# THE DESIGN OF A SYSTEM FOR EVALUATING GLARE FROM SMALL LIGHTING SOURCES

**By**

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**DEDICATION**

I dedicate this work to my loving and supportive parents, John and Joey van der Merwe.

## ABSTRACT

Discomfort glare is a topic that has been investigated for many years without any reasonable explanation regarding its effect on the human visual system. Results of previous research concluded that established methods have a lot of similarities in implementation; but a number of differences when comparing the results of observer's evaluations with the mathematically calculated glare ratings. Therefore, an alternative method of evaluating the influence of exposure to an unshielded light source was investigated to establish a more reliable and realistic response from observers.

In order to address the discrepancies of previous evaluation systems concerning observer's varying opinions regarding the level of discomfort experienced, it was decided to investigate the feasibility of evaluating the brain activity of the observers exposed to an unshielded incandescent lamp. This was done in order to facilitate the differences in each individual observer's sensitivity to bright light sources and the influence of personal taste therefore, eliminating the effect of personal interpretation.

The main purpose of this study was to determine whether it would be possible to get any response regarding brain functions when an observer is exposed to a bare light source. In order to determine the pathway of visual stimuli it was necessary to investigate the operating principles of the human eye in detail. Because the eye is only an instrument that makes seeing possible; it was also important to investigate the brain and all its different functions. The part of the brain where visual interpretation takes place was indicated as the occipital lobe. This is the part of the brain monitored for any change of functional status by taking measurements with an electroencephalogram (EEG).

Measurements were indeed possible; it was presented as a suppression of the alpha brain activity. During the testing procedure it was observed that the observers were not equally photosensitive. There was also a difference in the amount of alpha suppression with the observer's eyes open and closed respectively. Because the alpha rhythm has a tendency to increase with closed eyes it was much easier to notice the suppression.

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## GLOSSARY OF TERMS

### TERMS:

| | |
|---|---|
| • Footcandle (ft-c) | The unit of illumination when the foot is taken as the unit of length. |
| • Footlambert (ft-L) | The average brightness of any surface emitting light at a rate of 1 lumen per square foot. |
| • Illumination (E) | Density of the luminous flux on a surface. |
| • Luminaire | A complete lighting unit consisting of a light source, reflector, refractor and housing. |
| • Luminance | The luminous intensity of any surface. |
| • Luminous flux (F) | This is the time rate of flow of light. |
| • Luminous Intensity | The solid angular flux density in a given direction. |
| • Neurophysiology | Scientific study of how people's bodies function based on the nervous system. |
| • Physiology | Scientific study of how people's bodies function. |
| • Psychological | Concerned with a person's mind and thoughts. |
| • Psychophysical | Influence of surrounding things on the mind of a person. |

(Brink 1979, Collins 1989, Sharp 1951:1-4)

### ABBREVIATIONS:

| | |
|---|---|
| • BCD | Borderline between comfort and discomfort |
| • CIE | Commission on Illuminance |
| • CNS | Central nervous system |
| • DGR | Discomfort Glare Rating |
| • DNA | Deoxyribonucleic acid |
| • EMG | Electromyographic |
| • GI | Glare Index |
| • LGN | Lateral geniculate nucleus |
| • $L_oS$ | Line of sight |
| • RAS | Reticular activation system |

- UGR Unified Glare Rating
- VCP Visual Comfort Probability

**SYMBOLS:**

- $E_d$ Direct vertical illuminance at the observer's eye
- $E_i$ Indirect illuminance at the observer's eye
- ft-L Footlambert
- $L_b$ Background luminance
- $L_s$ Luminance of the glare source
- P Position index
- $\gamma$ Viewing angle
- $\omega_s$ Solid angle

# CHAPTER 1 – ORIENTATION

## 1.1 Introduction

Visual performance is defined as an organised set of results that form links between the visual sciences and illuminating engineering. The word 'organised' implies a model that relates these two disciplines, and therefore visual performance can be seen as a hybrid discipline which is not pure visual science or pure illuminating engineering (Rea 1982:35). People concerned with developing or applying lighting recommendations should be familiar with certain fundamental relationships among light, vision, and seeing. The eye is the primary gateway to the surrounding world. Without light seeing is impossible, with inadequate light or the wrong kind of lighting, seeing may be inefficient, uncomfortable, or hazardous. It is evident that the lighting engineer has a great responsibility to provide adequate visibility in order for tasks to be performed with required standards of speed and accuracy, provide lighting levels that will permit a person to work with minimum effort, and provide lighting conditions that will result in maximum safety and absence of visual disability and visual discomfort (IES 1966:2-1). The visual mechanism for experiencing discomfort when exposed to a glaring source; is still not well understood (Bullough & Van Derlofske 2003:18). Glare has two effects upon those exposed to it. If it is slight it may cause only a vague and indefinitely disagreeable feeling. When it is more intense it may be distracting and cause annoyance, irritation and a definite feeling of discomfort (Hewitt & Vause 1966:14).

## 1.2 The problem and its setting

### 1.2.1 Importance of the study

The increase in productivity is not only linked to illuminance but also to the quality of lighting installations. The limiting of discomfort glare has long been regarded as a major quality parameter of illumination (Pai & Gulati 1995:184). The fundamental causes of discomfort glare perception still remain an unanswered question. Further research is still required to determine the basic mechanisms that lead to the perception of discomfort glare, and to improve the correlation between calculated glare values and subjective assessment of glare sources (Perry 1991:61).

The sensitivity to sensory discomfort varies with personality. Therefore, psychological factors are insufficient for a total explanation of the pain response. Physiological mechanisms have an essential role in the response to discomfort glare. Individual attitudes, and its effect on the perception of glare, the ability of the person to make decisions about different glare levels, differences in individual physiological activity including different states of the visual systems, all need to be explored further in order to better understand the significance of glare to individual subjects (Stone & Harker 1973:49).

### 1.2.2 Problem statement

Lighting and vision are closely linked, but technically the link is weak. The ability to relate visual response to a given lighting condition suffers because the scientific understanding of visual response is undeveloped due to the fact that visual processing is more complex than any computational model available and the inability to specify the visual stimulus easily. Even with a satisfactory model of vision, it is difficult to predict visual response to realistic materials because current technology seriously restricts the ability to specify the visual stimulus accurately. Therefore, there was little reason to extend the understanding of the link between lighting and vision, due to the lack of the technical means of acquiring the information necessary to make the link (Rea & Jeffrey 1990:64).

The purpose of this study is to evaluate discomfort glare by addressing fundamental mechanisms involved in experiencing glare, and its neurophysiological effect on humans, with special reference to developed models evaluating discomfort glare and the mathematical procedures followed to calculate glare ratings, the operating principles of the human eye, the visual pathway to the brain and the measurement of different brain frequency bands by means of an electroencephalogram (EEG) in order to determine the effect of exposure to an unshielded light source on the functional status of the brain.

Although it is relatively easy to perceive and report the sensation of discomfort caused by the presence of an offending light source of high luminance, a reliable objective correlate of discomfort glare has not yet been found (Berman, Jacobs, Bullimore, Baily, Ghandi and Greenhouse 1991:183). A possible reason is that since comfort and discomfort are sensations, its appraisal can be made only by those who experience such sensations. Different individuals may vary considerably in the appraisals, but the trends are decisive (Luckiesh & Guth 1949:650).

As a result; a new method of evaluating discomfort glare will be investigated where the researcher will not have to rely on the observer's verbal assessment on the level of discomfort experienced, instead the observer's brainwaves will be monitored for any signs of discomfort experienced by the observer. Collura (1997) stated that EEG's are read in frequency bands and is an electrical waveform that is recorded from the brain by electrodes appropriately placed on the head, the readings are then amplified and the electrical signal is displayed on computer.

### 1.2.3 Objective of the research

The lighting engineer and the layman can testify that the presence of glare can be recognised upon sight, but will be at a loss to describe the specific characteristics by which it may be diagnosed and the remedy prescribed. Glare has been described as any brightness within the field of vision of such character as to cause discomfort, annoyance, interference with vision and eye fatigue. Recognition of glare has been largely a matter of intuitive judgment and an expression of a feeling as to whether conditions are right or wrong. In short, data are needed from further research in order for simple rules to be developed that will assure engineer as well as layman of a pleasant and gratifying result (Fowler & Crouch 1941:897). Therefore, rather than attempting to refine the glare prediction systems any further, it would be better to concentrate efforts on developing an understanding of the causes of glare within the context of sensory discomfort (Boyce & Beckstead 1991:93). In order to evaluate sensory discomfort, with the emphasis on visual stimuli, a thorough understanding of the working principles of the eye as well as the visual pathway in the brain is essential. The knowledge of the eye and brain will assist in understanding the methodology of EEG measurements and will lay the groundwork for further research investigating the effect of various external factors on the perception of discomfort glare.

### 1.2.4 Value of the research

During an experiment conducted by Stone and Harker (1973:49) it was demonstrated that the wide variability between individuals in reaction to discomfort glare was a finding consistent with other studies of discomfort in sensory systems. Such variability complicates the task of the designer because it makes the conception of a discomfort glare threshold, which possesses the more concise sensory threshold, very difficult.

If the results of such experiments are applied to the lighting design practice it is quite probable that glare is experienced more frequently in designed interior lighting schemes than would be predicted by the Illuminating Engineering Society (IES) glare index system; although people may not complain (Stone & Harker 1973:49). It would not be unreasonable to say that the vast majority of people in the work place do not recognize a discomfort glare situation. However, what the people do experience is a headache, sore eyes, feeling of irritability and a short temper (Poulton 1991:37). As a result, Stone and Harker (1973:48) suggested that in order to offer an adequate explanation of the wide differences in individual and group responses to discomfort glare, it demands an understanding of both the psychological attitudes to glare as well as an understanding of the physiological mechanisms which glare stimulates. By conducting electrophysiological and neurophysiological studies, data, methods and theories will be evaluated and will therefore form a linking model between visual science and illuminating engineering (Rea 1982:35).

## 1.3 Research methodology

### 1.3.1 Historical overview

The first form of artificial light used by man was firelight, created by the combustion of wood. Developments in basic technology led to the creation of the candle and the oil lamp, and then the gas lamp, all of which depended on combustion. However, combustion is not involved in any of the more common light sources used in modern lighting practice. These light sources can conveniently be divided into two broad classes, incandescent lamps and discharge lamps. Both rely on electricity as a source of energy but it has different basic mechanics. There are a large number of different sources of light available, each with different properties. Due to the complexity of the human visual system and the difference between individuals, any one standardized measure of visual effect is inevitably an approximation. Using the appropriate spectral-sensitivity curve the four basic photometric quantities can be derived: luminous flux, luminous intensity, illuminance and luminance (Boyce 1981:33-34).

The visual sensations that the human eyes are capable of exiting have two fundamental characteristics, namely colour and brightness (Hewitt & Vause 1966:2). Light sources with high brightness or uneven distribution in the field of view can cause glare of varying degrees from a mild sensation of discomfort to an intolerable feeling of pain. The physiological and psychophysical processes underlying the origins of the feeling of discomfort experienced under bright lights are poorly understood (UMIST 1998:1). As a result of many years of appraisal by researchers there are certain accepted factors that affect discomfort glare. These are:

- luminance of the light source (the dominant component),
- luminance of the background,
- size and number of glare sources, and
- relative position of the glare source in the field of view (Topalova 2003:22).

The differences in individual responses from the observers towards the abovementioned factors, add to the obscurity of discomfort glare (UMIST 1998:1).

There are a number of different national systems for controlling discomfort glare, each of which has its own advantages and disadvantages (Boyce 1981:314). Different models, namely: British Glare Index, American Visual Comfort Probability (VCP) System and the Unified Glare Rating (UGR) method had many similarities, but were implemented differently. All these equations represented empirical relationships between the subjective degree of glare as experienced by an average observer and various parameters of the lighting installation. These equations were obtained by conducting various experiments with a high number of observers situated in full or reduced scale lighting installations (Topalova 2003:22). There are reasonable correlations for the predicted degree of discomfort glare from all these formulae but only weak correlations between the predicted discomfort glare and the ratings of individual observers (Boyce 1981:314). This implies that there must be factors influencing the experience of discomfort glare other than those considered in the formula prediction systems. Some of these factors are classified as physical, visual, procedural and psychological factors (Boyce & Beckstead 1991:93).

### 1.3.2 Previous research into discomfort glare

Basically all the previous research work on visual performance has been of two types, face validity studies or psychophysical studies. Face validity studies is where a person goes into an office and interview workers on how that particular lighting conditions are perceived. Psychophysical studies are where an experimenter must determine a threshold when presented with luminous increments (Rea 1982:35). In all cases the observer was either required to make adjustments of parameters or to comment on adjustments made by the experimenter. Adjustments made by the observer often took the form of 'direct' or/and 'buffer' tests. A 'direct' setting is made by adjustments of the source intensity until a specified degree of discomfort glare is reached, with the background/field luminance previously set by the experimenter. A 'buffer' setting is made by adjustments of the background/field luminance until a specified degree of discomfort glare is reached, with the source intensity previously set by the experimenter (Paul 1997:56). Factors indicated as possible causes of discomfort glare and the evaluation processes implemented are as follows:

#### 1.3.2.1 Overloaded retina as a cause of discomfort glare

With regard to investigations on the fundamental mechanism in receiving, transducing and processing the glare stimulus and the subsequent response of the observer resulting in a glare sensation, no successful understanding of what discomfort glare really is has been achieved. There are suggestions that the primary process involved is connected with the mechanisms of local adaptation of overloaded parts of the retina as related to the general adaptation level of the retina (Bodmann *et al* 1966:347). When an eye is exposed to light from a point source, the light admitted through the pupil produces on the retina a distribution which can be considered as having two components, focused light and stray light (Fry 1965:333). Glare can be defined as the contrast lowering effect of stray light in a visual scene. Glare forms a veil of luminance which reduces the contrast and thus the visibility of a target is decreased. It is difficult to see intensity differences efficiently in the presence of a high background of light intensity. The sensitivity to glare is amplified as scattering in the cornea or lens increases. The intraocular light scatter in normal eyes is as follows: cornea 30 %, lens 70 % and aqueous and vitreous < 1 % (Dhawan 2002:1).

#### 1.3.2.2 Influence of distraction as a cause of discomfort glare

Distraction has been suggested as another important factor that causes discomfort glare (Lynes 1977:51). When the light sources in a room are quite bright with reference to the field brightness of the room, it will serve as attraction points for involuntary fixation. Discomfort glare has always been associated with the brightness of the light source, a brightness that the eye involuntarily struggles to avoid but is compelled to transmit as a complaint to the conscious or subconscious mind (Fowler & Crouch 1941:898).

Seeing is a dynamic activity of human beings, and therefore any concept of the evaluation of brightness in the visual field should take cognizance of a variable line of visual fixation and of the work-world demands of a critical visual task. Sources displaced from the normal line of vision while a worker is performing a visual task may be fixated directly, or nearly directly, when the worker's eyes are raised for relaxation or to view another task-area (Guth 1951:65). It appears to be rather common practice when thinking or doing routine tasks to swing the eyes away from the details of the work and relax upon distant points. This action is involuntary and is perfectly natural due to the deep seated dislike to constant fixation at a near point. Even though the glance is momentary, if there is discomfort glare present, the eyes will communicate a complaint to the brain, and the resulting irritation may be a serious disturbance to the process of thought, as well as adding to nervous tension. This irritation has been proved by public dissatisfaction with bright enclosed globes in areas devoted to critical seeing (Fowler & Crouch 1941:903).

