on Lithium therapy were also excluded.

Ophthalmoscopy was carried out on each potential subject to insure that their eyes were free from any signs of abnormal ocular or systemic conditions. Only those subjects with normal ocular pathology and normal visual acuity (emmetropic refraction), without eccentric fixation problems, were accepted into study. All remaining potential subjects underwent visual field screening to ensure they were free from scotomas. Fields were screened on the Henson 2000 or Henson 4000 visual field screeners.

Upwards of 30 potential volunteer subjects underwent a through ophthalmic examination which resulted in a total of 19 subjects been chosen for the study of
which 12 were male and 7 female; the age range was 19 – 29 years and comprised final year science degree and postgraduate research students within the School of Physics. All volunteer were unbiased and had never undergone prior dark adaptation examination. A total of 16 subjects completed the full study and were tested on the ADA and GWA, three subjects absconded.

9.1.2 GWA Modifications and Test Protocols
As the GWA used a 4cm diameter single circular stimulus, a modification was made so that it matched more closely the ADA, specifically a rectangular opaque card with a 35 mm × 35 mm transparent aperture was placed over the GWA stimulus to match the stimulus size applicable to the ADA: in addition a 40 mm × 40 mm schott glass green filter (peak 540 nm ± 50 nm) was placed over the GWA stimulus to match the wavelength of the LEDs used by the ADA. The eccentricity of the target was 10° with the target subtending 9° at fixation.

Calibration on both the ADA and GWA was performed using the UDT 40X Optometer as previously described. A luminance scale was determined for the GWA which matched that of the ADA, thus the initial luminance, presented by both instruments, was identical. As before, the pre-adaptation period was 2 minutes at 1500 mL.
9.2. ADA and GWA Individual Test Results

In a typical GWA examination upwards of 80 plus unique “paper pricked” data points are recorded (over 20 minutes) for each subject (Figure 1.1) and it requires the subjective skill of the principle investigator to interpret these points and draw the best fit curve through the data points. The difficulty encountered with the GWA test results is that it difficult to determine the luminance of all 80 plus “pricked” thresholds making it difficult to compare test results to the ADA.

Thus it was decided to abandon the spline curve algorithm used by Sigma plot and to draw the adaptation curve by hand instead using the subjective interpretation and expertise of the investigator to determine the best fit curve. The dark adaptation data that is presented here comprises the operator determined curves for both the ADA and GWA.

Of the 16 subjects examined, 2 case studies are presented below which are typical of the results obtained, the remaining curves are presented in Appendix 8.
Case Study 1.

Figure 9.1. The ADA and GWA dark adaptation curves are coded red and purple respectively. The luminance axis has resolution of ± 0.1 μL while time axis 10 second resolution. The threshold times at 4.5 μL are 470 (ADA) and 540 (GWA) seconds. The starting luminance on both instruments was identical.

Figure 9.1 shows the dark adaptation curves obtained on a 19 year old female when examined on the ADA and a week later on the GWA. The cone rod break occurs at just over 200 seconds (3.3 min) (GWA) and 280 seconds (4.6 min) (ADA) at approximately the same threshold luminance. The cone-rod break in this instance is more clearly identifiable on the ADA compared to GWA. The ADA curve also shows a classic fast initial rod phase, whereas the GWA shows a more gentle decay initially. The difference in absolute rod threshold on both instruments is about 0.1 log units, however, the ADA reaches final rod threshold after 1300 seconds (21.6 min) while the GWA is longer at 1600 seconds (26.6 min). The rod luminance depth in both
instruments is just over 2.6 log units. The significant point here is that on average 0.2 log units of luminance separates the results on both units throughout the rod phase.

A precise manual extraction of adaptation times (estimated error ± 5 seconds) at increments of 0.1 log units of luminance was performed on the results presented in Figure 9.1 (and all 16 subjects) in order to obtain an accurate quantitative assessment of the correlation and significance level between the results obtained on both instruments. A plot of the extracted times for the ADA and GWA for 33 discrete thresholds shown in Figure 9.2

![Regression line showing 95% confidence limits, showing the adaptation threshold times obtained on the ADA and GWA. The difference in luminance between adjacent datum points is 0.1 log units. The plateau at 200 seconds (x axis) corresponds to the cone-rod break.](image)

Figure 9.2. Regression line showing 95% confidence limits, showing the adaptation threshold times obtained on the ADA and GWA. The difference in luminance between adjacent datum points is 0.1 log units. The plateau at 200 seconds (x axis) corresponds to the cone-rod break.
The number of data points presented in Figure 9.2 was $N = 33$, with yields a correlation coefficient $r = 0.94$ and $\alpha < 0.05\%$, a highly significant result indicating that the data obtained on both instruments are highly statically related.

**Case Study 2**

![Graph showing dark adaptation curves]

*Figure 9.3. The ADA and GWA dark adaptation curves are red and purple respectively.*

Dark adaptation for another typical set of results is presented in Figure 9.3 on Subject 58 a 20 year old female. This figure demonstrates the similarity of the test data obtained on both instruments, for example while poorly defined, the cone-rod break can be discerned at about 190 (ADA) and 205 (GWA) seconds (3.1 min and 3.4 min); thereafter, both curves track each other very closely. The average difference in luminance thresholds during the rod phase is about 0.3 – 0.4 log units. The final
threshold for the ADA occurs after about 900 seconds (15 min) compared to 1500 seconds (25 min) for the GWA. The rod luminance depth is just over 2.7 log units, with virtually the same final rod threshold. The correlation between the threshold times (increments 0.1 log units) was determined as before and is shown in Figure 9.4.

Figure 9.4. Regression line showing 95% confidence limits, showing the adaptation threshold times obtained on the ADA and GWA. The difference in luminance between adjacent datum points is 0.1 log units.

The number of data points presented in Figure 9.4 is N = 38, with yields a correlation coefficient of $r = 0.99$ and $\alpha < 0.05\%$, representing a close relationship between the performance of the ADA and GWA which is highly significant.
9.3 Presentation and Analysis of Test Data on 16 Subjects

The results of all 16 subjects tested on both the ADA and GWA are presented separately in Figure 9.5 and Figure 9.6 where the characteristic dark adaptation curve features are compared and contrasted. A number of observations may be made when comparing the results in Figure 9.5 and Figure 9.6 (i) the duration of the cone-rod breaks occurs on both units at just over 200 seconds (ii) similarly both the cone phase extents over 1.0 log units of luminance (iii) the rate of rod adaptation is similar (iv) the time to reach final rod threshold is about 1000 seconds in both cases (v) the final threshold appears to be in the range $\log_{10} 3.5 \pm 0.5 \mu\text{L}$ (vi) between 400 and 600 seconds the spread in results appears to be slightly greater in the ADA data compared to the GWA data.

Both sets of results are superimposed in Figure 9.7 which clearly shows that the performance of the ADA and GWA are comparable. However, while Figure 9.7 demonstrates graphically the similarity of two sets of data, a quantitative comparison was required, the manual process already described on Subjects' 45 and 58 was repeated on all subject curves in this study, a painstaking process that nevertheless yielded excellent results which are presented in Table 9.1 below.
Figure 9.5. ADA dark adaptation curves for all 16 subjects, 20 – 29 years

Figure 9.6. GWA dark adaptation curves for all 16 subjects, 20 – 29 years.
Table 9.1 shows the *Absolute Rod Threshold* and *Rod Luminance Depth* which were calculated on each of the 16 subjects in this study. The correlation and significance level for each subject is also shown. From Table 9.1 it was found that the mean luminance level at absolute rod threshold was $3.7 \pm 0.33 \log_{10} \mu\text{L}$ (ADA) and $3.6 \pm 0.28 \log_{10} \mu\text{L}$ (GWA). The average time to reach absolute rod threshold using the ADA was $1093 \pm 239$ seconds and $1108 \pm 172$ seconds on the GWA; the depth of the rod phase was $2.3 \pm 0.35 \log$ (ADA) and $2.4 \pm 0.29 \log$ (GWA). The correlation between test results obtained on the ADA and GWA was calculated $0.95 \pm 0.04$ with $\alpha < 0.05\%$, $N = 16$. 

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*Figure 9.7. The superimposition of both curves in Figure 9.5 and 9.6 which demonstrates the similarity of the results obtained on the ADA compared to the GWA.*
These results strongly indicate that the ADA's performance is closely matched to the GWA.

These results strongly support that the ADA can the required performance to assess human dark adaptation in a reproducible and reliable way.

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Table 9.1. Final rod luminance thresholds and rod depth obtained on the ADA and GWA. The correlations between the each subject's test data obtained on the ADA and GWA is shown, significance levels $\alpha < 0.05\%$, 26 < $N$ < 37. The blanks represent an inability to accurately quantify the cone-rod break location. Subjects 52 and 58 were used in case studies 1 and 2.
9.3.1 Analysis - Absolute Rod Threshold
The results in Table 9.1 may be used to compare the ADA and GWA using a statistical method pioneered by Bland and Altman\(^{(1)}\). Using this technique the difference in the luminance at absolute rod threshold between both instruments, ADA - GWA, was found and plotted against the mean of the performance \((\text{ADA} + \text{GWA})/2\). The mean of the differences was determined to be \(\bar{x} = 0.09 \, \mu\text{L}\), which suggests a small bias in the results, indicating that the ADA will report a slightly higher luminance at absolute rod threshold. The standard deviation \(\sigma\) was calculated at \(\pm 0.33 \, \mu\text{L}\). The 95% confidence limits of this bias were also calculated, standard error = 0.086 and the \(t\) distribution = 2.13, \(df = 15\); hence the interval for the bias is 0.09 ±0.18. It is expected that 95% of the differences between both instruments will lie between \(\bar{x} - 2\sigma\) and \(\bar{x} + 2\sigma\), thus at absolute rod threshold

\[
\bar{x} - 2\sigma = 0.09 - (2 \times 0.33) = -0.57 \, \mu\text{L}
\]
\[
\bar{x} + 2\sigma = 0.09 + (2 \times 0.33) = 0.75 \, \mu\text{L}
\]

From Figure 9.9 it can be seen that the ADA may be 0.57 \(\mu\text{L}\) below or 0.75 \(\mu\text{L}\) above the GWA at absolute rod threshold.

The 65% confidence limit was also determined for the data was found to lie between \(\bar{x} - \sigma = -0.24 \, \mu\text{L}\) and \(\bar{x} + \sigma = 0.42 \, \mu\text{L}\). Is this an acceptable result?

To answer this question it is worth recalling that standard deviations determined on same subjects using identical testing conditions and instrumentation have shown that the best estimate of the luminance at absolute rod threshold has an associated uncertainty of \(\pm 0.3 \, \mu\text{L}\)\(^{(2,3,4)}\) (see Section 5.3.3). This reported inter subject variation

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of ± 0.3 is within the uncertainty range of that was measured between the ADA and GWA, that is ± 0.33 μL. Thus there is reason to suggest that the ADA can determine the absolute rod threshold to a similar precision the ADA albeit with a 0.09 μL bias.

Figure 9.9. At absolute rod threshold, the difference in luminance between the ADA and GWA, obtained from Table 9.1, is plotted against the mean of the luminance. The mean difference or bias is ±0.09 μL and is identified by the blue line, the 95% and 68% confidence limits are shown in red and green respectively. Between the red lines, i.e. between $\bar{x} \pm 2\sigma$, 95% of the differences will lie within these limits for a normal distribution.

9.4 Conclusion

In this Chapter the ADA was evaluated by comparison with the GWA with the assistance of the School of Optometry and final year students under the author’s direction. The totality of results presented in this chapter clearly demonstrate that the ADA test results obtained on 16 healthy volunteer subjects are closely correlated with...
test results obtained using the GWA. The results presented here strongly supports the argument that the new instrument can accurately and reproducibly record dark adaptation data.

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10. Conclusions and Further Work

At the commencement of the research work described in this thesis the primary objective was to design and construct an inexpensive portable instrument that could faithfully determine human dark adaptation. It was the intention that the instrumentation so devised could be used both in first world health care systems and in third world subsistence economies, particularly with those children at risk of vitamin A deficiency. The intention was to develop an instrument that could acutely determine the features of the dark adaptation curve, without the disadvantages of bulk, weight and other disadvantages of the Goldmann Weekers Adaptometer (GWA), but with the advantages of digital instrumentation such as data storage and display. This thesis outlined the detailed development, design, construction and evaluation of the Concept Prototype Adaptation (CPA) and its successor, the Automatic Dark Adaptometer (ADA), which included modifications and improvements to the original design.

The philosophy behind the design of the new instrument was that it be as simple as possible to use, thus the test protocol as described provided for a game like experience that maintained subject concentration throughout the testing period which would be of particular use with testing children.

A novel feature of the new instrument is that the test is completely controlled by the subject who interacts directly with the apparatus; thus a clinician was not required to sit in the dark with the subject under test for long periods, thus the operator/clinician
can monitor the test externally in real time and supervise/direct the subject as and when required. Another novel feature is that unlike the GWA where the luminance is continuously varied by the operator, the new instrument’s luminance was adjusted in predetermined decrements over 37 luminance levels.

The CPA and ADA also featured several unique features that included the use of a plurality of test stimuli consisting of four test green LED arrays located about a central red fixation LED that were randomly presented to the subject, which minimised the likelihood of a learning curve by the subject, which is a possibility with single stimulus instruments like the GWA.

The new instrument was designed to be light and very portable, thus a rechargeable battery was used which maximised the portability and avoided regulatory issues concerning electrical safety relating to medical devices.

Parallel with the development of the new instrument, a long and detailed process was undertaken to write a patent application and submit it to the US patent office. Following vigorous review and literature searches by patent officials, the US patent office decreed that the new instrument possessed sufficient novelty and innovation that a patent was granted on the new instrument. Subsequently, patents were granted in other major countries listed in appendix 2.

As stated the initial objective of the research undertaken required the construction of a simple adaptometer capable of determining dark adaptation, however, as the work developed these objectives changed and became more ambitious.
As discussed in this thesis the first instrument constructed was the CPA which was built according to well established principles based on the physiology of vision which were outlined in Chapter 1. Just how important these principles are, was demonstrated during the initial commissioning of the CPA, where it was found that an error in the viewing distance and thus eccentricity of the test stimuli, was found to adversely affected the results. The design and construction has been discussed extensively, however, it is worth commenting that ability to control the luminance of the LED arrays over a dynamic luminance range of $4.5 \log_{10}$ units was a notable achievement.

While the CPA was very much a laboratory prototype with external power supplies and signal generators, it has been clearly shown that the CPA could obtain accurate dark adaptation results over several repeat examinations on the same subject, even when the duration between examinations was of the order of months in many cases. Case studies were presented on several of the 22 volunteer subjects which detailed repeat test results which showed high correlations and significance values between tests. These results highlighted the repeatability of test results obtained on the CPA using Bland Altman methods for example, Subject 3, a 40 year old male showed excellent measurement repeatability and well established cone-rod break times over 4 examinations Figure 5.4, page 127.

The comparison of the CPA with published results by Hecht and Mandelbaum\(^{(1)}\), Hunt and Hayden\(^{(2)}\), Sheard\(^{(3)}\), Sloan\(^{(4)}\), Mote\(^{(5)}\) and Henson and Allen\(^{(6)}\) (using the Hecht and Schlaer, Goldmann Weekers and Henson and Allen adaptometers) showed very close correlations with the CPA data. The repeatability of the CPA was further
demonstrated by considering the standard deviation variability which proved to be very similar to those reported by Hecht and Mandelbaum, and Sheard.

A significant factor in proving the precision and performance of the CPA was that it should be capable of identifying changes in dark adaptation as a function of age. Analysis showed that the CPA could observe, (i) a slowed rate of adaptation and, (ii) an elevation in absolute rod threshold in older subjects. The CPA data suggested that for every 12.9 years increases in age, the absolute rod threshold was elevated by 0.3 log units which compared well to McFarland-Fisher(7) and Fisher-Domey(8) who reported a rise on 0.3 log for every 13 year interval.

The results obtained and finding made during the evaluation stage of the CPA were sufficiently promising that a second fully automated pre-production instrument was envisaged and subsequently constructed, although with changes and modifications. During the CPA’s evaluation a number of limitations were discovered that needed to be addressed in any future design. Specifically it was identified that the 0.3 log luminance decrement was too large particularly during the rod phase of adaptation. Near the asymptote of the decay curve, it was found that subjects sometimes had to wait several minutes before the next stimulus became visible which caused them to lose concentration, which adversely affected the results in some instances. In addition at the bottom of the decay curve there was an uncertainty as to the luminance at absolute rod threshold, for example a subject may have been waiting in the dark for many minutes and just as there sensitivity has almost increased to the next luminance level, the test is terminated, thus the recorded maximum rod sensitivity for that
subject may be elevated. This uncertainty lead to some dark adaptation curves lacking a monotonic shape.

The improved instrument as outlined in this thesis was constructed with the assistance of several companies providing expertise in circuit design, software programming, ergonomic design, printed circuit design layout and production and enclosure construction. The improved instrument devised was a completely independent portable instrument that was powered by a rechargeable battery with all circuit, oscillators, buzzers, all enclosed within a single enclosure housing.

While the test protocols employed on both the CPA and ADA were identical, it is worth commenting that the use of a programmable EPROM, allows for the development of alternative test protocols to be implemented, for example a protocol to increase and decrease the luminance in a similar manner to the GWA is readily achievable, thereby demonstrating the versatility of the design.

The single most important new feature incorporated into the ADA included additional luminance levels, such that the number of discrete luminance levels increased from 16 (CPA) to 37 presented over a 4.5 log luminance range. At the start of a dark adaptation test there was a 0.3 log decrease in luminance for the first 8 luminance levels, thereafter the decrease was 0.075 log over the remaining 29 luminance levels. The effect of these extra luminance levels were 3 fold, (i) the resulting dark adaptation curves, particularly in rod phase, were much improved with a decidedly smoother shape decreasing monotonically (ii) approaching the asymptote near absolute rod threshold, the additional luminance levels increases the precision
(decreases the uncertainty) of the luminance measurement determination at absolute threshold (iii) the additional levels resulted in addition interaction by the subject with the instrument as a consequence of the extra levels, this increased concentration by the subject and improved test curve profiles.

The evaluation of the ADA on 15 normal subjects in the 20-29 age group showed that there was a strong inter-correlation and coefficient of repeatability between all test results which demonstrated good reproducibility. These results were also compared to published results, notably by Hecht and Mandelbaum using the Hecht-Schlaer\textsuperscript{(9)} adaptometer. The direct comparison of the mean and standard deviations presented in Figure 8.4, page 213 demonstrates conclusively that the ADA obtained near identical results to those reported by Hecht and Mandelbaum. This singular result provides conclusive evidence that the ADA can function to the precision demonstrated by the Hecht-Schlaer adaptometer. Supplemental support to this conclusion can be seen in Figure 8.5, page 214; where the ADA’s results are compared to results reported by Hecht, Haig and Chase\textsuperscript{(10)}, once again it is evident that the ADA’s performance correlates well with accepted dark adaptation curves.

There was a requirement to compare the performance of the CPA and ADA to ensure that the ADA could perform as well as its predecessor, without any loss of precision. Subject 7A, underwent detailed examination on the CAP, and two years later, was examined on the ADA. There was a strong correlation between both sets of results albeit with the ADA providing improved resolution of data throughout the rod phases of the test. The results from both instruments showed, that there was no loss of functionality nor precision observed in the ADA. Comparison of the CPA and ADA
was also made between groups of subjects in the 20-29 age group which also showed strong group correlations, thus indicating no loss of precision in the ADA compared to the CPA. It is therefore reasonable to conclude that the ADA would possess the ability to observe age changes in the older subjects; however, it was not possible to confirm this directly.

The gold standard GWA was also used to assess the ADA: a detailed investigation was completed under the supervision of the author, who designed the test protocols and trained final year Optometry students to operate the ADA and GWA instruments. A total of 16 healthy subjects in the 19-29 age group were examined on both the ADA and GWA. A number of typical case studies were presented, which showed there is a close correlation and confidence intervals between both instruments with demonstrated similarities in absolute rod threshold values and the depth of the rod luminance as presented in Table 9.1, page 236. A comparison between the two sets of data was made using a Bland-Altman plot which showed the ADA functioned as well as the GWA. A small bias in the results suggests that the ADA will report a slightly higher luminance at absolute rod threshold corresponding to 0.09 μL.

The results and analysis reported in this thesis strongly suggests that the new instrument demonstrates the accurately, repeatability and sensitivity to reliably quantify dark adaptation and produced results comparable to that in published literature.
Further Work

It is planned to continue research using the ADA in a number of areas, including the review of several patients that have been referred to Dr. Peter Davison with suspected congenital night blindness: it is planned to carry out a full ophthalmic examination including examination of night vision using both the ADA and GWA. A number of Optometry Schools have expressed an interest in obtaining the ADA on loan to carry research and as a teaching tool, the completion of this thesis with associated publications will greatly facilitate and enhance these development. Other developments include the interfacing of the ADA with Labview to control the ADA from a PC and store patient information and patient test results using a user friendly interface.

The object at the start of this work was the construction of a simple dark adaptometer that could assess nutritional night blindness and vitamin A deficiency in children living in subsistence economies. The Automatic Dark Adaptometer outlined here is one such attempt to achieve this objective, it has been shown here that the ADA has the accurately, reproducibility and sensitivity to quantify dark adaptation. It is hoped that some of the ideas presented here may assist and inspire others to develop a similar or other suitable technique that can address the devastating consequences of vitamin A deficiency on childhood morbidity and mortality globally.

Epilogue

It is several months since the successful defense (22/1/09) of this thesis. The author has since had time to consider the research work presented herein and reflect on the views expressed at the viva voca by Professor David Henson, External Examiner,
Manchester University and Professor Eugene Coyle, Internal Examiner, Dublin Institute of Technology.

The author acknowledges that the use of staff/students volunteers, while comprising a convenient sample, is not best clinical investigative practice. Ideally, data should have been collected from a wider range of subjects in order to establish a normal sample baseline. Also, the absence of vitamin A deficient subjects makes it difficult to evaluate fully the sensitivity and specificity of the ADA - this is an area of further work. Similarly, in order to establish and quantify the age effects a more representative sample should have been examined. Ideally, at least ten subjects in each decade of life should have been examined to establish normal dark adaptation values for comparison with vitamin A subjects.

Following the thesis defense, additional analysis was completed using Bland Altman methods which established that the ADA demonstrates good test repeatability, a finding that supports the conclusions made using conventional correlation coefficient methods.

In this thesis spline curve fitting was liberally used, however, this curve fitting method sometimes gave odd results, subsequent to the viva, two decreasing exponential curves were fitted to the data where appropriate. In order to improve the quantitative comparison of the dark adaptation curves, it was suggested that the exponential curve fit residuals could be used to compare dark adaptation curves more fully - a suggestion worth investigating further.
Throughout this report the old unit of $\mu L$ambert was used as the principle unit while the SI unit $cd.m^{-2}$ was used as the secondary unit, all dark adaptation curves were subsequently modified to include the SI unit of luminance.

It was perhaps unclear from reading this thesis that the light adaptation method used in evaluating both the CPA and the ADA used the integrating sphere from the GWA. While light-adaptation of subjects was attempted using a photoflash tube, this method yielded poor results. Thus, it is acknowledged there is a requirement to construct a portable light-adaptation device; for example, the idea that bright white light LEDs be incorporated into a miniature sphere, appears to be a promising option and is worth investigating – such a small integrating sphere could readily be incorporated into the ADA rendering it completely portable.


Appendices

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Appendix 1  Bitot's Spots and Fundus lesions

PLATE 2
A. BITOT'S SPOT (X19) WITH CONJUNCTIVAL XEROSIS

* Early Bitot's spot, the foam covering a patch of mild conjunctival xerosis. Five-year-old Indonesian boy with a 6-month history of night blindness. Reproduced by courtesy of Dr A. Sommer.

B. CONJUNCTIVAL AND CORNEAL XEROSIS (X2)

* Conjunctival and early corneal xerosis in a 2-year-old Indonesian boy. Both the conjunctiva and cornea have a coarse, dry, granular appearance in place of their normally smooth, shiny luster. Reproduced by courtesy of Dr A. Sommer.

PLATE 3
A. CORNEAL ULCEATION (X3A) WITH XEROSIS

* Marked conjunctival thickening and wrinkling and infiltration of the cornea with vascularization. Early ulceration is present. Child aged 2 years 3 months (Case No. 15437). Plasma vitamin A: 3 μg/100 ml; liver vitamin A: 0.3 μg/g. For a more pronounced example of X3A, see McLaren et al (64). Reproduced by courtesy of Dr D.S. McLaren.

B. KERATOMALACIA (X3B)

* Child aged 14 months with colliquative necrosis affecting the greater part of the cornea (Case No. 17957). The relative sparing of the superior aspect is typical. Plasma vitamin A: 4 μg/100 ml; liver vitamin A: 3 μg/g. Reproduced by courtesy of Dr D.S. McLaren.
Fundus photograph showing typical seed-like, raised, whitish lesions scattered rather uniformly over the part of the fundus at the level of the optic disc. Reproduced by courtesy of Dr A. Sommer.

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20/10/2008
Appendix 2    Publications and US Patent

Publication:


D.O. Brien, Dr. P. Davison, and Dr. T. Grennan. Australian Patent, *Apparatus for testing dark adaptation*, Optometrics Limited, AU4980590 (A)

D.O. Brien, Dr. P. Davison, and Dr. T. Grennan. New Zealand Patent, *Apparatus for testing dark adaptation*, Optometrics Limited, No. NZ232555 (A)
Apparatus for testing dark adaptation comprises a test panel. Four test stimuli, comprising arrays of light emitting diodes, are arranged on the test panel around a fixation light emitting diode. Translucent covers are mounted over the arrays of light emitting diodes. Four switches to enable a subject to input the identity of a visible test stimulus are provided, each switch is operated by a button formed by a respective cover of the test stimuli. A test stimulus is randomly selected and switched on at a predetermined level of luminance. On a correct identification, another test stimulus is selected and switched on at a reduced level of luminance. The times from the commencement of the test until the various correct identifications are recorded, as are the corresponding level of luminance of the test stimuli.

20 Claims, 7 Drawing Sheets
APPARATUS FOR TESTING DARK ADAPTATION

FIELD OF THE INVENTION

The present invention relates to apparatus for testing dark adaptation of the eye of a subject.

BACKGROUND TO THE INVENTION

The process of dark adaptation is the process by which sensitivity of the visual system, namely the eye and the brain, to light increases when an individual is placed in darkness. The ability of one or both eyes to adapt to darkness may be impaired by a number of causes, for example nutritional deficiencies, diseases and inherited abnormalities. When the ability of the eye of an individual to adapt to darkness is impaired, either the speed or the extent or both at which the eye can adapt to darkness may be adversely affected. Attempts in the past have been made to provide apparatus for testing dark adaptation of the eye of an individual; however, all such apparatus suffer from disadvantages. In particular, it has been found that such known apparatus are unsatisfactory for use in testing dark adaptation of a child. Further, most tend to be relatively cumbersome and/or relatively expensive and in general must require a relatively skilled operator to measure dark adaptation.

A typical example of apparatus for testing dark adaptation is disclosed in U.S. Pat. No. 3,936,162. This apparatus comprises a face mask having an eye piece for viewing the subject. A pair of test stimuli provided by two light emitting diodes are mounted in the eye piece so that, in use, the light emitting diodes are in alignment with the optical axis of the subject's eyes. A control circuit provided in a remotely mounted cabinet controls the level of luminance of the diodes in a time ordered sequence. The level of light intensity of the diodes sequentially increases from commencement of the test until it reaches a maximum and then is returned to its minimum value and it increases again sequentially in a time ordered sequence to the maximum and so on. On a subject perceiving the light, the subject operates a switch which stops the sequence. The level of luminance of the diodes when it becomes visible to the subject is displayed. The person carrying out the test manually times the test and on a level of luminance being displayed records the time and level of luminance. The test is continued in this fashion and the ability of the subject to adapt to darkness is determined from the recorded results.

However, this device is particularly unsuitable for use with children, since a child could indicate that the light emitting diodes were visible to it when in fact they weren't. This obviously would give incorrect results. A further problem with this apparatus is that by virtue of the fact that the level of luminance of the diodes continuously alters in a time ordered sequence, the apparatus tends to give relatively inaccurate results, whether in a child or adult subject. Furthermore, by virtue of the fact that the person carrying out the test must determine the time at which the light emitting diodes become visible to the subject an accurate determination of time is relatively difficult to obtain. Additionally, a further problem with this apparatus is that the area of the retina being tested is limited to the central region. This is because the light emitting diodes are located on the optical axis of the eye, and in close proximity to the eye.

Another apparatus for testing dark adaptation as well as other parameters of the eye is described in British Patent Specification No. 2,114,406. This apparatus comprises a cathode ray tube which displays to a subject a fixation point anywhere in the field of the tube screen and a test stimulus which moves on the screen. The brightness of the test stimulus is adjustable over a range of 10,000 to 1. The background brightness of the screen is also adjustable. By moving the test stimulus and altering the brightness and determining the time at which the test stimulus becomes visible the dark adaptation of the eye of the subject may be determined. However, this device also suffers from the serious disadvantage that it is unsuitable for use with a child since the child could indicate that the test stimulus was visible to it when, in fact, it wasn't, thus giving spurious and inaccurate results. Furthermore, a particular disadvantage of this device is that it tends to be relatively complex, difficult to operate and relatively expensive to produce.