#### 1.3.2.3 Ocular fatigue and the rate of blinking as an indicator of discomfort

In the process of determining the optimum conditions for easy seeing the criteria of ocular fatigue has been found useful. It is supposed that eyelid movements (blinking) may be altered by reverberations in the central nervous system and will therefore correlate with factors pertaining to the expenditure of human energy in seeing. Therefore, it is expected that an unfavourable situation would increase the rate of blinking. This possibility was investigated directly with many subjects by observing the rate of blinking under different experimental conditions. One of these conditions included reading with and without a glare source within the visual field. From the experiments it was demonstrated that a glare source within the visual field encouraged the development of nervous muscular tension with reference to the performance of a critical visual task. Because of this, the rate of blinking increased with a more difficult or prolonged specific visual task. This indicated that the rate of blinking while performing critical visual tasks is a function of both the duration and severity of the specific visual task, and that an augmentation of either of these factors increases the rate of blinking (Luckiesh & Moss 1937:589).

### 1.3.2.4 Pupil responses as an indication of discomfort glare

Previous research into physiological basis of discomfort glare has been concerned with pupillary responses (UMIST 1998:1). Hopkinson speculated that changes in pupil behaviour could serve as an objective method of indicating discomfort glare, and Fry (Fugate & Fry 1956:537) and co-workers claimed to have detected glare induced changes in the power spectrum of the involuntary pupillary oscillations commonly known as hippus (Berman *et al.*1991:183). It was reported by Hopkinson in 1956 that the pupil becomes unstable in conditions producing discomfort glare, this implies that the dynamic characteristics of pupillary hippus are exaggerated under discomfort glare conditions (UMIST 1998:1).

In 1975 Fry and King obtained pupil response data at various levels of luminance. When the retinal illuminance produced by the glare source was low, the pupil stayed quite stable. Fry and King also made a Fourier analysis of the response of the pupil to a sinusoidally modulated light, at different levels of discomfort glare, and reported that a low frequency oscillation (0.3 Hz) was a dominant feature of the involuntary pupillary oscillations (hippus). However, the experiment was inconclusive because the pupil became massively contracted in the presence of the intense glare source and was therefore effectively static and virtually no pupillary oscillations could be measured (Fry & King 1975:307, UMIST 1998:1).

In attempting to verify possible changes in the power spectrum of hippus when discomfort and no discomfort were present, the average pupil size stayed the same, even when the reported discomfort was nearly intolerable. It was concluded that because there are no dominant frequency characteristics in the amplitude spectra of the pupillary hippus, it is very unlikely that discomfort glare could be associated with pupillary hippos. However, there is a possibility that the effect of accommodation might have affected the power spectrum of hippus and the fact that the recordings of the pupil size with discomfort glare started which might have lead to an adaptation to the bright light about five seconds after the glare source was turned on (UMIST 1998:2).

### 1.3.2.5 Pain detectors at extra-ocular muscles indicating discomfort

It is possible that a completely different set of physiological processes are involved in the generation of discomfort from glare. The basis of this response is possibly the pain (discomfort) detectors in the extra-ocular muscles. It has been known for quite some time that discomfort glare is accompanied by a strong flinch in the extra-ocular (facial) muscles surrounding the eye (UMIST 1998:2). In order to find an objectively measured correlate of discomfort glare, the electrical activity associated with the two major facial muscles that surround the eye were examined (Berman *et al.* 1991:183).

The orbicularis occuli is the muscle which is responsible for closing the eye and other nearby muscles such as the corrugator supercilii can be monitored with electromyographic (EMG) techniques (UMIST 1998:4). The EMG techniques are used to monitor the easily measured electrical activity spontaneously generated by the muscles. When measuring the time-locked change in electrical activity in the muscles when glare is introduced, the response of the glare can be quantified. The EMG recordings were made using small silver/silver chloride electrodes applied to the skin above muscles and measured electrical potentials while lighting conditions have been changed (Berman *et al.* 1991:183). The two small electrodes were positioned one below the lower eye lid (active electrode) and the other lateral to the eye but as close as possible to the edge of the eye (reference electrode). A third electrode was placed on the forehead to serve as a ground. Intensities were changed over a range extending both above and below the border between comfort and discomfort (BCD) (UMIST 1998:4).

Blinking causes an artefact which power spectrum differs a lot and can therefore be determined independently of the glare source. For a given adapting luminance, the power spectrum of the EMG response remains essentially unchanged from baseline until the intensity of the glare source reaches BCD. Thereafter the response increases monotonically with increasing luminance of the glare source (Berman *et al.* 1991:183). Therefore, it is shown that the EMG based technique can be reliably used to evaluate discomfort glare under laboratory conditions (UMIST 1998:5).

### 1.3.2.6 Muscle tension as an indicator of discomfort

Sometimes, in specific cases, it is possible to select a criterion which will satisfactorily denote the relative degree or the seriousness of a glare-condition. It has been established that a glare-condition which may be judged quite uncomfortable often produces no detectable reduction of visibility. Therefore, a glare-condition which appreciably reduces visibility is certainly an adverse condition to the eyes. If the effect of glare is appraised upon a basis of discomfort, the intrinsic brightness of the glare source becomes an influence in addition to the foregoing factor (Luckiesh & Moss 1933:455-460).

It is reasonable to assume that the estimation of the discomfort produced by glare represents an integrated reaction to several physiological and psychological factors. The tightening of the muscles of the hand, for example, is a common reaction to pain or discomfort. Therefore, it is conceivable that such a muscular reaction may be produced by glare. Whether or not this reaction is of sufficient magnitude to serve as a criterion for appraising glare is a matter to be determined experimentally. It is also uncertain how completely muscular tension in the hand indicates the presence of ocular discomfort. This investigation relating illumination intensity, preventable glare and nervous muscular tension formed one phase of an extensive investigation which showed conclusively that the tension decreases considerably with increasing intensity of illumination for such a visual task as reading (Luckiesh & Moss 1933:455-460).

The subjects were required to observe steadily a rotating test-object and to press a key at certain intervals as prescribed by the position of a detail on the test-object. The test involved extremely difficult visual work and the relatively easy mechanical task of operating the key. The task, as a whole, was of such an exacting nature that the subject's fingers rested instinctively upon the knob of the key continuously during the test-period of ten minutes. It was thus possible to record changes in pressure which the subjects unconsciously exerted upon the key. The changes in nervous muscular tension, as indicated in the fingers of the right hand which operated the key, were correlated with changes in the experimental variables of preventable glare and level of illumination.

This is additional evidence that the human seeing-machine is often able to operate under severe handicaps without influencing the accuracy of its performance, but, doubtless, at a cost to it which is unappreciated or at least unmeasured (Luckiesh & Moss 1933:455-460).

#### 1.3.2.7 Neural response to discomfort glare

The behavioural response of sensory systems as a function of stimulus intensity has always been a concern of sensory physiology and psychophysics. The mathematical formulations, often set down as laws, also raised some concern and have been a long-standing topic of debate. This has led to much research exploring the relations between stimulus magnitude, neural response and behavioural response. One important factor of the response of striate cells (cells from the visual cortex) has received little experimental attention, namely the response as a function of luminance contrast. This is quite surprising as the striate cells are exquisitely tuned to respond to specific spatial-temporal variations of luminance contrast (Albrecht & Hamilton 1982:218). It is known that the neurons early in the visual pathway have certain coding properties. Each cell has a selective sensitivity for certain characteristics of the images falling on its receptive field. For instance, the neurons in the visual cortex of monkeys and cats were selectively sensitive to bar-shaped patterns of light. This physiological evidence for the fragmentation of sensory processing has prompted much enquiry into elements of the human visual perception (Blakemore *et al.* 1973:1915).

## 1.4 Delimitations

The following delimitations are applicable to this study:

- Only the effects of discomfort glare are investigated.
- Only small incandescent lamps are used in the study.
- The age, gender and eye colour of the observers are not taken into consideration.
- The external factors that influence the effect of glare do not form part of this study.

## 1.5 Overview of the report

Chapter one states the problem as experienced under the term discomfort glare and give some background on previous evaluation systems and discusses the purpose of the study. Chapter two gives a description on discomfort glare. The different models that were developed and the implementation thereof are discussed in detail. Chapter three explains the construction and operating principles of the human eye. Chapter four discusses the visual pathway in the brain in order to determine the areas in the brain responsible for visual interpretation. Chapter five explains the history of the electroencephalogram (EEG) and the experimental set-up of this research project where the analyses and discussion of the results are given. Chapter six consists of the findings and deductions concerning the experimental phase of the project as well as conclusions and recommendations for further studies.

# CHAPTER 2 – DISCOMFORT GLARE

## 2.1 Introduction

The subject of glare has fascinated researchers in the field of vision since the early years of this century and even after eighty years of study the nature of glare is not fully understood (Poulton 1991:33). It is differentiated into disability glare and discomfort glare but for the purpose of this study only discomfort glare will be investigated.

A person experiences discomfort glare in interiors where high luminances occur in an otherwise low luminance field (Fischer 1991:1). Therefore, discomfort glare is experienced when luminaries and its relationships in the field of view cause visual discomfort but do not necessarily interfere with seeing. Direct glare from light sources or luminaires which are too bright, inadequately shielded, or of too great an area, is usually responsible for causing discomfort glare (IES 1968: 2-18).

## 2.2 Historical overview of glare fundamentals

- **Discomfort glare:18th and 19th centuries**

In the 18th and 19th centuries, Bourgier (Bourgier 1961) and Lambert (Phelps 1963:475-479) developed the fundamentals of photometry. Visibility studies were investigated and discussed in the scientific journals of the 1880's by Urbantschitsch (Cobb 1911:76) in 1883, and Sewall in 1884 (Poulton 1991:33). Two early researchers in the field of glare were Uhtoff during 1899 and Depene in 1900 (Cobb 1911:77). These two researchers were concerned with the effect of eccentric light sources on the visibility of the visual task (Perry 1991:63).

- **Discomfort glare:20th century**

During the first decade of this century, glare was very much in the mind of lighting engineers. An early attempt to quantify the effect of the presence of a glare source on the visibility of a visual task was made in 1904 by Brorschke (Cobb 1911:78). Parsons gave one of the first papers on the subject of glare to the newly formed Illuminating Engineering Society in Britain in 1907. Weber postulated that three of the four factors, accepted in present day glare formulation, namely source luminance, background luminance and the relative position of the light source, were the dominant factors influencing glare (Perry 1991:63, Poulton 1991:34).

- **Discomfort glare:1920's**

The first important work on glare was carried out in the 1920's by Holladay in America, investigating the nature of the relationship between glare and visibility (Holladay 1926:271-319). The reduction in task visibility in the presence of a glare source could be attributed to the scattering light by the optic media, the cornea, lens, aqueous and vitreous humours (Fischer 1991:1, Perry 1991:63-64).

Stiles (1929:146) responded to these conclusions stating that although there was scattering of light in the eye, the scattering was not enough to fully explain the reduction in task visibility, and concluded that the additional mechanisms at work were neurally based. The division of glare research into disability glare and discomfort glare interests, were probably initiated by the distinction made by Stiles (Perry 1991:63-64).

Unfortunately with Stiles representing an early British interest and Holladay the interest of the United States of America (USA), the research into glare was divided into national camps and has continued until today. This has possibly delayed the formulation of an internationally derived unified discomfort glare assessment system (Perry 1991:64).

- **Discomfort glare research: 1930 – 1960**

Following an intermission of about two decades, active research into discomfort glare was continued. Pioneers in the second line of research were Guth in the USA, Hopkinson in England and De Boer in the Netherlands. Unwittingly perhaps, these groups of workers perpetuated the division of national interests initiated by Holladay and Stiles. Once again two discomfort glare models were devised, the visual comfort probability system (VCP) and the glare index system (GI). It had many similarities but was implemented differently (Fischer 1991:2, Perry 1991:64).

## 2.3 Development of glare evaluation systems

The study of discomfort glare is characterized by a long history producing little understanding (Ostberg & Stone 1974:4). At that time no endeavours were made to arrive at a compromise formula to serve as a basis for one international glare evaluation system, and even more so in 1951 when the International Commission on Illumination (CIE) committee 'Estimation of Comfort in Lighting' was formed (Fischer 1991:3). This is partly due to the unwillingness by later experimenters to reconsider the fundamental concepts hidden beneath the agglomeration of past results and partly because of a failure to change unreasonable experimental techniques. There do, however, exist a number of equations which relate some of the characteristics of the lighting to subjective judgments of the degree of discomfort experienced (Boyce 1981:305). Continuous research on the discomfort glare prediction systems, concluded that there are four factors influencing the degree of discomfort glare namely:

- source luminance ($cd/m^2$)
- background luminance ($cd/m^2$)
- the solid angle subtended at the eye by the glare source
- the position of the glare source relative to the line of sight.

Different systems have different ways of quantifying and of combining these four factors but these are the four factors used in nearly all the systems based on a formula for calculating discomfort glare (Boyce & Beckstead 1991:93).

For a single glare source these equations all have the following form:

$$\text{Glare Sensation} = \frac{(\text{luminance of the glare source})^m \times (\text{angular subtense of the glare source of the eye})^n}{(\text{luminance of the background})^x \times (\text{deviation of the glare source from the line of sight})^y} \quad (1)$$

Each component of the formula has a different exponent and this also differs between the different equations. This formula shows that increasing the luminance of the glare source, increasing its angular size or decreasing its deviation from the line of sight would all increase the sensation of discomfort glare experienced, but increasing the luminance of the background would decrease it (Boyce 1981:305-306). However, in spite of this direction no real effort was made to develop a common system. Instead of this, three different methods of glare prediction were created (Fischer 1991:3). This equation forms the basis of two of the three most widely used methods of discomfort glare prediction, as discussed in the next section (Boyce 1981:305-306).

### 2.3.1 The Visual Comfort Probability system (American)

In America, Guth was carrying out independent studies investigating discomfort glare (Perry 1991:66). Measurements of the discomfort produced by single glare sources were performed by determining the luminance representing the 'Borderline between Comfort and Discomfort' (BCD) (Fischer 1991:3).

The method used by Guth was different from that of the British workers. Earlier work into glare, carried out by Luckiesh, presented the glare source intermittently to the observers. The presentation cycle consisted of a ten second sequence, three one second 'on' periods separated by one second 'off' periods, followed by a five second 'off' period. The sequence was then repeated. Guth used this presentation sequence in the experiment to develop a fundamental equation for calculating discomfort glare. A further difference between Guth's experimental set up and that used by Britain was that the glare source used was a small high luminance source presented against an otherwise uniform field (Perry 1991:66). A small high luminance source was introduced in a fixed position and the observer was asked to adjust either the luminance of the field or the source until the situation seemed to be at the BCD (Boyce 1981:307). This subjective threshold measure has been equated with the 'just uncomfortable' rating of the British Glare Index system (Perry 1991:67). An intermittent exposure was used in an attempt to simulate a worker looking up from a task to a glare source, therefore the high luminance source was presented intermittently on a schedule of 1sec exposure, 1 sec interval, 1 sec exposure, 1 sec interval, 1 sec exposure, followed by a 5 sec rest interval (Boyce 1981:307).