There is therefore a need for apparatus for testing dark adaptation of the eye which overcomes the problems of known apparatus. The present invention is directed towards providing such apparatus.

OBJECTS OF THE INVENTION

One object of the invention is to provide apparatus for testing dark adaptation of the eye of a subject which is relatively easy to use and operate. It is a particular object of the invention to provide such apparatus which is suitable for use in testing dark adaptation of children. A further object of the invention is to provide apparatus for testing dark adaptation of the eye of the subject which is relatively inexpensive. A still further object of the invention is to provide such apparatus which has a relatively low power consumption and can be used in relatively primitive locations and is also not cumbersome.

A further object of the invention is to provide a method for determining dark adaptation of the eye of a subject.

SUMMARY OF THE INVENTION

According to the invention, there is provided apparatus for testing dark adaptation of the eye of a subject comprising: a plurality of test stimuli, switch means for switching on one of the test stimuli, input means for permitting the identity of a test stimulus perceived by the subject to be visible to be inputted, comparing means for comparing the identified test stimulus with the test stimulus switched on, first selecting means responsive to the comparing means for selecting a test stimulus to be switched on, on a correct identification being made. In one embodiment of the invention, the input means is operable by the subject.

In another embodiment of the invention, the selecting means is a random selecting means.

In a further embodiment of the invention, second selecting means for selecting the level of luminance of the test stimulus to be switched on is provided, the second selecting means being responsive to the comparing means, the second selecting means sequentially reducing the level of luminance at which a test stimulus is switched on each time the comparing means detects a correct identification.

Preferably, the second selecting means reduces the level of luminance in predetermined decrements.

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Preferably, timing means are provided for timing the times at which a correct identification is made by the input means from the time the test stimulus is presented to the subject. In one embodiment of the invention, the test stimuli are arranged in proximity to the fixation means and each test stimulus being illuminated against the levels of luminance at which the test stimuli is provided the test stimulus being illuminated against the levels of luminance at which the test stimuli is provided to a subject attempting to indicate visibility of a test stimulus when the test stimulus is in fact not visible to him or her. Further, when the test stimulus is randomly selected from the test stimuli the possibility of an attempt to cheat the apparatus is further reduced.

Another advantage of the invention is that the power requirements of the apparatus are relatively low. This is achieved by virtue of the construction of the apparatus and its related circuitry and method of operation of the apparatus. A further advantage of the invention is that the apparatus is relatively cheap and inexpensive to produce. A particularly important advantage of the invention is that it is relatively simple to operate and in particular by virtue of the method used by the apparatus for obtaining readings of level of luminance of the test stimulus against time from the commencement of the test to the time the stimulus becomes visible the results can readily be plotted to form a curve which graphically represents the dark adaptation of a subject's eye. This is a particularly important and advantageous feature of the apparatus. Advantageously, the apparatus is further reduced.

A further advantage of the invention is that it provides a relatively effective and efficient method for testing dark adaptation.

These and other objects and advantages of the invention will be readily apparent to those skilled in the art from the following description of some preferred embodiments thereof given by way of example only, with reference to the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a perspective view of apparatus according to the invention for testing dark adaptation of the eye. Fig. 2 is an elevation view of a detail of the apparatus of FIG. 1. Fig. 3 is an elevation view of a further detail of the apparatus of FIG. 1. Fig. 4 is a block diagram of circuitry of the apparatus of FIG. 1. Fig. 5 is a detailed circuit diagram of portion of the apparatus of FIG. 1. Fig. 6 is a detailed circuit diagram of other circuitry of the apparatus of FIG. 1. Fig. 7 is a detailed circuit diagram of further circuitry of the apparatus of FIG. 1. Fig. 8(a) to (c) are graphical representations of wave forms used in the operation of the apparatus of FIG. 1 and

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FIG. 8 is a graphical representation of a plot of results read from a test carried out on the apparatus of FIG. 1.

DETAILED DESCRIPTION OF THE INVENTION

Referring to the drawings, there is illustrated apparatus according to the invention indicated generally by the reference numeral 1 for testing dark adaptation of the eye of a subject. The apparatus 1 comprises a test housing 2 and a control housing 3. Both housings 2 and 3 are provided by cabinets 5 and 6 respectively both of which are provided with a front panel, namely a test panel 8 and a control panel 9 respectively. During a test, the test panel 8 is used by the subject as will be described below, and the control panel 9 is used by the person administering the test.

Dealing initially with the test panel 8, a fixation means provided by a red light emitting diode 12 is mounted on the test panel 8 for enabling the subject to focus his or her eyes on the test panel 8 during a test. In this embodiment of the invention, the fixation light emitting diode 12 is of diameter 5 mm. A plurality of diodes 14, namely five rows 15, each row having five diodes, see FIG. 2. A translucent cover 17 of glass covers the light emitting diodes 14 are of diameter 5 mm. Each diode 14 is spaced from its adjacent diodes in each row 15 a distance a. In this case 7 mm centre line to centre line. Each row 15 of diodes 14 is spaced from its adjacent row a distance b, in this case 7 mm centre line to centre line. Each cover 17 comprises a translucent illuminated area 16, namely: by d, in this case, 35 mm by 35 mm, respectively, for diffusing light from the diodes 14. The light emitting diodes 14 are centrally arranged relative to the area 16. The covers 17 are equi-spaced from and around the fixation light emitting diode 12. The horizontal and vertical distances between the centre lines of the covers 17, namely the dimension e, is 50 mm, see FIG. 3. The horizontal and vertical distances between the centre line of the fixation light emitting diode 12 and the centre line of the covers 17, namely the dimension e, is 34.5 mm.

The fixation light emitting diode 12 remains on throughout a test, however, at any one time, only one test stimulus 11 is switched on. Electronic control circuitry described in detail below comprises switch means for switching on a test stimulus 11 and first selecting means for randomly selecting the test stimulus 11 to be switched on. Second selecting means also provided in the control circuitry selects the level of luminance at which the test stimulus is to be switched on. The fixation light emitting diode 12 and the test stimulus light emitting diodes 14 are so chosen that the wavelength of the light being emitted by the test stimulus 11 is predominantly shorter than the wavelength of the light being emitted by the fixation light emitting diode 12. In this case, the peak wavelength of the fixation light emitting diode 12 is 635 nm (red light), while the wavelength of the test stimulus 11 is 565 nm (green light). This ensures that the appropriate receptors within the retina of the subject's eyes are stimulated. The fixation light emitting diode 12 stimulates the cones preferentially, the test stimulus 11 stimulates the rods.

Input means for permitting the subject to input the identity of the test stimulus 11 which is perceived by the subject to be visible is provided by four switches 18 see FIG. 5. Each switch 18 corresponds to a test stimulus 11. Each switch 18 is button operated, and the button of a switch 18 corresponding to a test stimulus 11 is provided adjacent the test stimulus 11. In this case the cover 17 of each test stimulus 11 forms part of the button of the corresponding switch 18. The switches 18, while illustrated in the circuit diagram of FIG. 5, are not illustrated in FIGS. 1 to 3 of the drawings, however, the switches 18 are mounted behind the test panel 8 in the test cabinet 5 in a suitable location. Thus, on a subject perceiving a test stimulus 11 being visible, the subject presses the cover 17 of that test stimulus 11 to operate the switch 18, thus identifying the test stimulus 11 which is perceived to be visible.

During the test, as will be described below, each time a subject correctly identifies a test stimulus 11 as being switched on, the first selecting means randomly selects the next test stimulus 11 to be switched on, and the second selecting means reduces the level of luminance at which the next stimulus 11 is to be switched on by a predetermined decrement.

A pair of alerting means, namely a bell 20 and a buzzer 21 are provided on the test panel 8 to indicate to a subject if the test stimulus 11 is correctly identified. The bell 20 indicates that the correct stimulus has been identified while the buzzer 21 indicates to the subject that an incorrect test stimulus 11 has been identified.

The test housing 3 comprises an on/off mains switch 22 for switching the apparatus 1 on and off mounted on the control panel 9. An indicator lamp 24 mounted on the control panel 9 indicates whether the apparatus 1 is on or off. A start/test push button 25 is provided on the control panel 9 for activating the apparatus 1 to carry out a test or for resetting the apparatus 1. Display means in this case provided by digital displays 27, 28 and 29 are provided for displaying data and information on a test as the test progresses. The digital display 27 indicates which of the test stimuli 11 are switched on. The digital display 28 displays the level of luminance at which the test stimulus 11 is switched on. The digital display 29 displays time. A two position switch 30 mounted on the control panel 9 selects which time is to be displayed on the digital display 29. In one position of the switch 30, the digital display 29 displays the cumulative time from the time the test commences while in the second position of the switch 30, the digital display 29 displays the time for which a particular test stimulus 11 has been switched on. On a test stimulus 11 being correctly identified as being switched on, the display 29, depending on the position of the switch 30, displays the cumulative time from the commencement of the test to the time the test stimulus was correctly identified or the time that the specific test stimulus 11 was switched on at the particular level of luminance until it was correctly identified.

Cable outlets 33 and 34 are provided in the cabinets 5 and 6 respectively for accommodating a cable connecting the circuitry of both cabinets. In practice, it is envisaged that during a test the cabinets 5 and 6 will be mounted remotely of each other. They may be mounted in the same room, or indeed in different rooms. It is believed to be important that the two cabinets should be arranged so that the control panel 9 is not visible to a subject during a test.

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Referring now to FIG. 4, a block diagram of the circuitry of the apparatus 1 is illustrated. For convenience, the parts of the circuitry mounted in the respective test and control housings 2 and 3 are grouped together, and the broken lines represent the test and control housings 2 and 3. Thus the components of the circuitry illustrated within the broken lines representing the test housing 2 are mounted within the test housing 2, while the remaining components are mounted within the control housing 3. The switch means and the first selecting means for selecting and switching on a test stimulus 11 is provided in a test stimulus selector circuit 37 which comprises a random number generator as will be described below, and on being activated randomly selects one of the test stimuli 11 to be switched on. The second selecting means for selecting the level of luminance at which the test stimulus 11 is to be switched on is provided by a luminance level control circuit 38. The level control circuit 38 also controls the luminance level of the fixation light emitting diode 12. In this embodiment of the invention, the level of luminance of the fixation light emitting diode 12 is reduced once on an appropriate line 54, corresponding line 50 which drives the alerting buzzer 21 and to retain the status of the test stimuli 11 unchanged.

Referring now to FIGS. 5, 6, and 7 the electronic control circuitry which controls the apparatus 1 will now be described. FIG. 5 illustrates the test stimulus selector circuit 37 and the subject response circuit 44, while FIGS. 6 and 7 illustrate the luminance level control circuit 38. The circuitry of FIGS. 5, 6, and 7 is powered by a power supply circuit 60 described generally, by the reference numeral 50 and illustrated in FIG. 6. Such power supplies will be well known to those skilled in the art and it is not intended to describe it in further detail here. The power supply circuit 60 receives an input voltage VCC of 9 volts on the line 51. A controlled output voltage VCC is provided on an output line 52 of the power supply circuit 60. In this case, the controlled voltage VCC is five volts. One side of the light emitting diodes 14 of the test stimuli 11 are fed from outputs 54 a to e of the luminance level control circuit 38 illustrated in FIG. 6 which will be described in detail below. The outputs 54 a to e applies a high to the diodes 14 to be switched on. The other side of the diodes 14 of the test stimuli 11 are controlled by the selector circuit 37. Returning now to FIG. 5, where the diodes 14 of a test stimulus 11 are to be switched on, a low is applied to the other side of the diodes 14 on an appropriate line 60 to 63 through the switch means which comprises transistor T1 to T4, one transistor T1 to T4 being provided for a corresponding test stimulus 11. The appropriate transistor T1 to T4 is selected by the first selector means for selecting the test stimulus to be switched on. The first selector means comprises a random number generator which comprises a clock chip 55 operating at 100 KHz, a flip flop counter circuit 55 to 58, and a NOR chip 57. The flip flop counter chip 55 in this case is provided by a 4017 CMOS chip. The chip 55 comprises a divide by ten decade counter with ten decoded outputs. The counter is cleared to one on its reset pin 15. The clock chip 55 clocks the counter chip 56 at 100 KHz. An AND gate 58 connected to the fourth output pin, namely pin 10 of the counter chip 56 limits the count sequence of the chip 56. The logic of the chip 56 is arranged so that on the clock pin 14 going high, the output on pin 3 of the AND gate 58 goes high, thereby resetting the counter to zero. Because the counter chip 56 is clocked at the high rate of 100 KHz, stopping the counter results in a discrete pseudo-random output, which controls the operation of the one-in-four selector chip 57. Accordingly, the outputs appearing on pins 12 to 15 of the one-in-four selector chip 57 are randomly selected. A high on any one of the output pins 12 to 15 switches on a corresponding transistor T1 to T4, thereby applying a low to the diodes 14 of the test stimulus 11 selected through the corresponding line 60 to 63. Comparing means for comparing the inputted response of the subject through the switches 18 with the status of the test stimulus 11 is provided by the comparing means in the subject response circuit 44. FIG. 5 illustrates the test stimulus selector circuit 37 and the light level selector circuit 38 to select and switch on the next test stimulus 11 and to select the level of luminance of the next test stimulus 11. On the subject response circuit 44 detecting operation of an incorrect switch 18 a buzzer circuit 46 which drives the alerting buzzer 21 is operated to activate the buzzer 21 and to retain the status of the test stimulus 11 unchanged.

FIG. 6 illustrates the test stimulus selector circuit 37 and the subject response circuit 44, while FIGS. 6 and 7 illustrate the luminance level control circuit 38. The circuitry of FIGS. 5, 6, and 7 is powered by a power supply circuit 60 described generally, by the reference numeral 50 and illustrated in FIG. 6. Such power supplies will be well known to those skilled in the art and it is not intended to describe it in further detail here. The power supply circuit 60 receives an input voltage VSS of 9 volts on the line 51. A controlled power supply voltage VCC is provided on an output line 52 of the power supply circuit 60. In this case, the controlled power supply voltage VCC is five volts. One side of the light emitting diodes 14 of the test stimuli 11 are fed from outputs 54 a to e of the luminance level control circuit 38 illustrated in FIG. 6 which will be described in detail below. The outputs 54 a to e applies a high to the diodes 14 to be switched on. The other side of the diodes 14 of the test stimuli 11 are controlled by the selector circuit 37. Returning now to FIG. 5, where the diodes 14 of a test stimulus 11 are to be switched on, a low is applied to the other side of the diodes 14 on an appropriate line 60 to 63 through the switch means which comprises transistor T1 to T4, one transistor T1 to T4 being provided for a corresponding test stimulus 11. The appropriate transistor T1 to T4 is selected by the first selector means for selecting the test stimulus to be switched on. The first selector means comprises a random number generator which comprises a clock chip 55 operating at 100 KHz, a flip flop counter circuit 55 to 58, and a NOR chip 57. The flip flop counter chip 55 in this case is provided by a 4017 CMOS chip. The chip 55 comprises a divide by ten decade counter with ten decoded outputs. The counter is cleared to one on its reset pin 15. The clock chip 55 clocks the counter chip 56 at 100 KHz. An AND gate 58 connected to the fourth output pin, namely pin 10 of the counter chip 56 limits the count sequence of the chip 56. The logic of the chip 56 is arranged so that on the clock pin 14 going high, the output on pin 3 of the AND gate 58 goes high, thereby resetting the counter to zero. Because the counter chip 56 is clocked at the high rate of 100 KHz, stopping the counter results in a discrete pseudo-random output, which controls the operation of the one-in-four selector chip 57. Accordingly, the outputs appearing on pins 12 to 15 of the one-in-four selector chip 57 are randomly selected. A high on any one of the output pins 12 to 15 switches on a corresponding transistor T1 to T4, thereby applying a low to the diodes 14 of the test stimulus 11 selected through the corresponding line 60 to 63. Comparing means for comparing the inputted response of the subject through the switches 18 with the status of the test stimulus 11 is provided by the comparing means in the subject response circuit 44. FIG. 5 illustrates the test stimulus selector circuit 37 and the light level selector circuit 38 to select and switch on the next test stimulus 11 and to select the level of luminance of the next test stimulus 11. On the subject response circuit 44 detecting operation of an incorrect switch 18 a buzzer circuit 46 which drives the alerting buzzer 21 is operated to activate the buzzer 21 and to retain the status of the test stimulus 11 unchanged.
their respective output pins 1 are low, while the output on the output pin 1 of the NOR gate 68 having two lows on its input pins 2 and 3 is high. This thus holds the output on pin 1 of the OR gate 69 high thus indicating that the switch 182 corresponding to the stimulus 136 has not been closed, in other words, operated. Should any other switch 182 be closed, the outputs on the pins 1 of the NOR gates 66 to 68 will remain low, thus leaving the output of the OR gate 69 unaltered. On the correct switch 182 being closed, the input on pin 2 of the NOR gate 68 goes high, thereby putting a low on the output pin 1 of the OR gate 65. Thus, in this case, since all the inputs to the OR gate 69 are low, the output on pin 1 from the OR gate 69 is also low. This thus indicates that the correct switch 182 has been closed. In this state, the inverter 70 applies a high to the reset pins 9 and 10 of the one-in-four selector chip 87 which causes random selection of the next test stimulus 31, by randomly altering the outputs on the pins 12 to 15 of the one-in-four selector 57.

Referring now to FIGS. 6 and 7 the luminance level selector circuit will now be described. The luminance level selector circuit essentially carries out two functions. Firstly, it controls the switching of the rows 15 of light emitting diodes 14 of the test stimulus 11 which is to be switched on, and secondly it controls the length of time the diodes 14 are left switched on. To conserve power, the rows 15 of light emitting diodes 14 of the test stimulus 11 which is switched on are switched on sequentially at the rate of 1 KHz. The level of luminance at which the test stimulus 11 is switched on is determined by the length of time the light emitting diodes 14 of each row 15 are left switched on during the sequential switching.

The rows of diodes 14 of each test stimulus 11 are connected through the lines 54 a to e and transistors T5 to T9 to the five volt control voltage VCC on the output line 52 of the power supply 50.

The bases of the transistors T5 to T9 are connected through resistors R8 to R10 of 6.8 kohm to output pins 1 to 5 of a decoder chip 73. The bases of the transistors T5 to T9 are also connected through pull-up resistors R11 to R14 of 1 kohm to the control voltage VCC. Thus, the bases of the transistors T5 to T9 are held high and thus switched off unless a low appears on any of the pins 1 to 5 of the decoder chip 73. The transistors T5 to T9 are selectively switched on by a low being applied sequentially on the pins 1 to 5 of the decoder chip 73. The decoder chip 73 receives binary coded decimal signals on the lines A, B and C from a clock counter chip 74 which cycles at 100 KHz. The decoder chip 73 decodes the signals, and depending on the signal on the output pins 1 to 5 of the decoder chip 73 sequentially gates these, thereby switching on the transistors T5 to T9 sequentially to the rows 15 of diodes 14 of the test stimulus 11 through the lines 54 a to e. The time period for which the pins 1 to 5 of the decoder chip 73 remain low is determined by the circuit 76. The circuit 76 applies a square wave signal on the input pin 6 of the decoder chip 73. The length of time a low remains on any of the output pins 1 to 5 of the decoder 73 is determined by the mark space ratio of the square wave signal, see FIG. 8. Maximum luminance is achieved when the mark space ratio is 1:1. Each time the level of luminance is to be reduced, the mark space ratio of the square wave is reduced by the circuit 76. This embodiment of the invention, the mark space ratio is reduced by a factor of 2 each time the level of luminance is to be reduced. In other words, the time the mark is halved each time, see FIG. 7. In this particular embodiment of the invention, the mark can be halved up to sixteen times. This thus gives a range of levels of luminance of 1:6,4536.

In FIG. 7. the mark is illustrated halved three times for the purposes of illustration only.

The signal on the pin 6 of the decoder 73 is derived from an oscillator (not shown) which is modified by the circuit 76. The circuit 76 comprises a timer chip 77 which is used as a retriggerable monostable multivibrator. An output pin 1 of the timer chip 77 is connected to one output pin of an NAND gate 78, the output pin of which is connected to the pin 6 of the decoder chip 73. A signal of the oscillator (not shown) is applied to the other input pin of the NAND gate 78 on a line 85. The signal from the oscillator (not shown) is also applied through the line 88 to the threshold pin 3 of the timer circuit 77. The output on the output pin 1 of the timer chip 77 is controlled by an RC circuit which comprises a capacitor C1 of 100 pF and a digital potentiometer 80 connected in series between the control voltage VCC and ground. The trigger pin 2 of the timer chip 77 is connected between the capacitor C1 and the digital potentiometer 80. A transistor T12 is connected across the capacitor C1. On a low being applied to the base of the transistor T12 by either the threshold pin 3 of the timer pin 77 or the signal on the line 85, the transistor T12 is switched on, thus discharging or preventing the capacitor C1 from charging.

Initially, the capacitor C1 is held discharged by the timer chip 77. At the negative transition of the trigger input pin 2 of the timer chip 77, the capacitor C1 is prevented from charging and is thus discharged through a transistor T12, and the transistor T12 keeps the capacitor C1 discharged until the trigger input pin 2 of the timer chip 77 goes high. The capacitor C1 is then charged. On the voltage across the capacitor C1 reaching two-thirds of the control voltage VCC, the output on the threshold pin 3 of the timer chip 77 goes low and the capacitor C1 is discharged. The transistor T12 continuously discharges the capacitor C1 when the trigger input pin 2 remains low, therefore the output of the timer chip 77 on the threshold pin 3 stays high if the voltage across the capacitor C1 never reaches two-thirds of the voltage VCC. The timer chip 77 outputs a pulse on its output pin 1 which is longer than the input pulse. Thus, the output from the NAND gate 78 effectively decreases the pulse length delivered to pin 6 of the decoder chip 73. In other words, the length of the space of the square wave signal is reduced. An input line 88 to the digital potentiometer 80 receives a high from the inverter 70, see FIG. 5, each time the next test stimulus 11 is to be selected and switched on. The high on the line 88 causes the resistance of the digital potentiometer 80 to change to the next value, to again halve the mark of the mark space ratio of the signal to be applied to pin 6 of the decoder chip 73.

An inverter 81 connected to the output pin 1 of the timer chip 77 is connected to the base of a transistor T14 through a resistor R15 and switches off the control voltage output on the output line 82 from the constant current power supply 50 during the space period of the square wave signal, thereby reducing drain through the resistors R11 to R14.

The clock circuit 39 (not shown in FIGS. 5, 6 or 7 but illustrated in FIG. 4) which controls the operation of
the apparatus 1 and also the timer (not shown) which displays the time on the time display 79 is connected to the input pin 2 of the clock counter chip 74 by the line 83. An enable signal is applied to the line 84 of the clock counter chip 74 by the reset circuit 40 on activation of the start/reset switch 25 or on a high being delivered from the inverter 70 on a correct identification of a test stimulus 11 being made by the switches 18. The high on the line 84 is in turn applied to pin 1 of the clock counter chip 74. The reset circuit 25 on activation of the start/reset switch 25 also applies a high to pins 9 and 10 of the one-in-four selector chip 97. The reset circuit 40 is also connected to the input line 86 of the digital potentiometer 80, so that on operation of the start/reset switch 25, the reset circuit 40 resets the resistance value of the digital potentiometer to the value which gives a signal on pin 6 of the decoder 73 with a mark space ratio of 1:1.

Although not illustrated, a suitable control circuit, in this case comprising a chain of resistors (not shown) controls the level of luminance at which the fixation light emitting diode 12 is switched on. This control circuit is connected to the circuit 76, so that on each fourth reduction of the mark space ratio of the signal applied to the pin 6 of the decoder 73, the level of luminance of the fixation light emitting diode 12 is reduced by a predetermined decrement.

A microprocessor (not shown) controls the operation of the apparatus 1. The microprocessor comprises means for storing the times at which the switches 18 correctly identify a test stimulus 11 as being switched on from the commencement time of the test, and the level of luminance at which the test stimulus 11 is switched on. The times are stored against the appropriate level of luminance of the test stimuli. Further, the storing means stores the numbers of the test stimuli which are switched on and their relevant level of luminance. Typical storing means would be provided by a random access memory.

In this embodiment of the invention, the test stimuli are switched on at sixteen different levels of luminance. The levels of luminance are sequentially reduced each time a test stimulus 11 is correctly identified by the subject. The sixteen levels of luminance are set out in Table 1.

**TABLE 1**

<table>
<thead>
<tr>
<th>Test-stimulus Sequence</th>
<th>Level of Luminance (micro-micro Lamberts)</th>
<th>Test-stimulus Level of Luminance</th>
<th>Test Stimuli</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 x 10^-6</td>
<td>2 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1 x 10^-6</td>
<td>3 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5 x 10^-6</td>
<td>7 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.5 x 10^-6</td>
<td>10 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6.25 x 10^-6</td>
<td>12.5 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>3.125 x 10^-6</td>
<td>6.25 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.56 x 10^-6</td>
<td>3.125 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>7.6 x 10^-7</td>
<td>1.56 x 10^-6</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3.8 x 10^-7</td>
<td>7.6 x 10^-7</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.9 x 10^-7</td>
<td>3.8 x 10^-7</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>9.5 x 10^-8</td>
<td>1.9 x 10^-7</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>4.75 x 10^-8</td>
<td>9.5 x 10^-8</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2.375 x 10^-8</td>
<td>4.75 x 10^-8</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1.1875 x 10^-8</td>
<td>2.375 x 10^-8</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>5.9375 x 10^-9</td>
<td>1.1875 x 10^-8</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>2.96875 x 10^-9</td>
<td>5.9375 x 10^-9</td>
<td></td>
</tr>
</tbody>
</table>

In use, with the test housing 2 mounted in a dark room or beneath a hood, the subject to be tested is placed in front of the test housing 2 with the test panel 8 spaced apart from the individuals face a distance of approximately 300 mm. Prior to the test commencing, the subject is exposed to a bright light of fixed duration and luminance in order to bleach the visual pigments of the subject's eyes. The mains on/off power switch 23 is switched on and the start/reset switch 25 is then switched on, thus commencing the test. The fixation light emitting diode 14 is switched on simultaneously with one of the test stimuli 11 which is randomly selected as already described. The test stimulus 11 selected is switched on at maximum luminance, namely, the value corresponding to the first test stimulus of Table 1, namely, 2 x 10^-6 micro-micro Lamberts. At this level of luminance, the mark space ratio of the input of the signal on the input pin 6 of the decoder 73 is 1:1 as illustrated in FIG. 8(b). The timer circuit 39 commences timing from the time the first test stimulus 11 is switched on. The subject focuses on the fixation light emitting diode 12. On the subject perceiving light from a test stimulus to be visible to him or her, the subject presses the cover 17 of the appropriate test light stimulus, thus operating the corresponding switch 18. If the correct switch 18 is activated, the time from commencement of the test to the time switch 18 is operated is recorded and displayed on the display 29 by appropriately operating the switch 30. The luminance level at which the test stimulus was switched on is also displayed on the display 28. This data is recorded in the microprocessor (not shown). On the correct switch 18 being closed, the next test stimulus 11 is selected by the selector circuit 37 as already described, and the level of luminance at which the next test stimulus 11 is switched on is selected by the level selector circuit 38 as already described. This level of luminance is the level of luminance shown in Table 1 against the test stimulus number 2, namely, 1 x 10^-6 micro-micro Lamberts. This level of luminance is achieved by halving the time of the mark of the mark space ratio of the signal being applied to the pin 6 of the decoder 73, see FIG. 8(b). The timer circuit 37 continues to time and on the subject correctly identifying the test stimulus 11 which has been switched on, by operating the appropriate switch 18, the time from the commencement of the test to the time at which the switch 18 was operated, and the level of luminance of the test stimulus 11 is recorded and stored in the microprocessor (not shown). This data is also displayed on the displays 28 and 29.

On the correct switch 14 being closed, the next test stimulus 11 is selected and the next reduced level of luminance is also selected by further halving the time of the mark of the signal being applied to pin 6 of the decoder 73. This gives the level of luminance of Table 1 which corresponds with test stimulus number 3. The test continues in this fashion and may be continued until the test stimulus 11 have been switched on at sixteen different levels of luminance. Each time the switched on test stimulus 11 has been correctly identified by the subject, the time from the commencement of the test until correct identification of the test stimulus and the level of luminance of the test stimulus are recorded and stored in the microprocessor.

The microprocessor then can print out the data on time or level of luminance or alternatively can plot a curve of level of luminance against time. At all times during the tests, the fixation light emitting diode 12 remains switched on, however, as the level of luminance of the test stimulus 11 is reduced, the level of luminance...
Ting diode, scope of the invention.

On a test stimulus being correctly identified, the alarm 20 is sounded, thereby indicating to the subject that the test stimulus 11 has been correctly identified, so that the subject can then expect the next test stimulus 11. On a test stimulus being incorrectly identified, the buzzer 21 is sounded, thus indicating the fact to the subject. The subject then merely continues to focus on the fixation light emitting diode 12 until light from the switched on stimulus is perceived. Additionally, on an incorrect identification of a test stimulus occurring, the test stimulus 11 remains switched on and the timer continues counting. This state continues until the switched on test stimulus is correctly identified.