From these studies Guth established the following relationship between subjective glare sensation and the experimental parameters (Perry 1991:67).

$$\text{Glare sensation index} = \text{M} = \frac{0.5 L_s Q}{P F^{0.44}} \qquad (2)$$

Where:

M = Glare sensation index of a single source

$L_s$ = Luminance of the glare source (cd/m$^2$)

$Q$ = $20.4\omega_s + 1.52\omega_s^{0.2} - 0.075$

$\omega_s$ = solid angle subtended at the eye by the glare source (steradians)

$P$ = an index of the position of the glare source with respect to the line of sight

$F$ = average luminance of the entire field of view including the glare source (cd/m$^2$) (Boyce 1981:306, Perry 1991:67).

This equation applies to a single glare source. To obtain the glare level for a number of sources in an installation the glare sensation values are summed using the following equation to obtain a value for the 'Discomfort Glare Rating' (DGR). This is a rather complicated summation formula with an exponent 'a' being a function of the number of glare sources 'n' (Boyce 1981:306, Fischer 1991:3, Perry 1991:67):

$$\text{DGR} = (\Sigma_n \text{M})^a \qquad (3)$$

DGR = Discomfort glare rating

M = Glare sensation index of a single source a $= n^{-0.0914}$

n = number of glare sources

Once the value of the DGR for a particular lighting installation has been calculated, it is converted to a quantity called visual comfort probability (VCP). This figure simply represents the percentage of people who would accept the lighting system as comfortable under the defined conditions represented by the DGR (Boyce 1981:306, Fischer 1991:3, Perry 1991:67). The higher the value for VCP, the greater the percentage of people finding the glare in the installation acceptable (Perry 1991:67).

### 2.3.2 The Glare Index system (British)

Hopkinson's early work into discomfort glare started initially in about 1939. Major work in the field did not start, however, until late into the decade of the 1940's. Working together with Petherbridge of the United Kingdom, extensive research projects were carried out investigating discomfort glare. The studies carried out by Hopkinson and Petherbridge during this period made use of a model made from a black and white photograph of a classroom. At the points in the photograph where diffusing globe light fittings appeared, holes were cut. Lights were placed behind these holes to simulate the presence of the light fittings in the room, the luminance of the light fittings could be adjusted. The photograph was also illuminated from the front by spotlights. These spotlights were hidden from the direct view of the observers. For a number of values of luminance of the simulated light fittings the observers were asked to adjust the values of the background luminance, provided by the spotlights, so that the light fitting luminances appeared at one of four criteria levels against the adjusted background. The following criteria of subjective sensation in the single source experiments were used:

- just intolerable
- just uncomfortable
- just acceptable
- just perceptible

The observers were very carefully selected. The observer's settings of background luminance under 'standard' conditions were obtained frequently and any inconsistency resulted in elimination from the experiment. The following glare sensation formula for a single glare source was developed by Petherbridge and Hopkinson (Boyce 1981: 308, Fischer 1991:64, Perry 1991:4):

$$\text{Glare Sensation} = G = \frac{0.48 Ls^{1.6} \omega s^{0.8}}{L_b P^{1.6}} \qquad (4)$$

Where:

$L_s$ = Luminance of the glare source (cd/m$^2$)

$\omega_s$ = Solid angle subtended by the glare source at the eye, in steradians

$L_b$ = average luminance of the field of view excluding the glare source (cd/m$^2$)

$P$ = An index of the position of the glare source with respect to the line of sight

The summation formula used in the Glare Index (GI) system is very straightforward. The combined effects of multiple sources are given by simple addition of the individual glare sensation values (Fischer 1991:4):

$$\text{Total glare} = G_{Total} = \Sigma \frac{L_s^{1.6} \times \omega^{0.8}}{L_b \times P^{1.6}} \qquad (5)$$

Taking ten times the logarithm of this sum produces numbers of convenient size, $G_{Total}$ is converted into the Glare Index (IES 1967:10) by using the following formula (Fischer 1991:4):

$$GI_{Hopkinson} = 10 \log_{10} G_{Total} \qquad (6)$$

This glare prediction method formed the foundation for the British Glare Index system. However, the glare equations required that the designer carry out a complicated set of calculations to arrive at the predicted glare index for an installation. At the time that the method was developed there was no easy access to computers. This situation provided the need to develop a tabular method, based on the glare equations above, which allowed the designer to arrive at a glare value for an installation without needing to carry out a string of calculations to arrive at a Glare Index value (Perry 1991:65).

### 2.3.3 The Luminance Curve system (European)

The work to establish the glare equations of Hopkinson and Petherbridge, and that of Guth was carried out primarily in the 1950's, with the development work spilling over into the 1960's (Perry 1991:68). De Boer doubted whether the summation methods used in the American and the British systems were in accordance with the more complicated process that determines the effect of multiple glare sources on the observer. Studies where observers were confronted with different numbers of glare sources were conducted, and it was discovered that none of the calculation methods were in acceptable agreement with the observations. As a result, de Boer was convinced that in order to overcome the unsolved problem of having to add glare effects of single sources by means of summation formulas, a reliable glare evaluation system should be based on subjective appraisals of lighting installations as a whole. Such investigations were carried out by Söllner (Bodmann *et al* 1966:351) with the objective of establishing an empirical glare evaluation system (Fischer 1991:6, Perry 1991:68).

Söllner (Bodmann & Söllner 1965:195) assumed that the only feature of the luminous environment the lighting engineer is likely to be able to control is the choice of the luminaire type. With this in mind a series of studies were carried out to establish a link between the luminance of the luminaire and the subjective rating of glare (Boyce 1981:309, Perry 1991:68). The basic experiments were conducted using a number of one-third scale models of offices in which real-life situations could be realistically simulated, refer to figure 1.

**Figure 1** **One-third scale model of a test room used by Söllner (De Boer & Fischer 1981:29)**

The lighting of the model was varied by using different fluorescent luminaries, with different luminous flux output of the luminiare, varying room dimensions, mounting direction of the luminaire (endwise or crosswise) and task illuminance. In all, 750 different situations were assessed by the observers, the glare sensations being rated on a seven point scale (Boyce 1981:309, Fischer 1991:7, Perry 1991:68) namely:

0 = No glare
1 = Glare between non-existent and noticeable
2 = Glare noticeable
3 = Glare between noticeable and disagreeable
4 = Glare disagreeable
5 = Glare between disagreeable and intolerable
6 = Glare intolerable (Fischer 1991:7)

The conclusions of the studies were that there were four parameters of importance on the assessment of glare namely:

- The luminance of the luminaire
- The room length and mounting height
- The type of luminaire, in particular glare rating was influenced by whether the luminaire had luminous side panels

- The adaptation of the eye (Perry 1991:68).

A series of curves were plotted, using the results of the studies, for regular arrays of luminaires showing the luminaire luminance as a function of emission angle, i.e. the angle between the normal to the central luminaire and the line from the luminaire to the observer, for a specified Glare Rating. These curves were called the 'Limiting Luminance Curves' (Boyce 1981:309, Perry 1991:68). By using this system it is possible to determine the degree of glare which will be experienced with any lighting installation, provided the dimensions of the room, the average illuminance and the luminances of the luminaires are known (Fischer 1972:97).

The basic diagrams of the system are shown in figure 2 and figure 3 in the form of Cartesian coordinates using a logarithmic scale for the luminance.

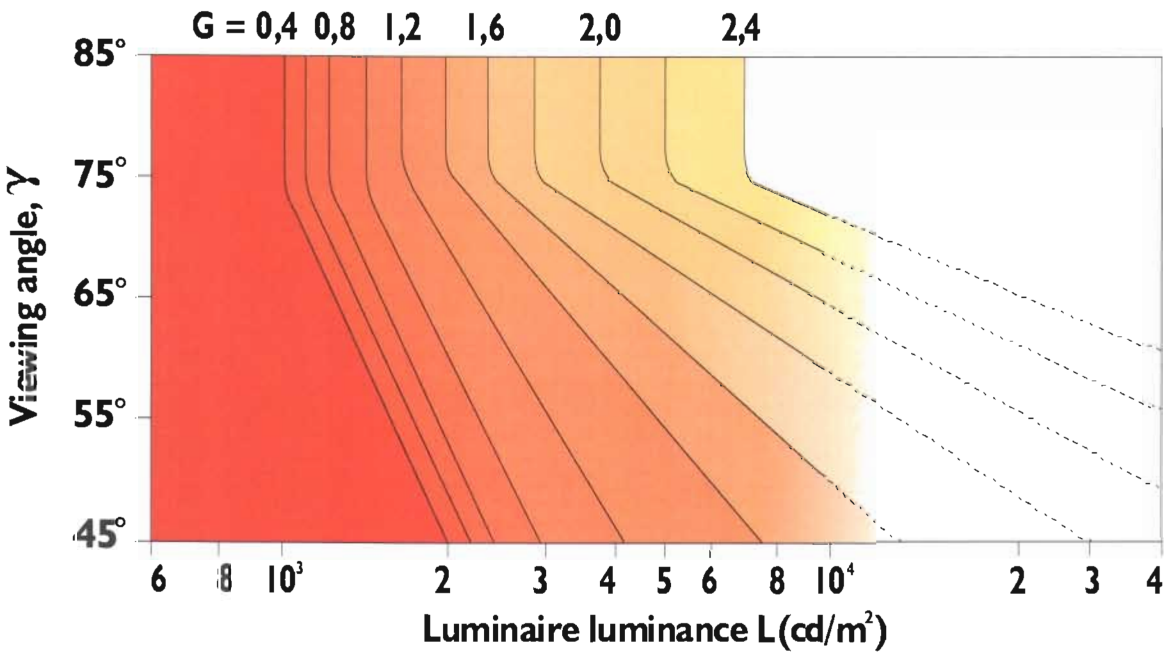



**Figure 2 Luminance limits of luminaires as a function of the angle, γ, from nadir, for different values of glare rating, G, and an illuminance of 1000 lux for luminaries without luminous sides (Fischer 1972:97)**

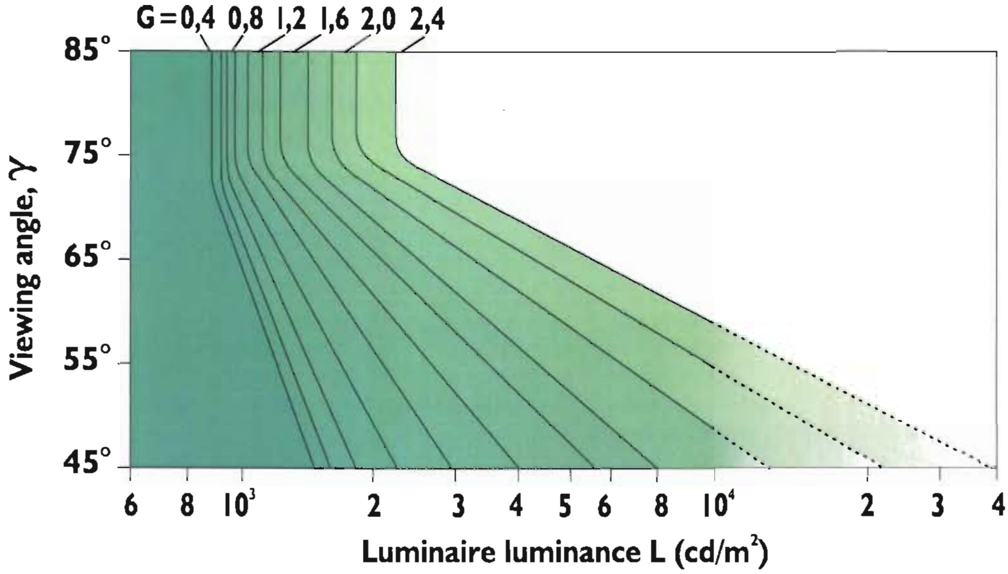



**Figure 3 Luminance limits of luminaires as a function of the angle, γ, from nadir, for different values of glare rating, G, and an illuminance of 1000 lux for luminaries with luminous sides (Fischer 1972:97)**

The luminance limits for luminaries are presented, based on the recommendations of 50 percent of satisfied observers, in relation to the viewing angle γ, from 45 degrees up to 85 degrees, for different values of the glare rating (G), from the seven point scale, an illuminance of 1 000 lux and a room width of b > 4h. The luminance limits only need to be considered for luminaries that are seen in a normal viewing direction at angles above 45 degrees, refer to figure 4. The value of γ up to which the luminance limits have to be observed is given by the following formula (Fischer 1972:97):

$$\tan \gamma_{max} = \frac{a_{max}}{h_s} \qquad (7)$$

where:

$a_{max}$ = the maximum horizontal distance between observer and luminaire

$h_s$ = the height of the luminaire above eye level

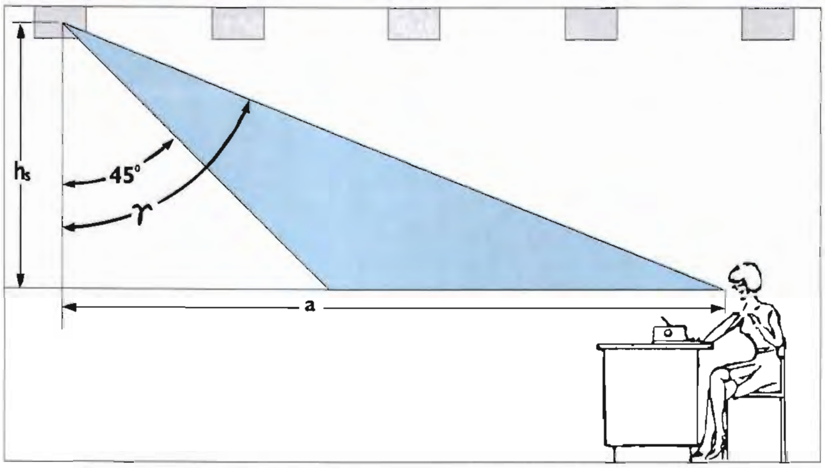



**Figure 4 Radiant zone of a luminaire in which the luminance has to be observed (Fischer 1972:97)**

The curves of figure 2 should be used for all luminaires that do not have luminous sides and for linear luminaires with luminous sides if it is viewed parallel to its long axis (e.g. bare-tube units viewed endwise). The curves of figure 3 are used for linear luminaires with luminous sides if it is viewed at right angles to the longitudinal axes of the units (e.g. bare-tubes units viewed crosswise) (Fischer 1972:97).

Fischer (1972:97) subsequently simplified the original curves to form the (German) European Glare Limiting system (Boyce 1981:309, Perry 1991:68). This new method specified limiting luminance distributions expressed as curves indicating luminance limits for different quality classes as a function of angle $\gamma$ in the 45 degree to 85 degree range (Fischer 1991:10). The Söllner glare evaluation system appeared to be too complicated for use in practical lighting calculations, therefore it was decided to adopt the following simplified versions, which transform the 'glare evaluation system' into a 'glare limiting method':

- the system was confined to a stepped scale of glare ratings, G, which are called 'quality classes';
- the luminance limiting curves corresponding to the selected glare ratings were prepared for a stepped scale of illuminances between 200 lux and 3 000 lux (Fischer 1972:98-99).