A plot of the results, if not made by a printer under the control of the microprocessor of the apparatus 1, is made by hand similarly. A typical plot of the results is illustrated by the curve C in FIG. 9. The level of luminance L is plotted on the y axis, while the time t is plotted on the x axis. The log of the level of luminance changes as can be seen the time taken to identify the test stimulus increases. In the curve C the portion D of the curve is referred to as the photopic region. The portion E of the curve C is referred to as the mesopic region. The portion F of the curve C is referred to as the scotopic region. In an average subject with good dark adaptation capabilities, the time distance of the photopic region should be relatively short typically 5 minutes while the time distance of the scotopic region should be of the order of 25 minutes. However, in a subject with poor dark adaptation characteristics the time distance of the photopic region and the scotopic region of the curve C tends to be significantly longer. Thus, by determining the time distance of the photopic and scotopic regions of the curve the ability of a subject's eyes to adapt to darkness can be determined.

While the apparatus has been described as comprising four test stimuli arranged around a fixation light emitting diode, any number of test stimuli may be used without departing from the scope of the invention. Indeed, in certain cases it is envisaged that only two test stimuli may be provided. Further, it will be appreciated that any other arrangement of test stimuli relative to a fixation means may be used without departing from the scope of the invention. It will also be appreciated that the test stimuli may be arranged at other distances from the fixation means than those described. Further, it is envisaged that other suitable test stimuli may be used besides light emitting diodes and besides arrays of light emitting diodes. For example, in certain cases a single light source may be used to form each test stimulus. Where arrays of diodes are used any number of diodes may be used in the array and indeed any arrangement of diodes in the array could be used. Further, it will be appreciated that arrays of other light sources besides light emitting diodes may be used without departing from the scope of the invention. It is also envisaged that while the person is in that condition typical power savings are achieved other means for varying the level of luminance of the test stimuli may be used besides that described. Further, other methods for randomly selecting a test stimulus to be switched on from the test stimuli may be used besides that described. It will of course be appreciated that fixation means other than a light emitting diode may be used, and further, in all cases it will not be necessary for the level of luminance of the fixation means to be reduced as the level of luminance of the test stimuli is reduced. Indeed, in many cases, the level of luminance of the fixation means may be fixed throughout the test. Additionally, while particular electronic circuitry has been described, other suitable electronic circuitry could be used without departing from the scope of the invention. Needless to say, other means besides NOR and OR gates could be used for comparing the switches 14 with the test stimuli. In certain cases, the fixation means may be dispensed altogether.

It is envisaged in certain cases that the apparatus may be provided with only a single housing, in which case the housing would be provided with two panels, one to form the test panel and the other to form the control panel. In many cases, it is envisaged that these panels will be on opposite sides of the housing or on different sides. It is, however, believed to be important that the control panel should not be visible to the subject during the test.

While particular dimensions have been given throughout the specification, it will be readily apparent to those skilled in the art that other dimensions could be used without departing from the scope of the invention. While the level of luminance of the test stimuli have been reduced by specific decrements on a test stimulus being correctly identified as being switched on, the level of luminance may be reduced by different and/or varying decrements without departing from the scope of the invention.

It will also of course be appreciated that while specific levels of luminance at which the test stimuli are switched on have been given, other levels of luminance may be used without departing from the scope of the invention.

Needless to say, it will be appreciated that while it is preferable that the input means to enable the subject to input the identity of the test stimulus which is perceived to be visible should be provided adjacent the test stimulus, this is not essential. The input means may be remotely provided relative to the test stimulus. Further, it is not essential that the input means be provided by operating buttons of switches within which the test stimuli are provided. Where the input means is to be provided adjacent the test stimuli, the switches may be provided separately on the test panel adjacent the corresponding test stimuli.

It is also envisaged in many cases that a light may be provided on the test panel directed at the subject for the purposes of bleaching the pigments of the subject's eyes. Such a light, it is envisaged, may be independently operated, but preferably would be operated from the control circuitry and on the start/reset switch being depressed to commence a test, it is envisaged that the light would be illuminated for the appropriate duration to bleach the pigments, and on the light being switched off, the test would then commence. At that stage, the timer circuit 37 would commence timing.

While the alerting means for indicating a test stimulus has been correctly identified has been described as being a bell, any other suitable alerting means could be used. For example, in certain cases, it is envisaged that a tune may be played, the use of this or other reinforcement or rewards would be particularly advantageous when the apparatus is being used with children. Similarly, other alerting means besides a buzzer could be
used to indicate an incorrect identification of a test stimulus.

In the event of hearing impaired or deaf persons being tested, other suitable means could be provided for alerting the subject to the fact that a correct or incorrect identification has been made. Needless to say, alerting means may also be provided on the control panel for the operator if desired.

It is also envisaged in certain cases that the luminance of the test stimuli may be varied by varying the area of the covers 17 through which light may be transmitted from the diodes or other light source. For example, an iris type diaphragm may be mounted in the covers 17. While digital displays have been described for indicating information and data, it is envisaged in certain cases that a mimic display consisting of four light emitting diodes indicating which test light source is activated may be provided. Further, it will be readily apparent to those skilled in the art that the variation of luminance in the various test stimuli and indeed if desired in the fixation means may be achieved by optical or electro-optical or other suitable means.

It is also envisaged in certain cases that where two consecutive incorrect responses are received the apparatus could be arranged to cause reselection of the test stimuli at the current level of luminance.

While the cover of the light emitting diodes of the test stimuli which forms the buttons of the switches 18 have been described as being of glass material it will be appreciated that the covers may be of any other suitable material such as plastic, glass, fiber, etc. The cover may be a plastic material or the like. It will of course be appreciated that in certain cases the material may be transparent instead of translucent. It is also envisaged that a neutral density filter could be provided between the light emitting diodes of the test stimuli and the cover, or alternatively, a plurality of fixation means may be provided over the cover, should the use of a neutral density filter be desirable. It is also envisaged in certain cases the fixation means could be movable. For example, a single fixation means may be provided which would be movable over the test panel, or alternatively, a plurality of fixation means may be provided one of which would be switched on at any given time. This would permit testing of different parts of the retina and/or different fields of the retina.

It will also be appreciated that while the first selecting means for selecting the test stimulus to be switched on has been described as being a random selector, any other suitable selecting means for selecting the test stimulus to be switched on may be provided. Indeed, it will be appreciated that in many cases the selection will not be a random selection. Further, it is envisaged that in certain cases the selection of the test stimuli may be arranged in a predetermined fashion to permit testing of different fields of the retina.

While the input means has been described as being provided by a plurality of switches operated by respective buttons, this while it is advantageous is not essential. In many cases, other suitable input means may be used. For example, in certain cases it is envisaged that the input means may be voice sensitive, it may be voice sensitive to the subject or indeed the person operating the apparatus. Further, it will be appreciated that while the input means has been described as being operable by the subject, it could likewise be operable by the operator if desired. Where operable by the operator, it is envisaged that the subject would give some signal to the operator to enable the operator to operate the input means.

It is also envisaged that the test stimuli instead of being in the form of square shapes, could be provided in any other suitable or desirable shape. For example, in certain cases, it is envisaged that the test stimuli could be in the shapes of numbers, letters, animals or the like. In fact, it is envisaged that means to selectively, whether randomly or otherwise, vary the shapes could be provided. Indeed, in certain cases, it is envisaged that each test stimulus may be provided that it may be switched on to form a number of different shapes. This latter embodiment of the invention, it is envisaged, may be of particular benefit in enabling tests to be carried out on a subject when the test has reached the mesopic region of the curve. For example, in such a case, it is envisaged that the test stimuli would be switched on in the shape of squares, and when the test reached the mesopic region, other shapes, for example, letters, numbers or other geometrical shapes could be formed by the test stimuli on being switched on.

While the apparatus has been described for testing dark adaptation of the eyes of a subject, it will be readily apparent to those skilled in the art that it may be used for testing dark adaptation of each individual eye independently of the other.

We claim:

1. Apparatus as claimed in claim 1 in which the input means for permitting the identity of a test stimulus perceived to be visible by the subject to be inputted.

2. Apparatus as claimed in claim 1 in which the first selecting means responsive to the comparing means for selecting the next test stimulus to be switched on, on a correct identification being made, and second selecting means for selecting means for selecting the level of luminance at which the selected test stimulus is to be switched on, said second selecting means being responsive to the comparing means for selecting the level of luminance of the selected test stimulus at a level less than the level of luminance at which the last correctly identified test stimulus had been switched on.

3. Apparatus as claimed in claim 1 in which the input means is operable by the subject.

4. Apparatus as claimed in claim 1 in which the second selecting means comprises means for reducing the level of luminance in predetermined decrements.

5. Apparatus as defined in claim 1 further comprising timing means for timing the times at which a correct identification is made by the input means from the time the test commences.

6. Apparatus as claimed in claim 1 in which the input means comprises a plurality of manually operable switches, the number of switches corresponding to the number of test stimuli, and each test stimulus having an associated switch provided adjacent thereto.
7. Apparatus as claimed in claim 1 in which each test stimulus comprises a plurality of light emitting diodes arranged in an array.
8. Apparatus as defined in claim 1 further comprising alerting means to indicate to a subject when a correct identification of the test stimulus has been made.
9. Apparatus as claimed in claim 1 in which the first selecting means comprises a random number selector.
10. A method for testing dark adaptation of the eye of a subject, the method comprising the steps of:
(a) presenting a test stimulus to a subject at a first predetermined level of luminance at the commencement of the test,
(b) recording the commencement time at which the test stimulus is presented to the subject at the first predetermined level of luminance,
(c) recording the level of luminance of the test stimulus and the time from the commencement time to the time at which the test stimulus becomes visible to the subject,
(d) on the test stimulus being visible reducing the level of luminance of the test stimulus to a second predetermined level,
(e) recording the second level of luminance and the time from the commencement time to the time the test stimulus becomes visible to the subject at the second level of luminance,
(f) repeating steps (d) and (e) a plurality of times and each time recording the level of luminance at which the test stimulus is switched on and the time from the commencement time to the time the test stimulus at that level of luminance becomes visible to the subject.
11. A method as claimed in claim 10 in which the method includes the step of plotting the recorded levels of luminance against the corresponding recorded times to construct a curve of the subject's response.
12. A method as claimed in claim 10 in which each time the level of luminance of the test stimulus is reduced, the test stimulus is selected from one of a plurality of test stimuli.
13. A method as claimed in claim 12 in which the test stimulus is randomly selected.
14. A method as claimed in claim 10 in which a fixation means is presented to the subject simultaneously with the test stimulus.
15. Apparatus for testing dark adaptation of the eye of a subject, the apparatus comprising:
(a) fixation means,
(b) a plurality of test stimuli arranged around the fixation means,
(c) switch means for switching on any one of the test stimuli,
(d) input means for permitting the identity of a test stimulus perceived to be visible by the subject to be inputted,
first selecting means responsive to the comparing means for selecting a test stimulus to be switched on, on a correct identification being made,
second selecting means for selecting the level of luminance of the test stimulus to be switched on, said second selecting means being responsive to the comparing means and comprising means for sequentially reducing the level of luminance at which a test stimulus is switched on each time the comparing means detects a correct identification, and
means for recording and storing the levels of luminance at which the test stimuli are illuminated against the respective times from the commencement of the test until a correct identification of the test stimulus has been made.
17. Apparatus for testing dark adaptation of the eye of a subject, the apparatus comprising:
(a) a plurality of test stimuli,
(b) switch means for switching on any one of the test stimuli,
(c) input means for permitting the identity of a test stimulus perceived to be visible by the subject to be inputted,
(d) comparing means for comparing the identified test stimulus with the test stimulus switched on,
(e) a method for testing dark adaptation of the eye of a subject, the method comprising the steps of:
(f) recording the commencement time at which the test stimulus is presented to the subject at the first predetermined level of luminance,
(g) recording the level of luminance of the test stimulus and the time from the commencement time to the time at which the test stimulus becomes visible to the subject,
(h) on the test stimulus being visible reducing the level of luminance of the test stimulus to a second predetermined level,
(i) recording the second level of luminance and the time from the commencement time to the time the test stimulus becomes visible to the subject at the second level of luminance,
(j) repeating steps (d) and (e) a plurality of times and each time recording the level of luminance at which the test stimulus is switched on and the time from the commencement time to the time the test stimulus at that level of luminance becomes visible to the subject.

Appendix 3  Dark Adaptometers Continued

Dark Adaptation and the Purkinje Shift
Thorton\(^1\) in 1977 developed a simple rapid test of deterring night vision based on the Purkinje shift. The subject is light adapted and the time taken to separate coloured discs are determined. In patient with retinal disease the Purkinje shift is delayed, yielding a prolonged rod-cone transition time. Thorton showed a high correlation between prolonged rod-cone break times and elevated absolute cone and rod thresholds.

Vinton and Russell\(^2\) in 1981 developed Thorton’s idea further. The subjects were required to separate out white, red and blue coloured discs from a collection in the mesopic phase of adaptation. The test time takes about 10 minutes to complete as opposed to the normal 30 - 40 minutes. Normal adults and adult patients with night blindness as a consequence of retinal disease; specifically vitamin A deficiency; were examined. The results showed the test data correlated well with cone and rod final threshold times obtained on the Goldmann-Weekers adaptometer. The test was successful in identifying patients with hypovitaminosis A.

Solomons, Russell\(^3\) et al in 1982 applied the Vinton and Russell rapid test described above to 45 children aged 4 to 13 years in Guatemala. The results indicated the test could be used on children, however, in this study the children were healthy and showed no signs of ill health or vitamin A deficiency.

Modified Field Analysers and Perimeters
Visual field analysers and perimeters may be used to obtain dark adaptation measurements. For example Harms\(^4\) (Türbinger University eye clinic) and the Oculus company developed the Türbinger static perimeter in 1960 called the Mesoptometer, it could be used for testing mesopic vision and glare sensitivity for night driving. Rodenstock developed the Nyktometer\(^5\) in the late seventies to investigate photopic visual acuity and mesopic vision and sensitivity to glare.

Ernst and Faulkner\(^6\), 1983, developed and evaluated a static perimeter/adaptometer based on the Lister perimeter described by Duke-Elder\(^7\) in 1962. The modified instrument uses green (530nm) and red light emitting diodes as target stimulus whose intensity is controlled to give a working luminance range of 5 log units.