For various activities and/or interiors the importance and extent of glare limitation is different, therefore, five different quality classes have been introduced. Refer to table 1 (Fischer 1991:12).

**Table 1 Quality classes of required glare limitation (Fischer 1991:12)**

| Quality Class | Glare Rating | Type of task or activity |
|---|---|---|
| A | 1.15 | Very precise visual tasks |
| B | 1.50 | High visual demands |
| C | 1.85 | Moderate visual demands |
| D | 2.20 | Low visual demands |
| E | 2.55 | Interiors, workers not confined to workstations, low visual demands. |

Recalculation of the curves shown in figure 2 and figure 3 were done using the above mentioned stepped scale of glare ratings, G, and illuminances E. The results are shown in figure 5 and figure 6. The numerical values for the luminance on which the curves are based, can be taken from table 2 in annexure A. As the values for the glare rating G, are hardly understandable by normal users, quality classes A to E have been introduced (Fischer 1972:99).

To use the Glare Limiting system the lighting engineer must select a particular luminaire type for use in the designed installation. From the luminaire's photometric data the designer will be able to asses whether the glare produced by the installation will fall below the glare threshold defined by the limiting curve. If the glare values fall above the limiting value; and this is unacceptable, then the only option open to the designer will be to change the luminaire type (Perry 1991:68).

| Quality Class | Valid for service illuminance (lux) | | | | | | | | G |
|---|---|---|---|---|---|---|---|---|---|
| A | 2000 | 1000 | 500 | ≦250 | | | | | 1.15 |
| B | | 2000 | 1000 | 500 | ≦250 | | | | 1.5 |
| C | | | 2000 | 1000 | 500 | ≦250 | | | 1.85 |
| D | | | | 2000 | 1000 | 500 | ≦250 | | 2.2 |
| E | | | | | 2000 | 1000 | 500 | ≦250 | 2.55 |

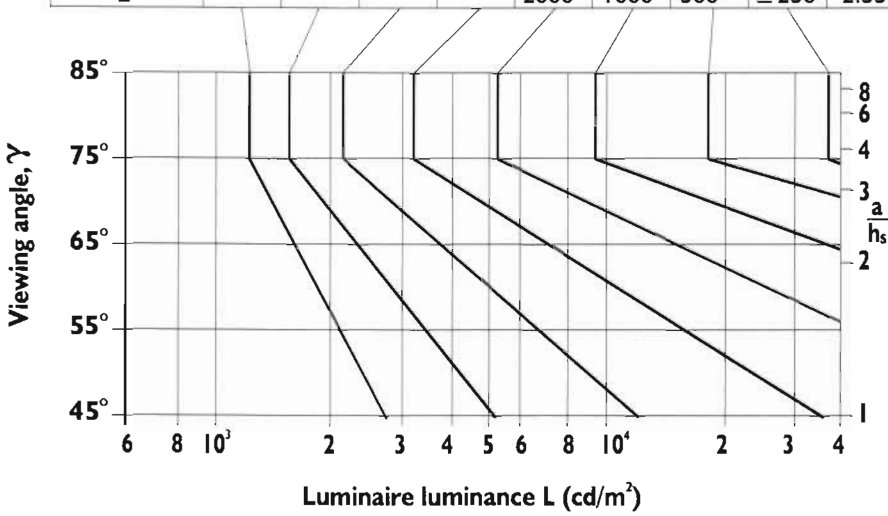



**Figure 5** Diagram *I* for directions of view parallel to the longitudinal axis of linear luminaires and for all luminaires without luminous side panels (Fischer 1972:97)

| Quality Class | Valid for service illuminance (lux) | | | | | | | | G |
|---|---|---|---|---|---|---|---|---|---|
| A | 2000 | 1000 | 500 | ≦250 | | | | | 1.15 |
| B | | 2000 | 1000 | 500 | ≦250 | | | | 1.5 |
| C | | | 2000 | 1000 | 500 | ≦250 | | | 1.85 |
| D | | | | 2000 | 1000 | 500 | ≦250 | | 2.2 |
| E | | | | | 2000 | 1000 | 500 | ≦250 | 2.55 |

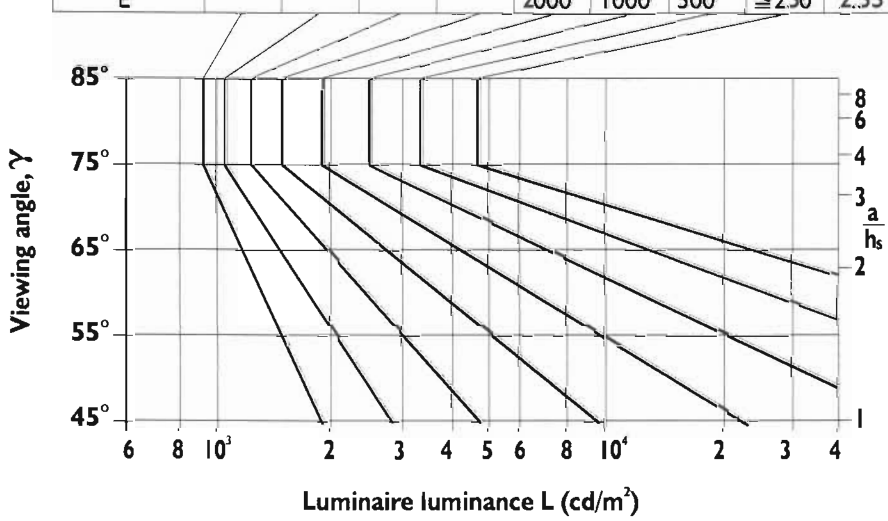



**Figure 6** Diagram *II* for directions of view at right angles to the longitudinal axis of luminaires with luminous side panels (Fischer 1972:97)

## 2.4 The International Commission on Illumination work on discomfort glare after 1971

In 1971 the International Commission on Illumination (CIE) on discomfort glare started another effort to study the existing systems and try to combine the best points of each into a single universally acceptable system (Fischer 1991:15). In 1979, Einhorn proposed an international 'CIE Glare Index' (CGI) formula for discomfort glare that would bridge differences in results from past research (Paul 1997:57). It was agreed by the CIE committee to be the best currently available mathematical compromise between the different national systems, it consisted of the following formula:

$$CGI = 8 \log 2 \left[ \frac{1 + E_d/500}{E_d + E_i} \Sigma \frac{L_s^2 \times \omega}{P^2} \right] \qquad (8)$$

Where:

$E_d$ = direct vertical illuminance on a vertical plane at the observer's eye due to all sources (lux)

$E_i$ = indirect illuminance at the observer's eye (lux)

Unfortunately, the Einhorn formula proved to be rather impractical in terms of setting up a glare index method. The nominator $(1 + E_d/500)$ ensures that there is a slight co-variance between discomfort glare and the general level of illumination, as has been found in the Söllner experiments. This meant that the Einhorn glare index was dependant on the reflectance of room surfaces and on room dimensions, as well as the illumination levels (Fischer 1991:15).

The British GI, based on the Hopkinson formula (Petherbridge & Hopkinson 1950:39), also had a weakness that lied in its mathematical inconsistency. Due to the exponent 0.8 of $\omega$, large glare sources could not be subdivided for the purpose of summing up glare contributions without influencing the results. The Luminance Curve system was also no longer regarded 'up-to-date' as the Söllner experiments were carried out with luminaires that were in use in the 1960's, and it was shown that errors can occur when applying the curves to modern luminaires. In 1987 the CIE committee decided that a compromise formula should be developed and introduced, in order to avoid the shortcomings of previous formulas (Fischer 1991:17). Such new formula was proposed by Sørensen (1987:236) and was called the Unified Glare Rating (UGR).

## 2.5 The Unified Glare Rating formula

The UGR formula is a combination of the features of the Einhorn and Hopkinson formulae and also incorporates the Guth position index. It is regarded as combining the best parts of the major formulae in terms of practicability and of familiarity with the results of glare prediction (CIE 1995:6).

### 2.5.1 The formula

The CIE's UGR is given by the following formula (also see figure 7) (CIE 1995:2):

$$UGR = 8 \log_{10} \left[ \frac{0.25}{L_b} \Sigma \frac{L^2 \omega}{P^2} \right] \qquad (9)$$

Where:

$L_b$ = the background luminance (cd/m$^2$)

$L$ = luminance of the luminous parts of each luminaire in the direction of the observer's eye (cd/m$^2$)

$P$ = the Guth position index for each luminaire (displacement from the line of sight)

$\omega$ = the solid angle of the luminous parts of each luminaire at the observer's eye (sr)

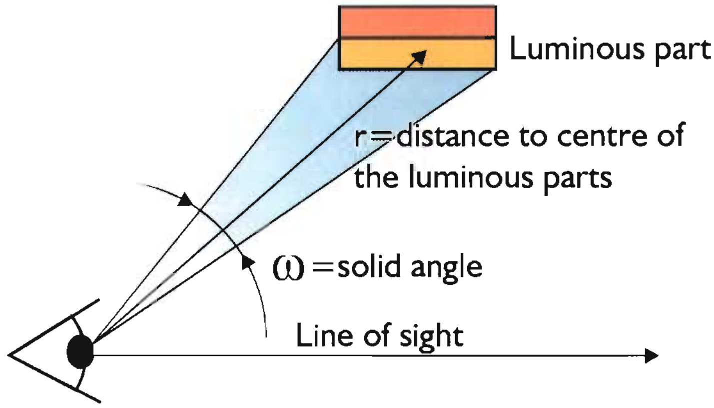



**Figure 7 The luminaire luminance L, and solid angle ω, seen by the observer (CIE 1995:3)**

### 2.5.2 The background luminance

The background luminance, $L_b$, is defined as the uniform luminance of the whole surroundings which will produce the same illuminance on a vertical plane at the observer's eye as the visual field under consideration excluding the glare sources. It may be obtained from the following formula (CIE 1995:3):

$$L_b = \frac{E_i}{\pi} \tag{10}$$

Where $E_i$ is the indirect illuminance at the eye of the observer (lux).

### 2.5.3 The luminaire luminance

The luminaire luminance, L, is generally derived from the luminous intensity of a luminaire in the direction of an observer, I, and the projected area of the luminaire, $A_p$.

$$L = \frac{I}{A_p} \tag{11}$$

(CIE 1995:3)

### 2.5.4 The solid angle at the observer's eye

The solid angular size may be derived from the projected area of all luminous parts of a luminaire, and the distance to the centre of a luminaire from the observer's eye. The solid angle is to be determined by the following expression (CIE 1995:3):

$$\omega = \frac{A_p}{r^2} \qquad (12)$$

Where:

$A_p$ = the projected area of the luminous parts of the luminaire ($m^2$)

r = the distance from the observer to the centre of the luminous parts of the luminaire (m).

### 2.5.5 The position index

The position index *P* is found by interpolating the data of table 3, in annexure B, and the parameters of the table are defined in figure 8.

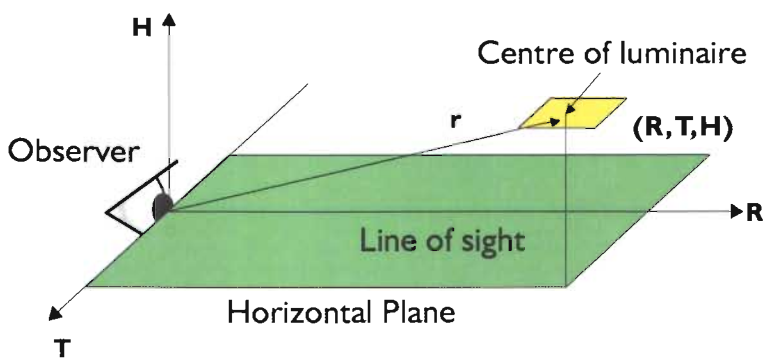



**Figure 8 The position index coordinate system (R, T, H) based on the observer (Fischer 1972:97)**

The parameters are defined as T/R and H/R where (R, T and H) form a coordinate system based on the observer. Assuming that the line of sight is horizontal, R is the distance as projected onto the line of sight, T is the horizontal offset from the line of sight (LoS), and H is the height above the eye of the observer. All coordinates are to the centre of the luminaire (CIE 1995:4-5).

### 2.5.6 Features of the UGR formula

The UGR formula produces a glare rating which can be used as a psychological parameter intended to measure any adverse subjective discomfort response to a visual environment containing light sources. The UGR scale has been designed in order to cover the range of the British scale. The practical range is from 10 to 30 with the majority lighting systems producing values in this range. A high value indicates significant discomfort glare, while a low value indicates a small change of discomfort glare. Lighting systems with a UGR below 10 are assumed not to produce discomfort and it is sufficient to characterize it by UGR<10 (CIE 1995:6).

### 2.5.7 Limitations of the UGR formula

The domain of the data used to develop the UGR system was limited and restricted to sources which have a maximum subtense at the eye of 0.1 steradian (a 1 $m^2$ luminaire, seen from about 3 m). Further discomfort glare for very small sources is determined by intensity rather than by luminance, therefore, the UGR system should not be used for sources smaller than 0.0003 steradian (CIE 1995:6).

Applying the UGR formula for glare index predictions for small sources, give results that would suggest far more glare than is actually experienced, verifying the fact that the UGR formula does not give realistic glare index predictions for small sources. As a result, it could predict very intolerable glare from an incandescent lamp installation which might actually be widely accepted. The following example will assist in explaining the statement. Consider a 200 W incandescent lamp with an intensity of 230 cd. The luminance of such a source is in the order of $5 \times 10^6$ cd/$m^2$, since A = I/L (pictured as a filament about 0.5 mm by 9 mm in projected dimensions). At a distance of 4 m, with an indirect illuminance of about 150 lux, such a source, when viewed at say

16 degrees above the LoS, would be generally accepted as 'comfortable' from a glare perspective (Paul 1997:1).

However, if the associated values (i.e. $L = 5 \times 10^6$, $p^2 = 3.42$, $\omega = 2.875 \times 10^{-6}$, $E_i = 150$) are substituted into the UGR formula, a UGR of above 40 are calculated. Anything above 30 is usually considered intolerable for a UGR value. From this it is clear that the formula needs modification for small sources (Paul 1997:1).

### 2.5.8 Derived methods of the UGR formula

The UGR formula can be used to generate standard sets of tables and curves, namely the derived tabular method and the derived UGR curve method. The simplified predicting of discomfort glare using tabulated data or luminance curves should give results that in most cases are in reasonable agreement with predictions using the formula, however, for conclusive and decisive evaluation of glare, the basic formula should be used wherever possible (CIE 1995:6, Pai & Gulati 1995:186).

## 2.6 Comparison of different glare evaluation systems

The three systems, the American VCP system, the British GI system and the Luminance Curve System, are the major systems that are used in various parts of the world today. Manabe (1976:9) has shown that there is reasonable agreement between the glare sensations predicted by these methods (Fischer 1991:13). Refer to table 4.