---

Neugebauer and Vernon (8) et al in 1989 developed a dark adaptometer based on the Lister perimeter, again the target stimuli consisted of green (555nm) and red LED's as target stimulus. This instrument was successfully used by Rayner and Tyrrell (9) to investigate nyctalopia in cystic fibrosis patients. Another modified Lister perimeter was used by Arden Carter Hogg (10) et al in 1983 on a study of patients with rod and cone dystrophy's. Again the target stimuli comprised both red and green LEDs.

**Patented Dark Adaptation Instrumentation**

A visual field analyser was developed by Murr (11) (1985), describes an instrument that uses 12 light emitting diodes (LEDs) that act as the test stimuli and may be individually illuminated. The LEDs are connected to a selecting means that are in turn connected to a driver circuit that pulses the LEDs to control the effective luminance presented to a subject. A visual field screener was described by Gonzalez (12) et al (1982). The instrument comprises a cathode ray tube (CRT) controlled by a computer. The target stimuli are presented on the CRT with a luminance range of ≈4 log units, however, the instrument cannot function adequately as a dark adaptometer as the CR tube is never sufficiently dark to obtain scotopic phase; it may be used to determine the photopic and mesopic phase of vision. An automatic visual field analyser is described by Lynn and Tate (13) (1975) comprising of a cathode ray tube (CRT) that acts as the presentation stimuli and circuitry to randomly present the stimuli on the CRT to various locations on the retina. There is a subject response button and feedback is provided indicating a correct or incorrect response. An interesting device that measures dark adaptation is described by Krakau (14) et al (1976). It consists of a scuba-divers face mask on which two light emitting diodes are placed that act as the presentation stimuli. Electronic circuitry is described that incrementally reduces the luminance of the stimuli. There are a number of problems with this device no least the lack of a suitable fixation. An early dark adaptation (1941) device described by Wigelsworth (15) is opto-mechanical device consisting of a single stimulus, with a fixation light. The luminance level is reduced after the subject makes the correct response by pressing the correct button.

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Appendix 4  LED Array

THREE-FIVE SYSTEMS, INC.

LARGE AREA LED DOT MATRIX DISPLAYS
2.0" HIGH, 5 x 7 FORMAT
TFB5X57 SERIES

TFB5757A/C — High Efficiency Red
TFB5457A/C — High Efficiency Green
TFB5357A/C — Yellow

FEATURES
- 100° Viewing Angle
- High On/Off Contrast:
  - Grey Face for Green and Yellow
  - Black Face for High Efficiency Red
- Internally Wired as X-Y Matrix
- Side and End Stackable
- Light Weight—Rugged Plastic-Fill Construction
- "A" Version is Row Anode (Column Cathode)
- "C" Version is Row Cathode (Column Anode)
- Dual-In-Line Pinout

APPLICATIONS
- Scrolling Message Signs
- Public Message Announcements
- Elevators

ABSOLUTE MAXIMUM RATINGS
- Power Dissipation Per Dot: 60mW
- Peak Power Current Per Dot (1mS, 1/10 Duty): 80mA
- Continuous Forward Current Per Dot: 20mA
- Derating Linear From 50°C Per Dot: 0.45mA/°C
- Reverse Voltage Per Dot: 5.0V
- Operating Temperature: -25°C to +85°C
- Storage Temperature: -30°C to +100°C
- Lead Soldering Time 4mm Below Seating Plane @ 260°C: 3 Seconds

SERIES PART NUMBERS

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Color</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFB5757A</td>
<td>High Efficiency Red</td>
<td>Row Anode</td>
</tr>
<tr>
<td>TFB5757C</td>
<td>High Efficiency Red</td>
<td>Row Cathode</td>
</tr>
<tr>
<td>TFB5457A</td>
<td>High Efficiency Green</td>
<td>Row Anode</td>
</tr>
<tr>
<td>TFB5457C</td>
<td>High Efficiency Green</td>
<td>Row Cathode</td>
</tr>
<tr>
<td>TFB5357A</td>
<td>Yellow</td>
<td>Row Anode</td>
</tr>
<tr>
<td>TFB5357C</td>
<td>Yellow</td>
<td>Row Cathode</td>
</tr>
</tbody>
</table>

DESCRIPTION
The TFB5X57A/C series is a 5 x 7 LED X-Y matrix. It is a 2.0" high alphanumeric character with a 0.200" diameter dot size on a 0.300" pitch. Three colors are available: high efficiency red, high efficiency green, and yellow. The series is available in row anode (A suffix part numbers), and row cathode (C suffix part numbers).
### LED DOT MATRIX DISPLAYS—2.0” HIGH, 5 x 7 FORMAT

#### TFB5X57 SERIES

**ELECTRICAL/OPTICAL CHARACTERISTICS**

#### TFB5757A or C — High Efficiency Red

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Test Condition TA = 25°C</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_r )</td>
<td>Average Luminous Intensity (per Dot)</td>
<td>( I_r = 10, mA )</td>
<td>800</td>
<td>1500</td>
<td></td>
<td></td>
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<tr>
<td>( \lambda_p )</td>
<td>Peak Emission Wavelength</td>
<td>( I_r = 20, mA )</td>
<td>630</td>
<td>35</td>
<td>nm</td>
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</tr>
<tr>
<td>( \Delta \lambda )</td>
<td>Spectral Line Half-Width</td>
<td>( I_r = 20, mA )</td>
<td>1.7</td>
<td>2.1</td>
<td>2.8</td>
<td>V</td>
</tr>
<tr>
<td>( V_F )</td>
<td>Forward Voltage, any Dot</td>
<td>( I_r = 20, mA )</td>
<td>10</td>
<td>V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_R )</td>
<td>Reverse Current, any Dot</td>
<td>( V_A = 5.0, V )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( I_{m} )</td>
<td>Luminous Intensity Matching Ratio</td>
<td>( I_r = 10, mA )</td>
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#### TFB5457A or C — High Efficiency Green

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<th>Symbol</th>
<th>Parameter</th>
<th>Test Condition TA = 25°C</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
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<tbody>
<tr>
<td>( I_r )</td>
<td>Average Luminous Intensity (per Dot)</td>
<td>( I_r = 10, mA )</td>
<td>1000</td>
<td>1800</td>
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<tr>
<td>( \lambda_p )</td>
<td>Peak Emission Wavelength</td>
<td>( I_r = 20, mA )</td>
<td>565</td>
<td>30</td>
<td>nm</td>
<td></td>
</tr>
<tr>
<td>( \Delta \lambda )</td>
<td>Spectral Line Half-Width</td>
<td>( I_r = 20, mA )</td>
<td>1.6</td>
<td>2.15</td>
<td>2.5</td>
<td>V</td>
</tr>
<tr>
<td>( V_F )</td>
<td>Forward Voltage, any Dot</td>
<td>( I_r = 20, mA )</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_R )</td>
<td>Reverse Current, any Dot</td>
<td>( V_A = 5.0, V )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( I_{m} )</td>
<td>Luminous Intensity Matching Ratio</td>
<td>( I_r = 10, mA )</td>
<td></td>
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#### TFB5357A or C — Yellow

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<th>Parameter</th>
<th>Test Condition TA = 25°C</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_r )</td>
<td>Average Luminous Intensity (per Dot)</td>
<td>( I_r = 10, mA )</td>
<td>800</td>
<td>1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \lambda_p )</td>
<td>Peak Emission Wavelength</td>
<td>( I_r = 20, mA )</td>
<td>585</td>
<td>32</td>
<td>nm</td>
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</tr>
<tr>
<td>( \Delta \lambda )</td>
<td>Spectral Line Half-Width</td>
<td>( I_r = 20, mA )</td>
<td>1.9</td>
<td>2.1</td>
<td>2.8</td>
<td>V</td>
</tr>
<tr>
<td>( V_F )</td>
<td>Forward Voltage, any Dot</td>
<td>( I_r = 20, mA )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_R )</td>
<td>Reverse Current, any Dot</td>
<td>( V_A = 5.0, V )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( I_{m} )</td>
<td>Luminous Intensity Matching Ratio</td>
<td>( I_r = 10, mA )</td>
<td></td>
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</table>
LED DOT MATRIX DISPLAYS—2.0” HIGH, 5 x 7 FORMAT
TFB5X57 SERIES

TYPICAL CHARACTERISTIC CURVES

FIGURE 1—Forward Voltage vs Forward Current

FIGURE 2—Forward Current vs Luminous Intensity

FIGURE 3—Luminous Intensity vs Wavelength

FIGURE 4—Ambient Temperature vs Forward Current

FIGURE 5—Directional Pattern

FIGURE 6—Solving Load Resistor

THREE-FIVE SYSTEMS, INC.
Optoelectronics Group
TEL: 602-496-0050; TWX: 510-601-1436; FAX: 602-496-8155

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Appendix 5  Data Sheets

ICM755 Precision Timer
General Purpose Timers

The ICM7555 and ICM7556 are CMOS RC timers providing significantly improved performance over the standard 555E555/5 and 355 timers, while at the same time being direct replacements for those devices in most applications. Improved parameters include low supply current, wide operating supply voltage range, low THRESHOLD, TRIGGER and RESET currents, no crowbarring of the supply current during output transitions, higher frequency performance and no requirement to decouple CONTROL VOLTAGE for stable operation.

Specifically, the ICM7555 and ICM7556 are stable controllers capable of producing accurate time delays or frequencies. The ICM7555 is a dual ICM7555, with the two timers operating independently of each other, sharing only V- and GND. In the one shot mode, the pulse width of each circuit is precisely controlled by one external resistor and capacitor. For astable operation as an oscillator, the free running frequency and the duty cycle are both accurately controlled by two external resistors and one capacitor. Unlike the regular bipolar 5555 devices, the CONTROL VOLTAGE terminal need not be decoupled with a capacitor. The circuits are triggered and reset on falling (negative) waveforms, and the output inverter can source or sink currents large enough to drive TTL loads, or provide minimal offsets to drive CMOS loads.

Applications

- Precision Timing
- Pulse Generation
- Sequential Timing
- Time Delay Generation
- Pulse Width Modulation
- Pulse Position Modulation
- Missing Pulse Detector

Features

- Exact Equivalent in Most Cases for 555/5555 or TLC555/555
- Low Supply Current
  - ICM7555 ........................................... 0μA
  - ICM7556 ........................................... 2μA
- Extremely Low Input Currents .......................... 2μA
- High Speed Operation ................................ 1MHz
- Guaranteed Supply Voltage Range .......... 2.0V to 18V
- Temperature Stability .......................... ±0.02%V/°C at 25°C

- Normal Reset Function - No Crowbarring of Supply During Output Transition
- Can be Used with Higher Impedance Timing Elements than Regular 5555 for Longer RC Time Constants
- Timing from Microseconds through Hours
- Operates in Both Astable and Monostable Modes
- Adjustable Duty Cycle
- High Output Source/Sink Driver can Drive TTL/CMOS
- Outputs have Very Low Offsets. HI and LO

Ordering Information

<table>
<thead>
<tr>
<th>PART NUMBER</th>
<th>TEMP RANGE(°C)</th>
<th>PACKAGE</th>
<th>PKG. NO.</th>
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<tbody>
<tr>
<td>ICM7555CBA (7555CBA)</td>
<td>0 to 70</td>
<td>14 LD SOIC</td>
<td>M8.15</td>
</tr>
<tr>
<td>ICM7555ABA (7555ABA)</td>
<td>-25 to 85</td>
<td>14 LD SOIC</td>
<td>M8.15</td>
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<tr>
<td>ICM7555PA</td>
<td>-25 to 85</td>
<td>14 LD PDIP</td>
<td>E8.3</td>
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<tr>
<td>ICM7555PD</td>
<td>-25 to 85</td>
<td>14 LD PDIP</td>
<td>F14.3</td>
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<tr>
<td>ICM7555UD</td>
<td>-55 to 125</td>
<td>14 LD CERDIP</td>
<td>F14.3</td>
</tr>
</tbody>
</table>

Pinouts

ICM7555 (PDIP, SOIC)

TOP VIEW

- GND
- TRIGGER
- OUTPUT
- RESET
- VOLTAJE

ICM7556 (PDIP, CERDIP)

TOP VIEW

- GND
- TRIGGER
- OUTPUT
- RESET
- VOLTAJE

Continued
### Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Test Conditions</th>
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<tbody>
<tr>
<td>Supply Voltage</td>
<td>VCC</td>
<td>VCC = 5V</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>VIL</td>
<td>-6V to 0V</td>
</tr>
<tr>
<td>Trigger, Control Voltage, Threshold</td>
<td>Vh</td>
<td>0V to GND</td>
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<tr>
<td>Output Current</td>
<td>Iout</td>
<td>100mA</td>
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### Operating Conditions

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<tr>
<td>ICM7555</td>
<td>0°C to 70°C</td>
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<tr>
<td>ICM7556</td>
<td>-25°C to 85°C</td>
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<tr>
<td>ICM7556M</td>
<td>-65°C to 125°C</td>
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### Thermal Information

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Test Conditions</th>
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<tbody>
<tr>
<td>Thermal Resistance (Typical, Note 2)</td>
<td>Rth</td>
<td>60 to 24</td>
</tr>
<tr>
<td>14 Lead PDIP Package</td>
<td>Rth</td>
<td>115 N/A</td>
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<tr>
<td>8 Lead PDIP Package</td>
<td>Rth</td>
<td>130 N/A</td>
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<td>8 Lead SOIC Package</td>
<td>Rth</td>
<td>170 N/A</td>
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<td>Maximum Junction Temperature (Hermetic Package)</td>
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<td>Maximum Junction Temperature (Plastic Package)</td>
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<tr>
<td>Maximum Storage Temperature Range</td>
<td>45°C to 105°C</td>
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<td>Maximum Lead Temperature (Soldering 10s)</td>
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### Thermal Information

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<td>MSOP</td>
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<tr>
<td>SSOP</td>
<td>Pd</td>
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### Electrical Specifications