**Table 4 Equivalent values of three glare evaluation systems (Fischer 1991:14)**

| | | | | | | |
|---|---|---|---|---|---|---|
| **Visual Comfort Probability System** | VCP (%) | 75 | 65 | 55 | 45 | - |
| **Glare Index System** | GI | 19 | 20.5 | 22 | 23.5 | 25 |
| **Luminance Curve System** | Quality Class | A | B | C | D | E |

The study by Manabe (1976:9) was one of the most comprehensive of the relative few studies carried out to test the correlation between the three glare systems (Perry 1991:69). Manabe calculated the VCP, GI and mean Glare Rating values for a range of installations and found the following correlation coefficients:

**Table 5 Correlation coefficients of different models for a range of installations (Boyce 1981:312)**

| | |
|---|---|
| VCP versus GI | -0.86 |
| VCP versus mean Glare Rating | -0.67 |
| GI versus mean Glare Rating | 0.66 |

When the VCP method was compared to other experiments it showed little difference in the setting of the boundary between comfort and discomfort for the intermittent presentation in relation to continuous exposure (Guth 1951:65). In later experiments simulated model and actual rooms were used. In this case either the luminance of the luminaires was adjusted to the borderline between comfort and discomfort or the luminance of a comparison source was adjusted to give the same overall glare effect as the complete installation. During these experiments it was not possible for the observers to give verbal comments other than through the medium of an adjusted luminance, and therefore, for this reason and the lack of context it is seen as the main failings of these experimental methods (Boyce 1981:307).

The Glare Index (GI) system is a comprehensive glare evaluation system which allows numerical predictions of expected glare to be carried out in situations where room dimensions, room reflectance and luminaire positions are known in advance. It is possible to make numerical comparisons of expected glare effects of different luminaires under specific conditions, and it is also possible to conduct studies into the influence of different parameters. The Luminance Curve System, on the contrary, is a simple 'glare safeguard system' or 'luminaire selection system'. People without the necessary special knowledge find it easy to work with the more sophisticated glare evaluation systems. Inspectors can also use the system to serve as a guiding rule for making field checks of lighting installations using simple measuring devices (Fischer 1991:14).

Due to the variety of people used, judging an interior with an established context, the quality of the experiments conducted by Söllner have placed the European Glare Limiting method in the strongest position of the three methods considered. The only drawback is that the rating scale used by the observers to give assessments on discomfort glare is a strange mixture of the magnitude and the acceptability of the glare experienced. In spite of the fact that the European Glare Limiting method had a better experimental base, it still has disadvantages in application. The main disadvantage is that mean Glare Rating can only be changed by varying the luminaire luminance distribution. In contrast, the VCP and Glare Index system both allow for this and for the effect of changing room reflectances and for having an irregular layout of luminaires. Because of this, the VCP and the Glare Index methods reflect the influence of the complete luminous environment on discomfort glare but the European Glare Limiting method only allows for differences in luminaires (Boyce 1981:312).

The Glare Limiting method is considerably different from the systems developed by the British and by the Americans. No equation is used in the system to define the relationship between glare sensation and the parameters influencing the glare sensation. This makes the Glare Limiting system more restricted in use than the VCP and GI systems; however, Söllner's objective of providing a system that was simple to use was satisfied (Perry 1991:69).

However, the obvious conclusion is that all methods point in the same direction and the lighting designer will be able to calculate the extent to which the installation will produce discomfort glare. There is no scientific reason to suggest that any one of these systems are completely wrong but equally there is plenty of reason to suppose that none are completely right (Boyce 1981:312-313).

According to Pai and Gulati (1995:187), the CIE Unified Glare Rating system is the most practical method as it overcomes the weaknesses of the existing systems. Both the lighting designer and the user have a practical interest in the calculations of both average and maximum values of discomfort glare. Unfortunately, the UGR system, like all other existing methods, leads to unrealistic limitation for very small sources such as incandescent lamps in transparent luminaires. There is no precise transition point for small sources to large sources and this subject still needs further research. For the interim, the UGR system should serve the purpose until there is better understanding of the nature of discomfort glare (Pai & Gulati 1995:187).

If it is true that the four factors namely, luminance of the glare source, luminance of the background, the solid angle subtended at the eye by the glare source and the position of the glare source relative to the line of sight, are the only factors influencing discomfort glare ratings, in principle, it should be possible to make perfect predictions of any individual's assessment of discomfort glare for a given situation. But as experienced from collected ratings of discomfort glare, there are wide individual differences that occur (Boyce *et al* 1979:260, Manabe 1976:9, Stone & Harker 1973:41). According to Poulton (1991:41) the four known 'fundamentals of discomfort glare' are far too simplistic and that the field of study richly deserves further research. Such wide individual and group differences and large unexplained variances suggest that there are other factors that need to be considered if the precision of discomfort glare measurement is to be improved (Boyce & Beckstead 1991:94).

## 2.7 Glare evaluator systems

The development of a simple and practical method for evaluating the visual discomfort produced by luminaires and other sources of brightness, is an important aspect in obtaining quality of lighting. However, it has long been recognized that generalized conclusions derived from laboratory experiments must be substantiated by, or modified in accordance with, the results if investigations conducted with practical situations. Therefore, it is necessary to devise instruments and techniques which can be used to study typical systems in such a way that the findings can be related to the fundamental data. Extensive investigations have provided considerable information about the relationship among factors that influence discomfort in lighting. Adapting these techniques and using it in basic studies, led to the design and construction of various Discomfort Glare Evaluators (Guth & McNelis 1959:398).

### 2.7.1 The McNelis evaluator

McNelis saw the need for an inexpensive, portable device, which could be used to calibrate an observer's sensitivity to discomfort glare in a standard environment. It was very difficult to use inter system comparisons because of differences in the observer's sensitivity, the viewing conditions, and a variety of available methods in quantifying the glare sensation. The glare evaluator could be used to calibrate observers, to determine the observer's sensitivity to glare, or for making comparisons between different installations. The primary use of the evaluator was to make comparative evaluations of lighting systems. For this purpose the method of operation was to alternatively expose the test source and the lighting installation to the observer in rapid succession. The exposures were of one second duration, separated by one second intervals. Each group of three exposures was followed by a five second period for evaluating the sensation and adjusting the test source until it produced the same sensation as the luminaires (Poulton 1991:42-43).

### 2.7.2 The Lowson evaluator

Lowson wanted to build an improved version of the Guth-McNelis glare evaluator which would be truly portable and capable of being used in a field situation and not just in a laboratory. Lowson thought that the Guth-McNelis evaluator was impracticably large at a length of ten feet (3 050 mm), but that 1 500 mm could be managed. It also required a large wattage light source to produce the high value of luminance. Lowson's evaluator took several years to complete and was very fragile and difficult to operate while making the observations. The fact that the observed array of luminaires were in the observer's parafoveal field of vision, and the compared source in the observer's foveal field of view, made it almost impossible not to glance down at the comparison source. This made the evaluation process very difficult, especially in situations which were borderline cases between comfort and discomfort (Poulton 1991:43).

### 2.7.3 The Einhorn and Case evaluator

At the Intersessional meeting of the TC-3.4 Committee, held at London, March 29-30, 1974; Einhorn suggested that some form of standardised 'glare box', based on the principles proposed by Guth and McNelis, should be developed in order to calibrate observers working in different countries. The evaluator was truly portable and used luminance values that were similar to present day practice. The glare evaluator; as shown in figure 9, allows the assessment of glare in an existing lighting installation by a paired comparison method. Comparison is with a source of variable luminance, controlled by dimming. The glare sources and the controlled comparison source are observed in turn: with the flap lifted all the glare sources of the installation is seen; with the flap down the comparison source is seen through the mirror. The observer then adjusts the luminance of the comparison source with a dimmer until its glare is considered the same as the glare from the installation (Einhorn & Case 1981:105, Poulton 1991:44).

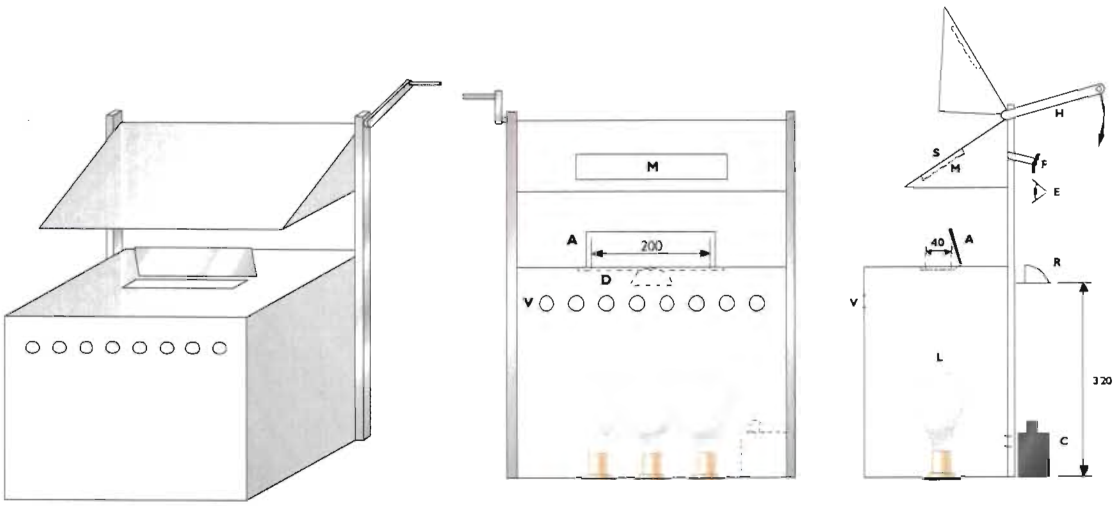



**Figure 9 Einhorn and Case glare evaluator as seen from different angles (Einhorn & Case 1981:106)**

The evaluator was a box type unit constructed of hardboard attached to an aluminium frame. All aluminium surfaces, including the shield, were left untreated. The diffuser was a sheet of Perspex 030. The box was painted with matt white on the inside and with matt pale grey on the outside. The luminance of the acrylic panel, or diffuser, was controlled by a thyristor dimmer. The major feature of the evaluator was not to restrict the view of the observer, in order for the observer's eyes to remain at the same state of adaptation when viewing either the luminaires or the evaluator. Therefore, no adaptation correction was required. This also meant that the effects of adaptation could not be tested and that co-variance could not be assessed. For this purpose the researcher had to rely on verbal statements from the observer (Einhorn & Case 1981:105, Poulton 1991:44).

Experiments done with trained observers were very satisfactory and showed good repeatability for the individual observer. However, when the evaluator was tested at a conference with untrained observers, the results were very disappointing since too wide a variation of results were obtained. Possible reasons given were the fact that the observations were hurried and that the test object was difficult. More important is the fact that some observers may not have understood the criteria of observing discomfort glare, and this emphasizes the need to carefully instruct inexperienced observers (Einhorn & Case 1981:105, Poulton 1991:44).

The results of an observation can be interpreted in terms of the data from the comparison source; its luminance after balancing is easily measured. The distance from the observer's eye, fixed by the forehead stop, via the mirror to the comparison source can be used to assess its size in steradian. The position of the comparison source is also adequately defined. The background luminance, that determines the indirect illuminance at the eye, can be estimated fairly well, but the vertical illuminance at the eye can be measured precisely. With this data it is possible to compute a glare index value (Einhorn & Case 1981:106).

Higher precision and consistency is expected from paired comparison tests with the glare evaluator than from verbal statements, but because the methods are complementary both should be used whenever field tests are arranged (Einhorn & Case 1981:106).

## 2.8 Luminaire brightness and glare

Luminaire brightness in certain angular zones below the horizontal has an important bearing upon glare. In rooms with average ceiling height the zone from 45 degrees to 90 degrees is considered the direct glare zone. If it is rooms with high ceilings this zone is considered to be 30 degrees to 90 degrees as illustrated in figure 10.

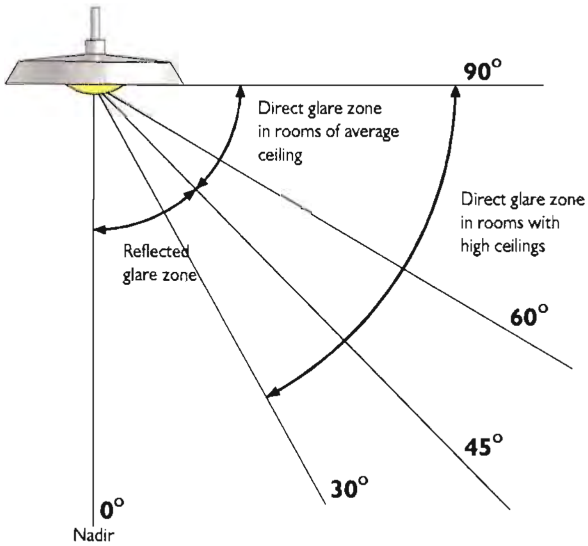



**Figure 10 Zones of brightness on a luminaire, which affect eye comfort and visibility (Sharp 1951:89)**

In average luminaires that make use of an incandescent or mercury lamp the brightness in these zones should not exceed 800 ft-L if it is to be just comfortable and 300 ft-L if it is to be very comfortable. Direct glare is dependant upon the area of the bright sources as well as the brightness in footlamberts. A large area that is emitting light must have a lower brightness than a small area. Because fluorescent luminaires are larger than incandescent luminaires a lower brightness is needed and therefore for 'just comfortable' it is better to adopt 600 ft-L as the upper limit and for 'very comfortable' 250 ft-L or less is recommended. The brightness in the zone from 0 degrees to 30 degrees or 0 degrees to 45 degrees determines to a large extent the degree of reflected glare, which is a difficult factor to assess. Reflected glare may cause some uncomfort and it always reduces the visibility of the seeing task. If the luminaire brightness is less that 400 ft-L in the zone from 0 degrees to 30 degrees or 45 degrees reflected glare will be minimized, a brightness of typically 225 ft-L or less is desirable. These brightness limits apply to installations where visual comfort and efficiency are important and are based upon illumination levels of the order of 30 to 50 ft-c (Sharp 1951:88-89).

## 2.9 Results

It has become apparent that a main factor influencing the quality of lighting is the control of discomfort glare; consequently, good lighting design should involve a method for the evaluation of discomfort glare (Bodmann *et al* 1966:347). There are a number of different national systems for evaluating and controlling discomfort glare. There is however, a weak correlation between the predicted discomfort glare from these methods and the assessment made by the observers because of the differences in assumptions at the start of devising these methods (Pai & Gulati 1995:186). If all of these many complicated factors involved are considered, it is not surprising that no agreed method is available for computing discomfort glare, for this is largely a matter of personal taste, and cannot be studied under limiting conditions (Stevens 1951:186).

To understand the reasons for these wide individual differences in reported glare sensation is still the real problem with discomfort glare. In order to do this it is necessary to face squarely the objections to the approaches adopted so far in the study of discomfort glare (Boyce 1981:313). Further research is necessary to determine the basic mechanisms that lead to the perception of discomfort glare, and to improve the correlation between calculated glare values and subjective assessment of glare sources (Perry 1991:61). The position with respect to discomfort glare is that in general, the existence of a precise mathematical formula should not be taken to prove that what it quantifies is equally precise (Boyce 1981:314).

## 2.10 Summary

Visual comfort is essential for good quality lighting; this means the absence of physiological pain, irritation and distraction. It is therefore important to keep the effects of discomfort glare to a minimum. During years of research different glare evaluators were developed, as well as a number of equations with which to calculate glare ratings.

Unfortunately the subjective assessments of the observers using the glare evaluators differed from the glare ratings as calculated with the mathematical equations. Due to the continuous discrepancies in the evaluations of the observers it seems necessary to investigate the possibility that the degree of discomfort glare that is experienced by an observer is a matter of personal taste. Each person's ability to accommodate the effects of discomfort glare will depend on the sensitivity of the visual system, and will vary accordingly. Therefore, it is essential to get a good understanding of the working principles of the human eye.

# CHAPTER 3 –THE VISUAL SYSTEM

## 3.1 Introduction

Light sources, luminaires, and the mathematics and procedures of design are all tools of an engineer, and in a sense only raw material. These aspects are subject to measurements. But what is seen and how it is seen involve many complex psychological factors. Light is the energizing force that makes vision possible, therefore by definition; light is 'visually evaluated radiant energy' (Sharp 1951:189).

An engineer must apply light with due regard to the workings of the visual sense, and the eye is but one part of the phenomenon of vision. A researcher has to work with observers and construct theories by questioning and deduction, therefore the lack of precision in lighting application is not always due to faulty technique but to the very nature of the end product, which is vision (Sharp 1951:189).

## 3.2 The visible spectrum

What is known as 'light' or 'visible radiation' is electromagnetic energy radiated at very short wavelengths and therefore at very high frequencies. The human eye is not equally sensitive to these different wavelengths and its corresponding frequencies of light (Hewitt & Vause 1966:1). According to Rowell (2002:9) the human eye will respond to only a small portion of the electromagnetic spectrum which extends from visible cosmic rays of the shortest known wavelengths to invisible radiation of longer wavelengths. Figure 11 shows the visible spectrum in a relative and expanded scale for clarity, showing changes in wavelengths between the limits perceived as colours.

The electromagnetic spectrum refers to a 'map' of different types of radiant energy and its correlating wavelengths. There are usually six subdivisions, radio waves, infrared, visible, ultraviolet, X-rays and gamma rays.

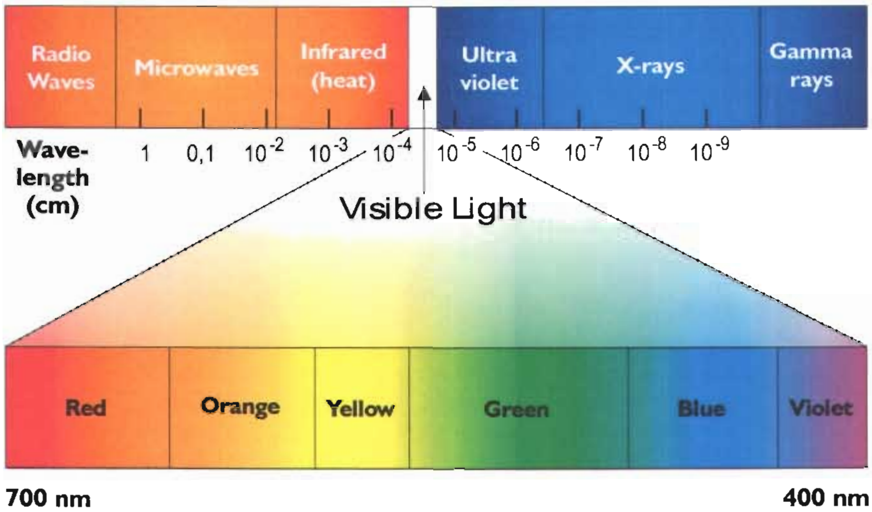



**Figure 11 The electromagnetic spectrum (Salazar 2000)**

Radiant energy exists in a range of wavelengths that extend from radio waves thousands of meters long to gamma rays with wavelengths as short as a million-millionth ($10^{-12}$) of a meter. As can be seen, the visible part of the spectrum is actually very small in relation to the other types of energy. From left to right, the spectrum is showing an increase in energy. This increase in energy correlates to the increase in frequency. The visible spectrum, from its violet to its red ends, is due to radiation varying from between 380 to 780 nanometres (nm). A nanometre is used to measure the wavelength of light and 1nm = $10^{-9}$ m, or 1 millionth of a millimetre (Rowell 2002:9, Salazar 2000).

## 3.3 The human eye

After millennia of recorded history, the understanding of the complexity and diversity of eyes are just beginning. Sight is essential for most creatures and the eye provides the most important link to the world by enabling the visualization of shape and colours (Deckert n.da). Man has one of the most remarkable vision systems in the world. The human eye's key features include a highly-corrected optical design, repeatable geometry of materials, control by the brain, processing of retina information, interfacing with the brain from six different levels of sensor cells in the retina, colour vision, compression of data going to the brain, and the highly specific material makeup and orientation that enables each eye to function (Deckert n.db).

At maturity, the human eyeball is approximately 24 mm in diameter and slightly flattened in the front and back. Each of its retina layers is unique. The outer fibrous layer encases and protects the eyeball and consists of the cornea and the sclera. The front one-sixth of the fibrous layer is the transparent cornea; it functions as a correction lens to help bend incoming light onto the lens inside the eye to form a sharp high-resolution image on the retina. A fine membrane then covers the cornea. The remaining fibrous layer of the eye, visible as the white of the eye, is a dense, tough, opaque coating. Its outer layer contains blood vessels, when the eye is irritated it will produce a 'blood-shot eye'. The middle layer of the eyeball is densely pigmented, well supplied with blood, and includes major complex structures and the innermost layer includes the retina. The iris and lens divide the eye into two main chambers; the front chamber that is filled with a watery liquid and is called the aqueous humor, and the rear chamber that is filled with a jellylike material called the vitreous body. The internal pressure exerted by the fluid inside the eye help in supporting the shape of the front cavity, while the fluid with the holding tissue holds the shape of the rear chamber (Deckert n.db, Kimball 2003b). Refer to figure 12 for a diagram of the human eye showing all the major components and to aid in the explanation of the overall vision system.

## 3.4 Structure of the human eye

### 3.4.1 Sclera

The eye may be considered as a sphere enclosed by a tough white/non-transparent covering called the sclera, except in the front of the eye where it forms the transparent cornea. The sclera helps keep the shape of the eye and is filled with a clear, jelly-like substance called the vitreous humor (Sharp 1951:190, Hahn 1995, Kimball 2003b).

### 3.4.2 Cornea

Light is admitted to the interior of the eye only through the front, this clear portion is known as the cornea. Light waves enter the eye through the cornea and because of its

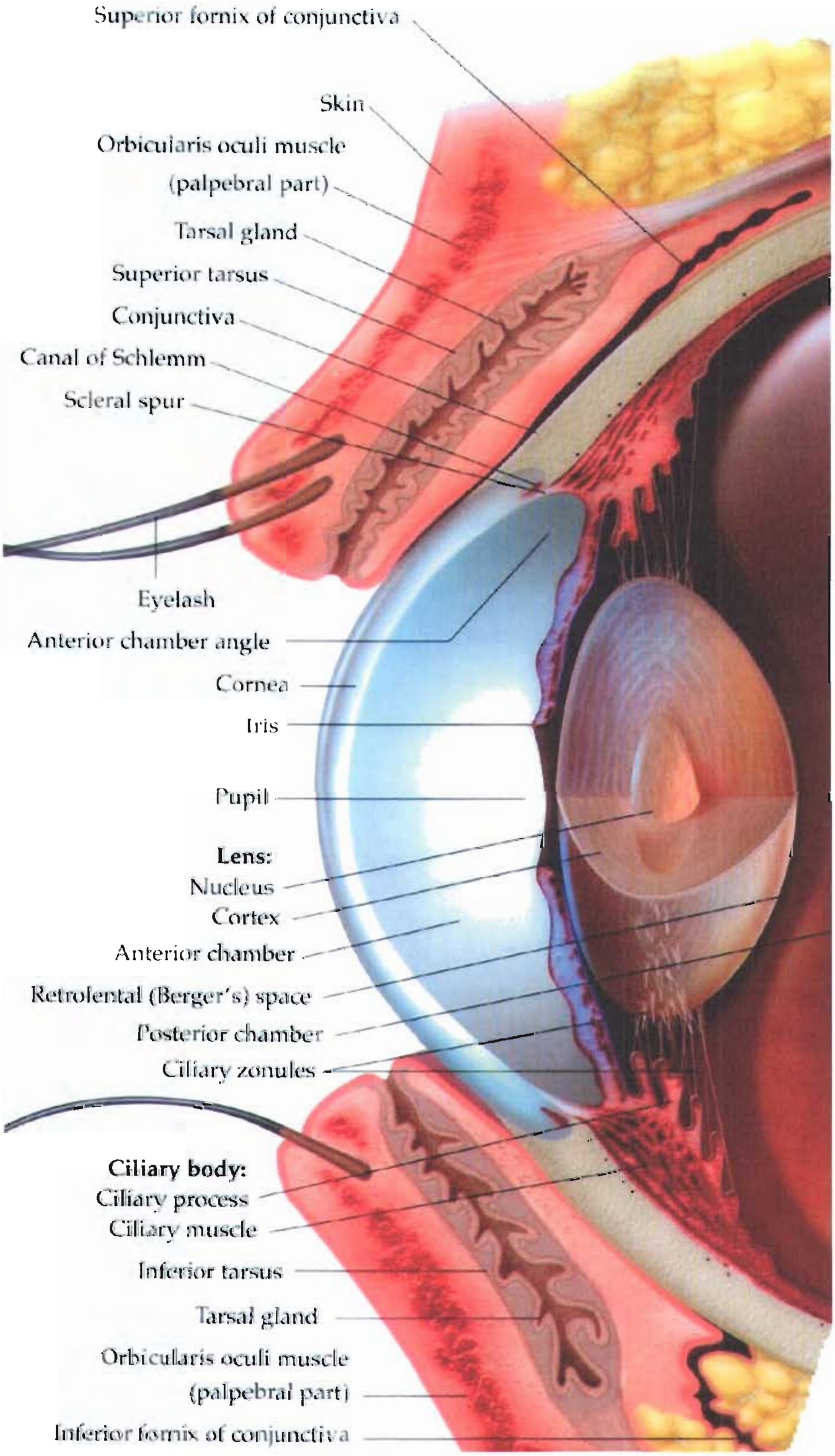



**Figure 12 The human eye diagram (Deckert n.db)**

convex shape, the image is bent inwards so the image can be brought to a focus (Rowell 2002:10, Kimball 2003b, Sharp 1951:190).

### 3.4.3 Anterior chamber

The most frontal chamber of the eye, between the cornea and the lens, contains a clear watery transparent fluid called the aqueous humor, it facilitates good vision. It helps to maintain eye shape and to regulate intra-ocular pressure, providing support for the internal structures, supplying nutrients to the lens and cornea, and disposing of the eye's metabolic waste (Deckert n.db).

### 3.4.4 Iris

The iris is a circular, adjustable diaphragm with a central aperture (the pupil). The iris is located in the chamber behind the cornea. The iris is responsible for eye colour, which is determined by the amount of pigment present. With dense pigment, the iris is brown. With a little pigment, the iris is blue. The iris is an extension of a large, smooth muscle, which is also connected to the lens via a number of suspensor ligaments. These muscles change the shape of the lens by expanding and contracting in order to adjust the focus of images onto the retina (Deckert n.db). It acts as a pigmented shutter. The iris opens and closes in response to light and also during the process of focusing objects upon the retina. The range of opening and closing of the iris is limited to between 2 mm and 8 mm. The iris therefore serves as a partial regulator of the amount of light that is admitted to the eye (Sharp 1951:190). In bright light, the iris muscles will constrict the pupil, thereby reducing the amount of light entering the eye. Conversely, in dim light the pupil will enlarge in order to increase the amount of incoming light allowed to go to the retina. As incoming light to the retina is reduced, the ability to see colour decreases (Deckert n.db). Figure 13 shows the human iris mechanism.

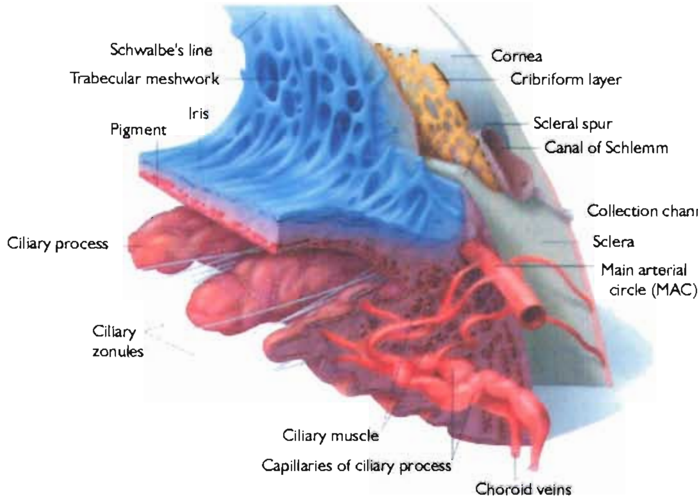



**Figure 13 Human iris mechanism (Anatomical Chart Co. 1999)**

### 3.4.5 Pupil

The pupil is the dark opening in the centre of the coloured iris that controls how much light enters the eye (Scott 2003). The pupil is a varying aperture and is used for control of light admission with the iris making small variations in the diameter of the pupil (Rowell 2002:10). When the field of view is very dim the pupil can dilate to about twice its normal diameter in order to admit four times as much light to the eyes. When the field is very bright, the pupil constricts to a minimum diameter of about 2 mm (Hewitt & Vause 1966:7). The pupilliary response is there to prevent the overwhelming of the eye with sudden exposure to relatively high brightness. It also prevents light starvation when the eye is suddenly exposed to some relatively very low brightness (Hewitt & Vause 1966:8).

### 3.4.6 Lens

Situated immediately behind the iris is the crystalline lens, a semi-solid flexible optical instrument filled with a remarkably clear, colourless fluid (Sharp 1951:190). It functions as the internal focusing element of the eye. The typical bi-convex (curving outward on both surfaces) is shaped like an elongated sphere. The entire surface of the lens is smooth and shiny, contains no blood vessels, and is encased in an elastic membrane. The lens is held in position by zonules extending from an encircling ring of muscle, refer to figure 14. When this ciliary muscle is relaxed, its diameter increases and the zonules are put under tension, and the lens is flattened. When this muscle is contracted, its diameter is reduced, the zonules relax and the lens becomes more spherical (Deckert n.db, Kimball 2003b). These changes in the ciliary muscles pushes or pulls the lens to a rounder or flatter shape that enables the eye to adjust its focus between far objects and near objects (Rowell 2002:10, Kimball 2003b). For distant vision the lens has the least curvature and places the least pull upon the ciliary muscles. When viewing near objects the lens becomes more convex due to contraction of the ciliary muscles (Sharp 1951:191). These muscles are short term rated and therefore like to be on the move all the time. Constant focusing on detail for too long, makes the eyes tired and is called eye-strain (Rowell 2002:10).