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<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>T&lt;sub&gt;A&lt;/sub&gt; = 25°C</th>
<th>T&lt;sub&gt;A&lt;/sub&gt; = 55°C TO 125°C</th>
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<tr>
<td>Static Supply Current</td>
<td>I&lt;sub&gt;DD&lt;/sub&gt;</td>
<td>ICM755 = V&lt;sub&gt;DD&lt;/sub&gt; = 5V</td>
<td>-0.40/0.20</td>
<td>-0.30/0.30</td>
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<td></td>
<td>ICM7556 = V&lt;sub&gt;DD&lt;/sub&gt; = 5V</td>
<td>-0.50/0.30</td>
<td>-0.30/0.30</td>
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<td>Monostable Timing Accuracy</td>
<td>R&lt;sub&gt;A&lt;/sub&gt; = 10K, C = 0.1μF, V&lt;sub&gt;DD&lt;/sub&gt; = 5V</td>
<td>-2</td>
<td>-</td>
<td>- 1000μs</td>
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<td>Drift with Temperature (Note 3)</td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 5V</td>
<td>-</td>
<td>-</td>
<td>- 150 ppm/°C</td>
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<tr>
<td></td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 10V</td>
<td>-</td>
<td>-</td>
<td>- 200 ppm/°C</td>
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<tr>
<td></td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 15V</td>
<td>-</td>
<td>-</td>
<td>- 250 ppm/°C</td>
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<tr>
<td>Drift with Supply (Note 3)</td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 5V to 15V</td>
<td>- 0.5</td>
<td>- 0.5</td>
<td>- %V</td>
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<td>R&lt;sub&gt;A&lt;/sub&gt; = R&lt;sub&gt;B&lt;/sub&gt; = 10K, C = 0.1μF, V&lt;sub&gt;DD&lt;/sub&gt; = 5V</td>
<td>-2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Drift with Temperature (Note 3)</td>
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<td>-</td>
<td>-</td>
<td>- 17177 μs</td>
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<tr>
<td></td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 10V</td>
<td>-</td>
<td>-</td>
<td>- 2323 ppm/°C</td>
</tr>
<tr>
<td></td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 15V</td>
<td>-</td>
<td>-</td>
<td>- 2323 ppm/°C</td>
</tr>
<tr>
<td>Drift with Supply (Note 3)</td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 5V to 15V</td>
<td>- 0.5</td>
<td>- 0.5</td>
<td>- %V</td>
</tr>
<tr>
<td>Threshold Voltage</td>
<td>V&lt;sub&gt;TH&lt;/sub&gt;</td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 15V</td>
<td>62 67 71 61</td>
<td>72 % V&lt;sub&gt;DD&lt;/sub&gt;</td>
</tr>
<tr>
<td>Trigger Voltage</td>
<td>V&lt;sub&gt;TR&lt;/sub&gt;</td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 15V</td>
<td>26 32 36 27</td>
<td>37 % V&lt;sub&gt;DD&lt;/sub&gt;</td>
</tr>
<tr>
<td>Trigger Current</td>
<td>I&lt;sub&gt;TR&lt;/sub&gt;</td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 15V</td>
<td>- - 10</td>
<td>- 50 nA</td>
</tr>
<tr>
<td>Threshold Current</td>
<td>I&lt;sub&gt;TH&lt;/sub&gt;</td>
<td>V&lt;sub&gt;DD&lt;/sub&gt; = 15V</td>
<td>- - 10</td>
<td>- 50 nA</td>
</tr>
<tr>
<td>Control Voltage</td>
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<td>V&lt;sub&gt;DD&lt;/sub&gt; = 15V</td>
<td>62 67 71 61</td>
<td>72 % V&lt;sub&gt;DD&lt;/sub&gt;</td>
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<tr>
<td>Reset Voltage</td>
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<td>V&lt;sub&gt;DD&lt;/sub&gt; = 2V to 15V</td>
<td>0.4</td>
<td>1.0 0.2</td>
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</table>

### Notes:

1. Due to the SCR structure inherent in the CMOS process used to fabricate these devices, connecting any terminal to a voltage greater than V<sub>DD</sub> +0.3V or less than V<sub>DD</sub> -0.3V may cause destructive latchup. For this reason it is recommended that no inputs from external sources not operating from the same power supply be applied to the device before its power supply is established. In multiple power supply systems, the supply of the ICM7555/6 must be turned on first.

2. The thermal information above assumes the worst case temperature, which may cause permanent damage to the device. This is a stress only rating and operation of the device at these or any other conditions above those indicated in the operational sections of this specification is not intended.

### Continued
FIGURE 2B. ALTERNATE ASTABLE CONFIGURATION

OUTPUT DRIVE CAPABILITY
The output driver consists of a CMOS inverter capable of driving most logic families including CMOS and TTL. As such, if driving CMOS, the output swing at all supply voltages will equal the supply voltage. At a supply voltage of 4.5V or more the ICM7555/6 will drive at least 2 standard TTL loads.

ASTABLE OPERATION
The circuit can be connected to trigger itself and free run as a multivibrator, see Figure 2A. The output swings from rail to rail, and is a true 50% duty cycle square wave. (Trip points and output swings are symmetrical). Less than a 1% frequency variation is observed, over a voltage range of ±5V to ±15V.

\[ f = \frac{1}{1.4RC} \]

The timer can also be connected as shown in Figure 2B. In this circuit, the frequency is:

\[ f = \frac{1.44(R_A - 2R_g)}{RC} \]

The duty cycle is controlled by the values of \( R_A \) and \( R_g \), by the equation:

\[ D = \frac{(R_A - R_g)\tau}{(R_A - 2R_g)} \]

MONOSTABLE OPERATION
In this mode of operation, the timer functions as a one-shot, see Figure 3. Initially the external capacitor (C) is held discharged by a transistor inside the timer. Upon application of a negative TRIGGER pulse to pin 2, the internal flip-flop is set which releases the short circuit across the external capacitor and drives the OUTPUT high. The voltage across the capacitor now increases exponentially with a time constant \( \tau = R_A C \). When the voltage across the capacitor equals \( \frac{2}{3} V_H \), the comparator resets the flip-flop, which in turn discharges the capacitor rapidly and also drives the OUTPUT to its low state. TRIGGER must return to a high state before the OUTPUT can return to a low state.

\[ \text{OUTPUT} = \frac{1}{2} (1/2) R_A C = \frac{1}{2} R_A C \]

FIGURE 3. MONOSTABLE OPERATION

CONTROL VOLTAGE
The CONTROL VOLTAGE terminal permits the two trip voltages for the THRESHOLD and TRIGGER internal comparators to be controlled. This provides the possibility of oscillation frequency modulation in the astable mode or even inhibition of oscillation, depending on the applied voltage. In the monostable mode, delay times can be changed by varying the applied voltage to the CONTROL VOLTAGE pin.

RESET
The RESET terminal is designed to have essentially the same trip voltage as the standard bipolar 555/6, i.e., 0.6V to 0.7V. At all supply voltages it represents an extremely high input impedance. The mode of operation of the RESET function is, however, much improved over the standard bipolar 555/6 in that it controls only the internal flip-flop, which in turn controls simultaneously the state of the OUTPUT and DISCHARGE pins. This avoids the multiple threshold problems sometimes encountered with slow falling edges in the bipolar devices.

\[ V_{CDN} \leq V \leq V_{CDH} \]

The frequency of the monostable mode can be changed by varying the applied CONTROL VOLTAGE. In the astable mode, the CONTROL VOLTAGE determines the trip voltages for the THRESHOLD and TRIGGER internal comparators.
74161 A 4-Bit Counter

National Semiconductor

54161/DM54161A/DM74161A
DM54163A/DM74163A Synchronous 4-Bit Counters

General Description
These synchronous, presettable counters feature an internal carry look-ahead for application in high-speed counting designs. The 161A and 163A are 4-bit binary counters. The carry output is decoded by means of a NOR gate, thus preventing spikes during the normal counting mode of operation. Synchronous operation is provided by having all flip-flops clocked simultaneously so that the outputs change coincident with each other when so instructed by the count-enable inputs and internal gating. This mode of operation eliminates the output counting spikes which are normally associated with asynchronous (ripple clock) counters. A buffered clock input triggers the four flip-flops on the rising (positive-going) edge of the clock input waveform.

These counters are fully programmable; that is, the outputs may be preset to either level. As presetting is synchronous, setting up a low level at the load input disables the counter and causes the outputs to agree with the setup data after the next clock pulse, regardless of the levels of the enable input. Low-to-high transitions at the load input of the 161A and 163A are perfectly acceptable, regardless of the logic levels on the clock or enable inputs. The clear function for the 161A is asynchronous; and a low level at the clear input sets all four of the flip-flop outputs low, regardless of the levels of clock, load, or enable inputs. The clear function for the 163A is synchronous; and a low level at the clear input sets all four of the flip-flop outputs low after the next clock pulse, regardless of the levels of the enable inputs. This synchronous clear allows the count length to be modified easily, as decoding the maximum count desired can be accomplished with one external NAND gate. The gate output is connected to the clear input to synchronously clear the counter to all low outputs. Low-to-high transitions at the clear input of the 163A are also permissible, regardless of the logic levels on the clock, enable, or load inputs.

The carry look-ahead circuitry provides for cascading counters for n-bit synchronous applications without additional gating. Instrumental in accomplishing this function are two count-enable inputs and a ripple carry output. Both count-enable inputs (P and T) must be high to count, and input T is tied forward to enable the ripple carry output. The ripple carry output thus enabled will produce a high-level output pulse with a duration approximately equal to the high-level portion of the Qn output. This high-level overflow ripple carry pulse can be used to enable successive cascaded stages. High-to-low-level transitions at the enable P or T inputs of the 161A through 163A may occur, regardless of the logic level on the clock.

Features
- Synchronously programmable
- Internal look-ahead for fast counting
- Carry output for n-bit cascading
- Synchronous counting
- Load control line
- Diode-clamped inputs
- Alternate Military/Aerospace device (54161) is available. Contact a National Semiconductor Sales Office/Distributor for specifications.

Connection Diagram

4-59

74145 BCD/Decimal Decoders/Drivers
INTEGRATED CIRCUITS

BCD/DECIMAL DECODERS/DRIVERS

GENERAL DESCRIPTION
These BCD-to-decimal decoders/drivers consist of eight inverters and ten, four-input NAND gates. The inverters are connected in pairs to make BCD input data available for decoding by the NAND gates. Full decoding of BCD input logic ensures that all outputs remain off for all invalid (0-15) binary input conditions. These decoders feature high-performance, NPN output transistors designed for use as indicator/relay drivers, or as open-collector logic-circuit drivers. The high-breakdown output transistors are compatible for interfacing with most MOS integrated circuits.

FEATURES
• Full decoding of input logic.
• 90 mA sink-current capability.
• All outputs are off for invalid BCD input conditions.

ABSOLUTE MAXIMUM RATINGS
Supply Voltage ........................................................................ 5.25V
Input Voltage ........................................................................ 5.5V
Output Voltage ........................................................................ 1.5V
Operating Temperature Range ................................................... 0°C to +70°C
Storage Temperature Range ...................................................... 65°C to +150°C
Lead Temperature (Soldering, 10 sec) ......................................... 260°C
Supply Voltage (Vil, Vih) ............................................................ 4.75—5.25V

TRUTH TABLE

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<th>NO.</th>
<th>INPUTS</th>
<th>OUTPUTS</th>
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<tr>
<td>9</td>
<td>H</td>
<td>L</td>
</tr>
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</table>

NOT A VALID

H = High Level (Off), L = Low Level (On)

40106 Schmitt Trigger

CD40106BM/CD40106BC Hex Schmitt Trigger

General Description
The CD40106B Hex Schmitt Trigger is a monolithic complementary MOS (CMOS) integrated circuit constructed with N and P-channel enhancement transistors. The positive and negative-going threshold voltages, \( V_T^+ \) and \( V_T^- \), show low variation with respect to temperature (typ 0.0005V/C at \( V_{DD} = 10V \)) and hysteresis, \( V_T^+ - V_T^- \geq 0.2 \ V_{DD} \) is guaranteed.

All inputs are protected from damage due to static discharge by diode clamps to \( V_{DD} \) and \( V_{SS} \).

Features
- Wide supply voltage range
- 3V to 15V
- 0.7 \( V_{DD} \) (typ.)
- Fan out of 2 driving 74L or 1 driving 74LS
- 0.4 \( V_{DD} \) (typ.)
- 0.2 \( V_{DD} \) guaranteed
- Equivalent to MEG54C14/MEG74C14
- Equivalent to MC14564B

Connection Diagram
Dual-In-Line Package

Switching Time Waveforms
Order Number CD40106B

Schematic Diagram

74194A Shift Register

282
DM74LS194A
4-Bit Bidirectional Universal Shift Register

General Description
This bidirectional shift register is designed to incorporate virtually all of the features a system designer may want in a shift register, they feature parallel inputs, parallel outputs, right-shift and left-shift serial inputs, operating-mode-control inputs, and a direct overwriting clear line. The register has four distinct modes of operation, namely:

- Parallel (transparent) mode
- Shift right (in the direction Qn to Q0)
- Shift left (in the direction Q0 to Qn)
- Initial state (no inputs)

Synchronous parallel loading is accomplished by applying the four bits of data and setting both mode control inputs, Q5 and Q1, HIGH. The data is loaded into the associated flip-flops and appear at the outputs after the positive transition of the clock input. During loading, serial data flow is inhibited.

Shift right is accomplished synchronously with the rising edge of the clock pulse when Q3 is HIGH and Q1 is LOW. Serial data for this mode is entered at the right-side data input, either 3D or 1D is HIGH data shifts left synchronously and new data is entered at the shift-left serial input.

Clearing of the flip-flops is inhibited when both mode control inputs are LOW.

Ordering Code:

<table>
<thead>
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<th>Package Description</th>
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<tr>
<td>NS1E</td>
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Connection Diagram

Function Table

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<tr>
<th>Clear</th>
<th>Shift Mode</th>
<th>Clock</th>
<th>Serial</th>
<th>Parallel</th>
<th>Outputs</th>
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<td>L</td>
<td>X</td>
<td>X</td>
<td>H</td>
</tr>
</tbody>
</table>

Legend:
- L = LOW level (active low)
- H = HIGH level (active high)
- T = Toggle (either input, changing both outputs)
- Qp = Propagate (data output unchanged)
- Q0, Q1, Q2, Q3 = The state of Q3, Q2, Q1, or Q0 respectively, before the inhibited data-state hold conditions were established

4
017BC Decade Counter/Divider
CD4017BC • CD4022BC
Decade Counter/Divider with 10 Decoded Outputs • Divide-by-8 Counter/Divider with 8 Decoded Outputs

General Description
The CD4017BC is a 5-stage divide-by-10 Johnson counter with 10 decoded outputs and a carry-out bit. The CD4022BC is a 4-stage divide-by-8 Johnson counter with 8 decoded outputs and a carry-out bit. These counters are cleared to their zero count by a logical "1" on their reset line. These counters are advanced on the positive edge of the clock signal when the clock enable signal is in the logical "1" state.

The configuration of the CD4017BC and CD4022BC permits medium speed operation and assures a hazard free counting sequence. The 10 decoded outputs are normally in the logical "0" state and go to the logical "1" state only at their respective time slot. Each decoded output remains high for 1 full clock cycle. The carry-out signal completes a full cycle for every 10 clock input cycles and is used as a ripple carry signal to any succeeding stages.