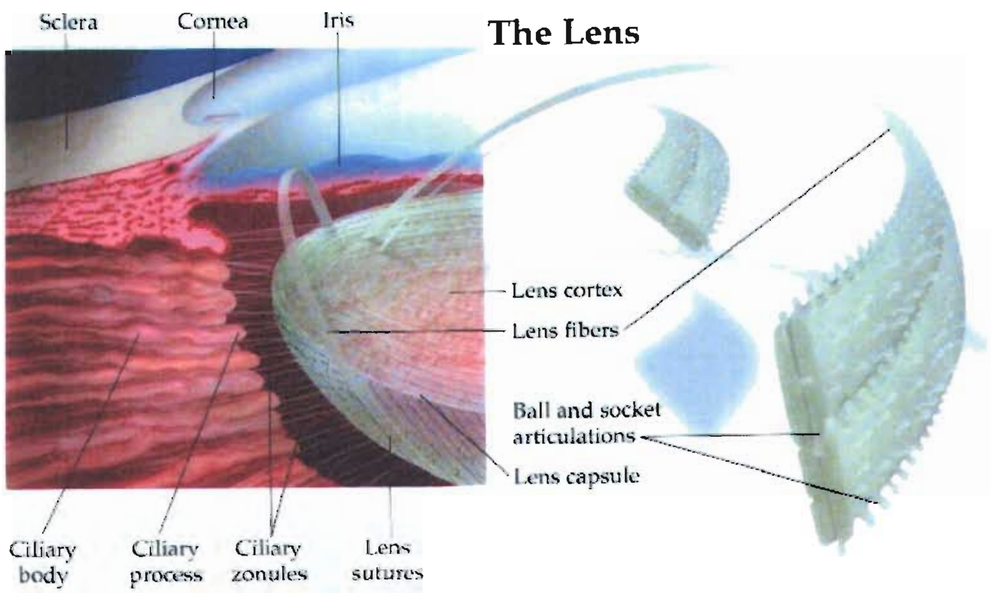



**Figure 14 The human lens (Anatomical Chart Co. 1999)**

### 3.4.7 Retina

The retina is the innermost layer making up the eye optical path. It is a thin, delicate, extremely complex sensory tissue composed of six layers light sensitive cells. These specialized cells are called photoreceptors (Deckert n.db). The function of these photoreceptors is to convert light energy into electrical impulses through photochemical action (Sharp 1951:191). The surface of the retina contains two types of light receptors called rods, which cell end is blunt, and cones, which cell end is conical (Rowell 2002:10). Refer to figure 15. The receptors are distributed over the whole interior of the back hemisphere of the eyeball (Hewitt & Vause 1966:3).

Rods function in dim light, allowing for limited night vision. Rods do not detect colour but do detect movement and fine detail. In each eye there are about 126 million rods and about 6 million cones. Cones function best in bright light and allow colour vision. Cones are mostly concentrated in a tiny hollow in the rear part of the retina. Dense fields of both rods and cones are outward, the cone density decreases and the ratio of rods to cones increases until both rods and cones disappear completely towards the edges of the retina (Deckert n.db). The start of the nervous system leading to the brain begins in the retina. It forms the outermost layer of a thin transparent lining that is an outgrowth of the brain reaching towards the surface of the body to sense light (Hewitt & Vause 1966:3).

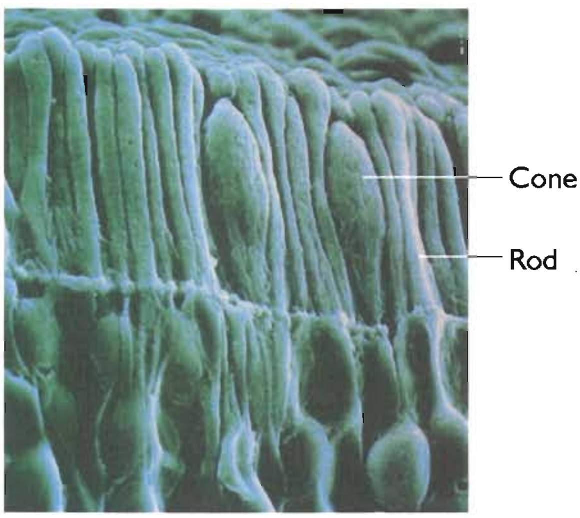



**Figure 15 Rods and cones in the human retina (Anatomical Chart Co. 1999)**

### 3.4.7.1 Rod vision

Rods do not provide a sharp image for the following reasons:

- adjacent rods are connected by gap junctions and therefore share changes in membrane potential
- a number of nearby rods often share a single circuit to one ganglion cell
- it is possible for a single rod to send signals to several different ganglion cells.

If only a single rod is stimulated, the brain has no way of determining exactly where on the retina it came from. However, rods are extremely sensitive to light and a single photon (the minimum unit of light) absorbed by a small cluster of adjacent rods is sufficient to send a signal to the brain. Therefore, rods are capable in certain conditions of responding to extremely weak light (Kimball 2003b). When rods alone are in operation vision is achromatic, that is, only brightness is appreciated (Hewitt & Vause 1966:3). Rods are not good for colour vision but are most sensitive to light and dark changes, shape and movement (Chudler 2004a).

#### 3.4.7.2 Cone vision

Cones are relatively insensitive and respond only to more intense stimulation. Adequate stimulation of the cones excites sensations of colour as well as luminosity or brightness (Hewitt & Vause 1966:3). Most of the six million cones in the human retinas are confined to a small region just opposite the lens called the fovea. Therefore, the sharp and colourful images are actually limited to a small area of view (Kimball 2003b). Cones are most sensitive to one of three different colours (green, red or blue) (Rowell 2002:12) as illustrated in figure 16. These three types of cones provide the basis of colour vision. Cones are 'tuned' to different portions of the visible spectrum, namely:

- red absorbing cones, those that absorb best at the relative long wavelengths peaking at 565 nm;
- green absorbing cones with a peak absorption at 535 nm; and
- blue absorbing cones with a peak absorption at 440 nm (Kimball 2003b).

Signals from these cones are sent to the brain that translates these messages into the perception of colour. People that are colour blind does not have a particular type of cone in the retina or one type of cone may be weak (Chudler 2004a).

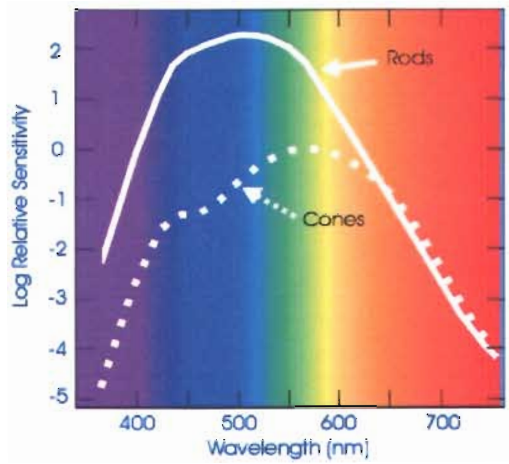
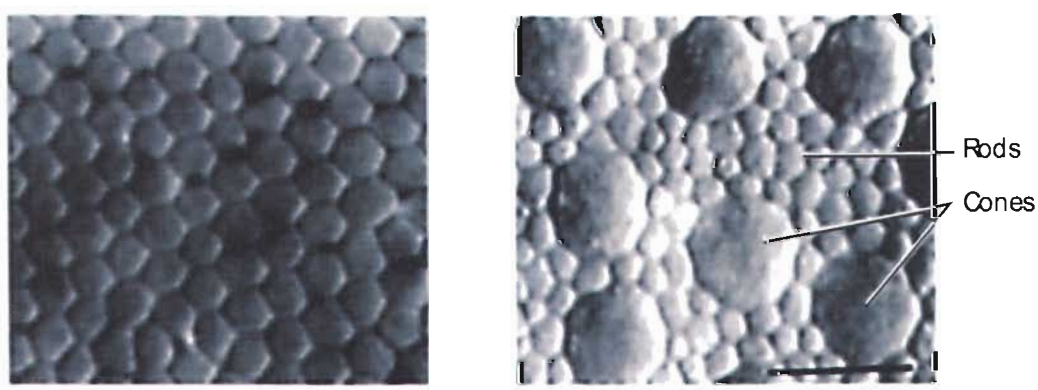



**Figure 16 Spectral sensitivity curves of rod and cone systems (Kaiser 2002d)**

### 3.4.7.3 Fovea

The fovea is a small area of the retina, close to the optical axis of the eye; the receptor population is particularly dense and consist of cones only (Hewitt & Vause 1966:3). Objects are focused on this area and most seeing and discrimination of detail results from this action. The retinal area outside the fovea is called parafovea. Here the rods are located interspersed with cones, but the cones decrease in number from the fovea outward, so that in the peripheral region there are none. The rods perceive objects indistinctly, but are alert to brightness and motion (Sharp 1951:192). Blood vessels and nerve fibres go around the fovea so light has a direct path to the photoreceptors (Chudler 2004a). Refer to figure 17 for a demonstration of the distribution of cones in the fovea.




Cones in the fovea — Cones in the periphery

**Figure 17 Distribution of cones in the fovea (Caceci 2001)**

### 3.4.7.4 Inter neurons in the retina

The retina also contains a complex array of inter neurons called bipolar cells and ganglion cells that together form a path from the rods and cones to the brain. The complex array of other inter-neurons form synapses with the bipolar and ganglion cells that modify its activity. Ganglion cells are always active, even in the dark it generates trains of action potentials and conduct it back to the brain along the optic nerve. Vision is based on modulation of these nerve impulses (Kimball 2003b). Light rays must penetrate two layers of neurons in the retina before reaching the precious rods and cones at the back: a middle layer of bipolar cells, and a front layer of ganglion cells whose long axons (fibres that transmit electrical impulses to other neurons) form the optic nerve leading into the brain (Montgomery 1994) as illustrated in figure 18.

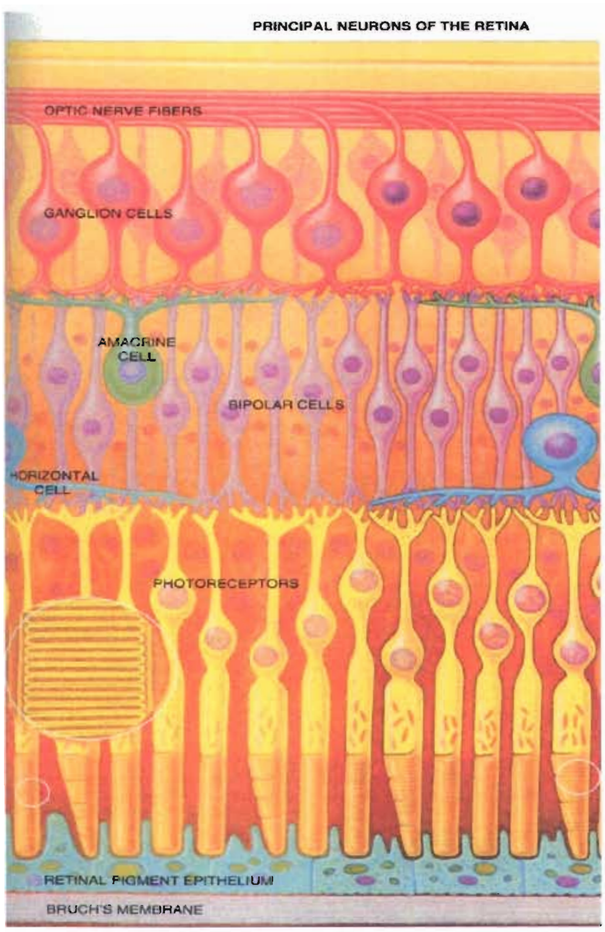



**Figure 18 Levels of sensor cells in the retina (Aramant 2000:21)**

### 3.4.7.5 How is an image formed?

The principles of how light energy is changed into electric energy in order for it to be sent to the brain's visual system, is all based on biochemistry (BioMedia 2003). Photoreceptor cells in the rods and cones convert light first to chemical energy and then electrical energy (Deckert n.db). The ends of the photoreceptors contain discs loaded with visual pigments. These pigments are the light absorbent portions of the photoreceptor cells (Photoreceptor stimulation n.d). The outer section of rods and cones are greatly expanded in size, and consists of a stack of highly folded membranes storing light-sensitive molecules (BioMedia 2003, Caceci 2001). In the rod, light is trapped by the trans-membrane protein called rhodopsin (BioMedia 2003). Rhodopsin is the light-absorbing pigment in the rods. It is incorporated in the membranes of discs that are neatly stacked (approximately 200) in the outer portion of the rod (Kimball 2003b). Figure 19 shows the discs loaded with visual pigments at the ends of the photoreceptors.

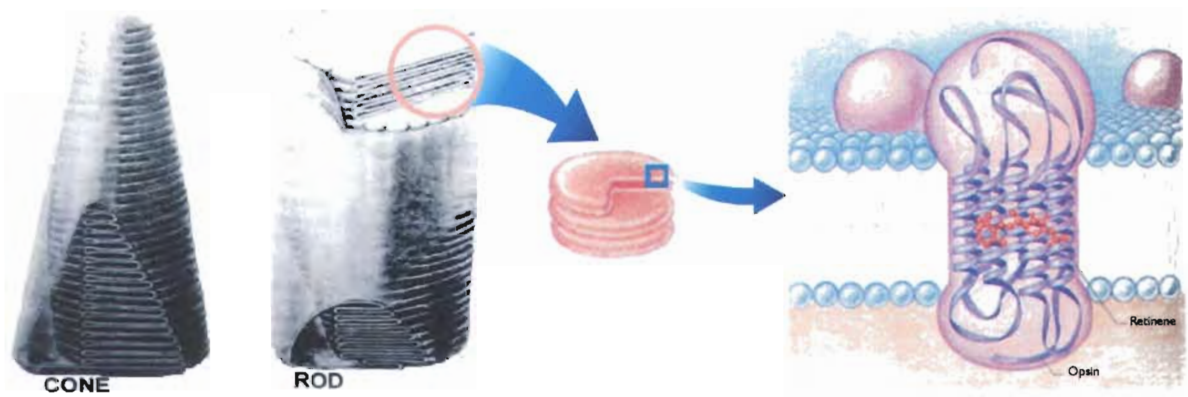



**Figure 19 Illustration of the discs at the ends of the photoreceptors (Discs n.d, Caceci 2001)**

In the rods there is a rose coloured chemical known as 'visual purple' or rhodopsin (IES 1968:2-2). The rhodopsin is made up of a retinal molecule bound to a protein called opsin. There are four different opsin proteins, one can be found in rod cells and one can be found in each of the three different cone cells (Photoreceptor stimulation n.d).

Upon exposure to light, the rhodopsin breaks down into retinene plus opsin (a protein) and finally into Vitamin A. The primary reaction results in the generation of a train of impulses which travel up through the layers of the retina to the optic nerve and on to the brain. The frequency with which these impulses follow one another depends upon the intensity of the stimulus. It is believed that similar reactions take place in the cones (IES 1968:2-2).

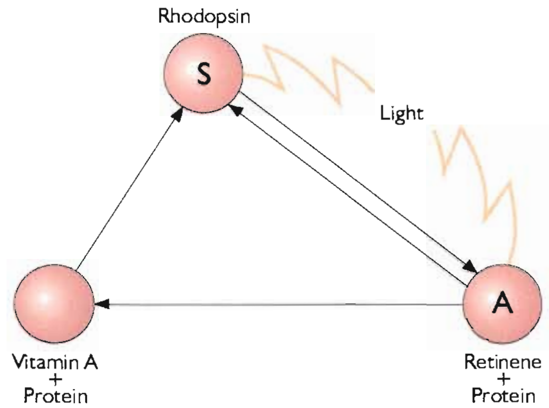



**Figure 20 Chemical process / Isomerization (IES 1968:2-3)**

Refer to figure 20 for an illustration of the process of isomerization. Rhodopsin consists of an amino acid sequence (opsin) and a chromatophore (retinal). When light hits a rod, the retinal molecule is 'photo-excited' and the light induces isomerization, a chemical phenomenon, where the molecule changes shape. The bonds between the retinal and the opsin are twisted and it separates. When chemical bonds are broken, energy is released in the form of an electrical impulse that is passed to the bipolar cell and on to the ganglion cell to gradually make its way to the optic nerve and on to the brain. The process for colour vision in cones is similar but different photo-chemicals are involved. There are three different general cone cell types and each with a different photo-sensitive protein. These proteins resemble the structure of rhodopsin but are specialized to react to red, green or blue light. The brain mixes these primary colours; therefore it is possible to distinguish innumerable colours (BioMedia 2003). The light points making up the image create a pattern of differentially stimulated cells on the retina. The electrical waves that arrive at the brain will reflect this pattern. The brain translates this information and allows 'seeing' the surrounding world (BioMedia 2003).