Features
- Wide supply voltage range: 3.0V to 15V
- High noise immunity: 0.4V (typ.)
- Low power: Fan out of 2 driving 74L
- TTL compatibility: or 1 driving 74LS
- Medium speed operation: 5.0 MHz (typ.) with 10V VDD
- Low power: 10 µW (typ.)
- Fully static operation

Applications
- Automotive
- Instrumentation
- Medical electronics
- Alarm systems
- Industrial electronics
- Remote metering

Ordering Code:
Order Code: Package Number: Package Description:
CD4017BCM M1EA 16-Lead Small Outline Integrated Circuit (SOIC), JEDEC MS-012, 2.125” Narrow
CD4017BCSU M1SO 16-Lead Small Outline Package (SOP), BGA TYPE II, 3.3mm Wide
CD4017BCN N1JE 14-Lead Plastic Dual-in-Line Package (PDIP), JEDEC MS-021, 3.300” Wide
CD4022BCM M1EA 16-Lead Small Outline Integrated Circuit (SOIC), JEDEC MS-012, 2.125” Narrow

Connection Diagrams

Quad 2-Input AND
MM74C08
Quad 2-Input AND Gate

General Description
The MM74C08 employs complementary MOS (CMOS) transistors to achieve wide power supply operating range, low power consumption and high noise margin. These gates provide basic functions used in the implementation of digital integrated circuit systems. The N- and P-channel enhancement mode transistors provide a symmetrical circuit with output swing essentially equal to the supply voltage. No DC power other than that caused by leakage current is consumed during static condition. All inputs are protected from damage due to static discharge by diode clamps to VCC and GND.

Features
- Wide supply voltage range: 3.0V to 15V
- Guaranteed noise margin: 1.0V
- High noise immunity: 0.45 VCC (typ.)
- Low power TTL compatibility
- Fan out of 2 driving 74L
- Low power consumption: 10 mW/package (typ.)

Ordering Code:

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<thead>
<tr>
<th>Order Number</th>
<th>Package Number</th>
<th>Package Description</th>
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<tbody>
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<td>M14A</td>
<td>14-Lead Small Outline Circuit (SOIC), JEDEC MS-012, 0.150&quot; Narrow</td>
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<td>MM74C08DN</td>
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Connection Diagram

Truth Table

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
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</thead>
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<tr>
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<td>L</td>
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<tr>
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<td>H</td>
</tr>
</tbody>
</table>

H = HIGH Level
L = LOW Level

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74LS00 Quad 2-Input NAND
74LS02 Quad 2-Input NOR
74LS04 Inverter
http://www.all datasheet.com/datasheet-pdf/pdf/53702/FAIRCHILD/MM74C00M.html

285
MM74C00 • MM74C02 • MM74C04
Quad 2-Input NAND Gate •
Quad 2-Input NOR Gate •
Hex Inverter

General Description

The MM74C00, MM74C02, and MM74C04 logic gates employ complementary MOS (CMOS) to achieve wide power supply operating range, low power consumption, high noise immunity and symmetric controlled rise and fall times. With features such as this, the 74C logic family is close to idea for use in digital systems. Function and pin out compatibility with series 74 devices minimizes design time for those designers already familiar with the standard 74 logic family.

Features

- Wide supply voltage range: 3V to 18V
- Guaranteed noise margin: 1V
- High noise immunity: 0.45 V(H)
- Low power: TTL compatibility
- Pin out of 2 driving 74L

Ordering Code:

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<th>Package Number</th>
<th>Package Description</th>
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Connection Diagrams

Connection Diagrams for DIP and SOIC


74LS08 Quad 2-Input AND
MM74C08
Quad 2-Input AND Gate

General Description

The MM74C08 employs complementary MOS (CMOS) transistors to achieve wide power supply operating range, low power consumption and high noise margin. These gates provide basic functions used in the implementation of digital integrated circuits. The N- and P-channel enhancement mode transistors provide a symmetrical circuit with output swing essentially equal to the supply voltage. No DC power other than that caused by leakage current is consumed during static condition. All inputs are protected from damage due to static discharge by diode clamps to \( V_{CC} \) and GND.

Features

- Wide supply voltage range: 3.2V to 15V
- Guaranteed noise margin: 1.0V
- High noise immunity: 0.45 \( V_{CC} \) (typ.)
- Low power & TTL compatibility
- Fan out of 2 driving 74L
- Low power consumption: 10 mW/package (typ.)

Ordering Code:

<table>
<thead>
<tr>
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<th>Package Number</th>
<th>Package Description</th>
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Connection Diagram

![Connection Diagram](image_url)

Truth Table

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
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<td>L</td>
</tr>
<tr>
<td>H</td>
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</tbody>
</table>

4072BC Quad 4-Input OR

4071B - QUAD 2-INPUT OR GATE
4072B - QUAD 4-INPUT OR GATE
4075B - TRIPLE 3-INPUT OR GATE

- MEDIUM-SPEED OPERATION (typ. tpd = 80ns, typ.) AT Vcc = 10V
- QUIESCENT CURRENT SPECIFIED TO 20mA FOR HCC DEVICE
- 5V, 10V AND 15V PARAMETRIC RATINGS
- INPUT CURRENT OF 100nA AT 18V AND 25°C FOR HCC DEVICE
- 100% TESTED FOR QUIESCENT CURRENT
- MEETS ALL REQUIREMENTS OF JEDEC TEN-TATIVE STANDARD NO. 12A, "STANDARD SPECIFICATIONS FOR DESCRIPTION OF "B" SERIES CMOS DEVICES"

DESCRIPTION
The HCC4071B/4072B and 4075B (extended temperature range) and HCF4071B/4072B and 4075B (intermediate temperature range) are monolithic integrated circuits, available in 14-lead dual in-line plastic or ceramic package and plastic micropackage.

PIN CONNECTIONS

The HCC/HCF4071B, 4072B and 4075B OR gates provide the system designer with direct implementation of the positive-logic OR function and supplement the existing family of COS/MOS gates.
LM350 Voltage Regulator

LM350
3-Terminal 3A Positive Adjustable Voltage Regulator

Features
- Output adjustable between 1.2V and 33V
- Guaranteed 3A output current
- Internal thermal overload protection
- Load regulation (Typ: 0.1%)
- Line regulation (Typ: 0.015% V)
- Internal short-circuit current limit
- Output transistor safe-area compensation

Description
The LM350 is an adjustable 3-terminal positive voltage regulator capable of supplying in excess of 3.0 A over an output voltage range of 1.2V to 33 V

Internal Block Diagram
DESCRIPTION
The 2N2219A and 2N2222A are silicon planar epitaxial NPN transistors in Jecdo TO-39 (for 2N2219A) and in Jecdo TO-18 (for 2N2222A) metal case. They are designed for high speed switching application at collector current up to 500mA, and feature useful current gain over a wide range of collector current, low leakage currents and low saturation voltage.

2N2219A approved to CECC 50002-100.
2N2222A approved to CECC 50002-101
available on request

INTERNAL SCHEMATIC DIAGRAM

ABSOLUTE MAXIMUM RATINGS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter Description</th>
<th>Value</th>
<th>Unit</th>
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</thead>
<tbody>
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<td>VCEO</td>
<td>Collector-Base Voltage (Ic = 0)</td>
<td>75</td>
<td>V</td>
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<tr>
<td>VCEO</td>
<td>Collector-Emitter Voltage (Ic = 0)</td>
<td>40</td>
<td>V</td>
</tr>
<tr>
<td>VCEO</td>
<td>Emitter-Base Voltage (Ib = 0)</td>
<td>6</td>
<td>V</td>
</tr>
<tr>
<td>IC</td>
<td>Collector Current</td>
<td>0.8</td>
<td>A</td>
</tr>
<tr>
<td>Ptot</td>
<td>Total Dissipation at Tamb ≤ 25°C</td>
<td>0.8</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td>for 2N2219A</td>
<td>0.5</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td>for 2N2222A</td>
<td>3</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td>at Tamb ≤ 25°C</td>
<td>1.8</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td>for 2N2219A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>for 2N2222A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tstg</td>
<td>Storage Temperature</td>
<td>65 to 200°C</td>
<td></td>
</tr>
<tr>
<td>Tj</td>
<td>Max. Operating Junction Temperature</td>
<td>175°C</td>
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</table>

June 1999 1/6

Transistor 2N2219

290
DESCRIPTION
The 2N2218, 2N2219, 2N2221 and 2N2222 are silicon planar epitaxial NPN transistors in Jecpec TO-99 for 2N2218 and 2N2219 and in Jecpec TO-18 (for 2N2221 and 2N2222) metalcases. They are designed for high-speed switching applications at collector currents up to 500 mA, and feature useful current gain over a wide range of collector current, low leakage currents and low saturation voltages.

2N2218/2N2219 approved to CECC 50020-102, 2N2221/2N2222 approved to CECC 50020-101 available on request.

INTERNAL SCHEMATIC DIAGRAM

ABSOLUTE MAXIMUM RATINGS

<table>
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<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>VCEO</td>
<td>Collector-emitter voltage (VBE = 0)</td>
<td>60</td>
<td>V</td>
</tr>
<tr>
<td>VCEO</td>
<td>Collector-emitter Voltage (VBE = 3)</td>
<td>30</td>
<td>V</td>
</tr>
<tr>
<td>VCEO</td>
<td>Emitter-base voltage (VBE = 3)</td>
<td>5</td>
<td>V</td>
</tr>
<tr>
<td>I(max)</td>
<td>Collector Current</td>
<td>0.8</td>
<td>A</td>
</tr>
<tr>
<td>P(max)</td>
<td>Total Power Dissipation at T(j) = 25 °C</td>
<td>0.8</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td>for 2N2219 and 2N2218 at T(j) = 25 °C</td>
<td>0.5</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td>for 2N2221 and 2N2222 at T(j) = 25 °C</td>
<td>3</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td>for 2N2219 and 2N2218 at T(j) = 125 °C</td>
<td>1.8</td>
<td>W</td>
</tr>
<tr>
<td>T(j)</td>
<td>Junction Temperature</td>
<td>-65 to 200</td>
<td>°C</td>
</tr>
<tr>
<td>T ambient</td>
<td>Storage Temperature</td>
<td>175</td>
<td>°C</td>
</tr>
</tbody>
</table>
Component Layout. Irish Printing Circuits
Component Layout. Component drill holes
Track layout for Automatic Dark Adaptometer. One of two
Appendix 7 ADA Evaluation

Female - Right Eye 23 Years
Subject 37

Male - Right Eye 24 Years
Subject 40

Male - Right Eye 22 Years
Subject 42

Female - Right Eye 27 Years
Subject 36

Male - Right Eye 23 Years
Subject 41
Appendix 8  ADA & GWA

Male - Right Eye 24 Years
Subject 44

Male - Right Eye 21 Years
Subject 45
Female - Right Eye 22 Years
Subject 46

Male - Right Eye 20 Years
Subject 47
Male - Right Eye 22 Years  
Subject 48

Female - Right Eye 20 Years  
Subject 49
Female - Right Eye 19 Years
Subject 50

Female - Right Eye 20 Years
Subject 51
Male - Right Eye 21 Years
Subject 54

- ADA Adaptation Curve
- Goldmann Weekers Adaptation Curve

Time/Seconds
Luminance/\log_{10} \text{lux Lambert}

Male - Right Eye 20 Years
Subject 55

- ADA Adaptation Curve
- Goldmann Weekers Adaptation Curve

Time/Seconds
Luminance/\log_{10} \text{lux Lambert}
Male - Right Eye 26 Years
Subject 56

Male - Right Eye 29 Years
Subject 57
Female - Right Eye 20 Years
Subject 58

Male - Right Eye 21 Years
Subject 59
# Appendix 9  Biographical Questionnaire

**Subject B**

**Dublin Institute of Technology, Kevin Street**

## OPTOMETRY COURSE  CLINICAL RECORD

<table>
<thead>
<tr>
<th>STUDENT'S NAME</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>

**HISTORY**

- 1 yr ago said needed specs for reading. Age 21 p.d.
- 800 graded lenses under R6 for long life. Opt removed from somewhere as a child.

**MEDICAL HISTORY & MEDICATION**

- No. None. No meds.

**FAMILY HISTORY**

- 3rd had kym.

## SYMPTOMS/SIGNS

**REASON FOR VISIT**

<table>
<thead>
<tr>
<th>UNAIDED V.</th>
<th>PREVIOUS EX</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/4 +3</td>
<td></td>
</tr>
</tbody>
</table>

**VA**

- Near/Inter Add.

**OCCUPATION**

- Student of Chemistry

**LEISURE/SPORTS**

- No ice.

**WORKING DISTANCE(s)**

- Unaided / with previous rx (delete one)

## EXTERNAL EXAMINATION

### General appearance

<table>
<thead>
<tr>
<th>L</th>
<th>R</th>
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</tbody>
</table>

### Lid & margins

- L: Normal
- R: Normal

### Conjunctiva

- L: Clear
- R: Clear

### Cornea

- L: Clear
- R: Clear

### Ant. Chamb. & Media

- L: Clear
- R: Clear

### Iris

- L: Blue
- R: Blue

### Pupil appear & size

- L: 3 mm
- R: 2 mm

### Refinences: direct

- L: +2
- R: +2

### Convergence

- L: +2
- R: +2

### Mutility/Saccades

- L: Normal
- R: Normal

### Confrontation

- L: Normal
- R: Normal

## OPHTHALMOSCOPY

### Disc:

- Colour: Yellow Red
- Cupping depth: 0.8
- C/D ratio: 1.3

### Lenses:

- Not seen
- Not seen

### Margins:

- Clear
- Clear

### Retinal Veins: course

- Slight
- Normal

### A/V crossings: number

- Normal
- Normal

### Macula

- Close-wound repar
- Close-wound repar

### Periphery

- Healthy
- Healthy

### Lens

- Clear
- Clear

### Vitreous

- Clear
- Clear

### Choroid

- Healthy
- Healthy

### Gen. Fundus Appear

- Healthy
- Healthy

### Sketch

- [Sketch Image]
RETI- R:
OSCOPT

SUBJ-

SUBJ-

MUSCLE | DIST Horis Vert Method
BALANCE | NEAR Horis Vert Method
SUPPRESSION Method
STEREOPSIS Method

W.P. CONV. JUMP CONV.
WORKING DIST. (cm) AMPL. ACCOM. (D)
WORKING ADD. METHOD NEAR V.A

STUDENT'S PROPOSED PRESCRIPTION

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>R</td>
<td></td>
<td></td>
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<tr>
<td>L</td>
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</tbody>
</table>

SUPERVISOR'S PRESCRIPTION

<p>| | | | | | | | |</p>
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<thead>
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<tbody>
<tr>
<td>R</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td></td>
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</tr>
</tbody>
</table>

INSTRUCTIONS TO PT.

SUPERVISOR'S NAME SIGNATURE

Rx ISSUED? DRIVING FORM ISSUED? REFERRAL?