### 3.4.8 Optic nerve

It is known that several rods are connected together in one nerve path. It is also suspected that each cone has its own nerve path to the brain (Sharp 1951:192). There is a small area in the fovea in which all the nerve fibres associated with the individual and collective light receptors are bunched together before leaving the eye as the optic nerve. The optic nerve connects the eyes to the brain. Thousands of fibres of the optic nerve cells run from the surface of the retina and converge to exit the eye at the optic disc (or blind spot), an area of about 1.5 mm in diameter. The human eye diagram of the optic disc is illustrated in figure 21.

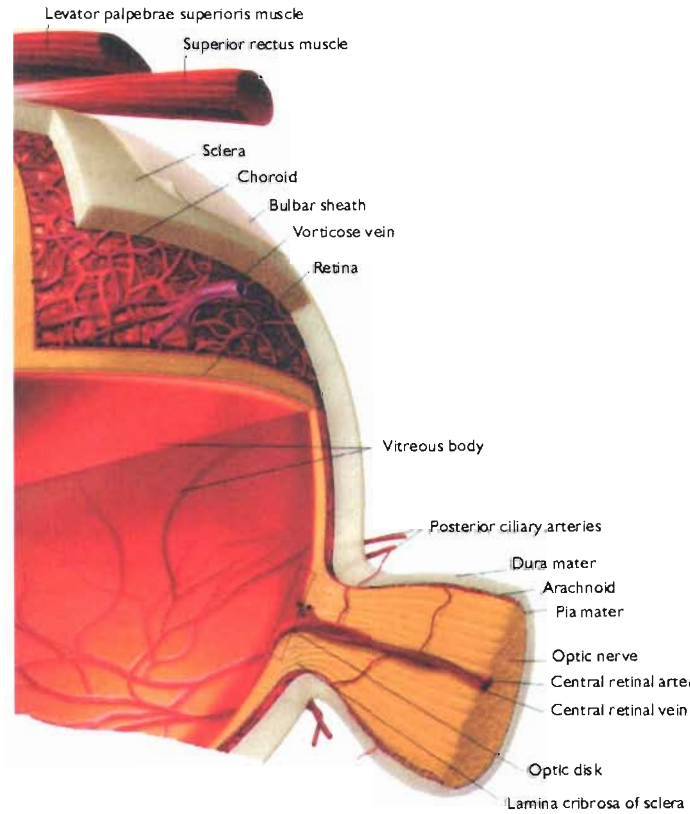



**Figure 21 Human eye diagram of the optic disc (Anatomical Chart Co. 1999)**

Since there are no receptors in this part of the retina and the fibres of the optic nerve are not directly stimulated by light, this retinal area is blind. The fibres of this nerve are made up of large number of cells, each having thousands of connections to carry electrical impulses from the retina to the brain. If the optic nerve is severed, vision is permanently lost. The blind spot is of no consequence as in binocular vision, which will be discussed later; that small part of the field of view which one eye does not see at any particular moment is seen by the other eye (Deckert n.db, Hewitt & Vause 1966:4).

### 3.4.9 Visual cortex

This is the part of the brain responsible for visual perception and will be discussed in the following chapter.

## 3.5 Adaptation of the eye

The light sense can respond effectively only to a much narrower range of luminance at any one time so its sensitivity has to be suitably adjusted when it is called upon to function within different ranges, the process of adjustment of the visual system to the prevailing conditions is called adaptation as shown in figure 22. The adaptation is a photochemical and nervous process and is not effected by changes in the pupil area (Boyce 1981:45, Hewitt & Vause 1966:7).

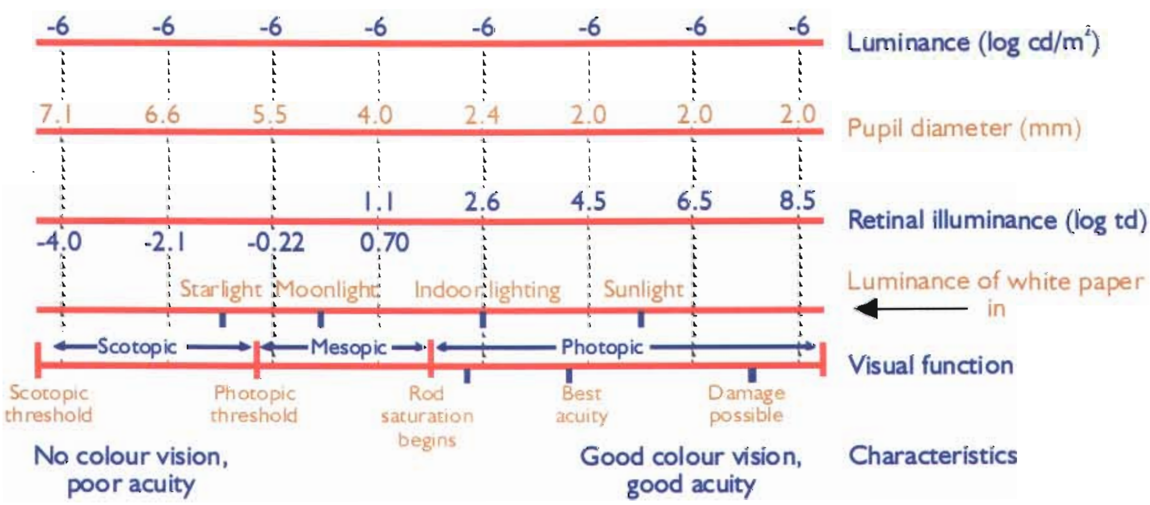



**Figure 22 Sensitivity of the eye (Kaiser 2002c)**

- **Photopic vision**

Photopic vision describes the normal daylight as well as good lighting conditions. This state covers a luminance range of about 1 000 cd/m$^2$ down to 10 cd/m$^2$, and vision is mainly achieved through the cone receptors (Rowell 2002:10). The eye is light-adapted when the ambient light is bright enough for the retinal cone receptors to be responsive (Hewitt & Vause 1966:8). During photopic vision complete colour vision is available (Boyce 1981:45).

- **Mesopic vision**

Mesopic vision describes visual field luminance between 10 cd/m$^2$ and 0,1 cd/m$^2$ where both rods and cones operate. This is a transition state and is called 'twilight vision' because the eye is adapted between light and dark, and in fact this is the time of day when problems are experienced (Rowell 2002:10). As the mesopic condition is reached, colour vision starts to appear. In this state discrimination of detail in the fovea improves above that for the scotopic condition, but is not as good as for photopic conditions (Boyce 1981:44-45, Sharp 1951:193).

- **Scotopic vision**

Scotopic vision describes visual field luminance between $10^{-6}$ cd/m$^2$ and 0,035 cd/m$^2$. In scotopic conditions colours are not visible, vision becomes acromatic, black and white. Only the rods are operating and therefore the fovea is blind, in other words the retinal area used for fine discrimination of detail is not functioning. At this level the eye is said to be dark adapted (Boyce 1981:44-45, Rowell 2002:10).

## 3.6 Field of vision

The eye is recessed into a bony socket which provides mechanical protection as well as a certain amount of shielding from light overhead. The nose offers some obstruction to side vision (Sharp 1951:194). Each eye receives a different visual image, firstly, because the foveas are 5-7 cm apart and secondly, because the nose and eye sockets block the view of the opposite side. Depth perception is obtained by comparing the positions of objects contained within the images received by both the left and the right eyes. It is an interpretation of the three-dimensional relationships among objects in view (Scott 2000). When a person with `normal seeing capabilities' looks at an object with both eyes at the same time, the visual fields of the two eyes intermesh as illustrated in figure 23. The areas seen by the two eyes are not coextensive because the nose, eyebrow, and cheek will block off a portion of the field of each eye. Therefore, the visual fields of both eyes are bigger than the field of either eye. The binocular field is that space seen by both eyes simultaneously and is approximately 60 degrees in radius (IES 1968:2-3).

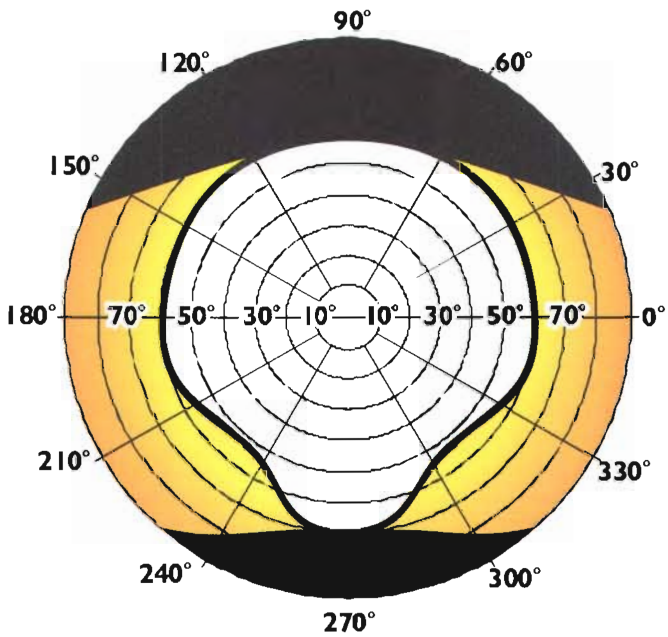



**Figure 23 The normal field of view of a pair of human eyes (IES 1968:2-4)**

With reference to figure 23, the white central portion represents the region seen by both eyes. The yellow portions, right and left, represent the region seen by the respective eyes alone. The cut-off by the eyebrows, cheeks, and nose is shown by the dark areas (IES 1968:2-4).

The angular extent of the visual fields from each eye (monocular field) and the combined or binocular vision is illustrated in figure 24. The possession of two eyes provides a very wide visual field (almost more than 180 degrees) although binocular vision is characteristic only within the overlapping areas of the monocular fields. Binocular single vision depends on each eye's line of sight (visual axis) meeting that of the other eye at a common point. No matter where the eyes look, near or far, straight ahead or in some other direction, the visual axis must converge in order to direct the two foveae to the same object (Hewitt & Vause 1966:9).

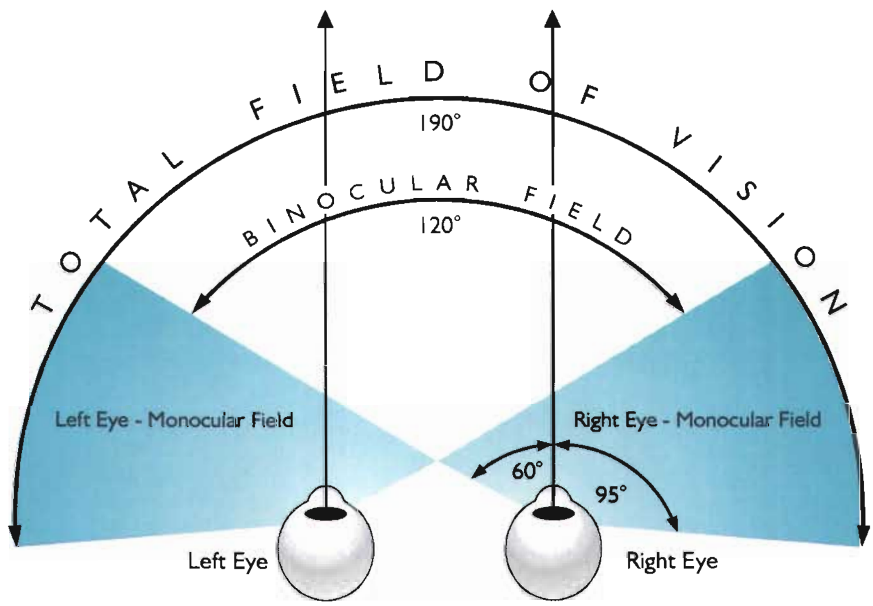



**Figure 24 Diagram showing the total width of the visual field and binocular portion of the field (Hewitt & Vause 1966:9)**

When looking ahead, the images received by both eyes are overlapped. The image received by the fovea of the eye, is the centre of the region of overlap. A vertical line drawn through this centre shows the division of the visual information at the optic chiasm (Scott 2000). When the different pictures overlap in the brain, it should supplement one another. Therefore, the eyes must work together to form a clear, life-like picture in the brain.

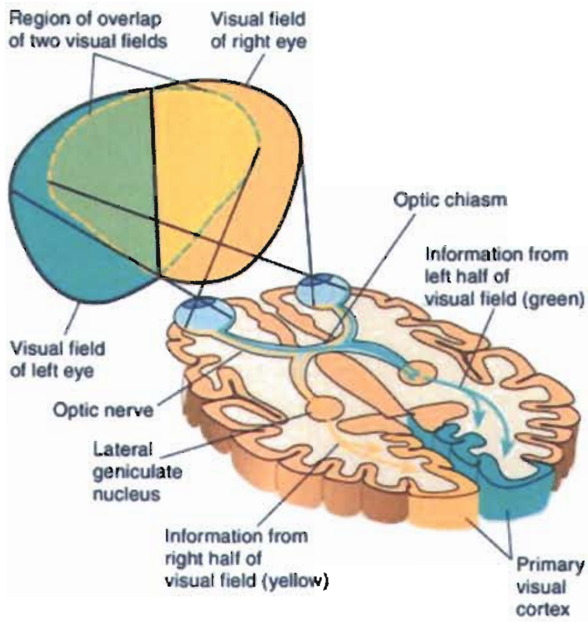



**Figure 25 The visual field and the pathway to the brain (Driesen 2004)**

It is important that both eyes must move together to ensure good interaction between the eyes (De Jager 2001:46). Therefore, the perception of a visual image is reflected by the integration of information that arrives at the visual cortex of the occipital lobes. Visual information from the left half of the combined visual field will reach the visual cortex of the right occipital lobe; information from the right half will arrive at the left visual cortex. The cerebral hemispheres thus contain a map of the entire field of vision (Scott 2000) as illustrated in figure 25. The visual pathway in the brain will be discussed in detail in the next chapter.

With the eye fixed on some object it is obvious that a large area of the surroundings is also within view, even if the details are not sharply clear. Thus, the surrounding brightness has an important bearing upon eye function. Of particular importance is the circular zone subtending an angle of 30 degrees about the line of vision. Figure 26 illustrates the loss of visibility due to direct glare in terms of wasted light. When an object is viewed it is focused on the fovea, which subtends an angle of not over 2 degrees in diameter. The object is viewed against a background which will almost certainly subtend the area of the fovea (Sharp 1951:194-195).

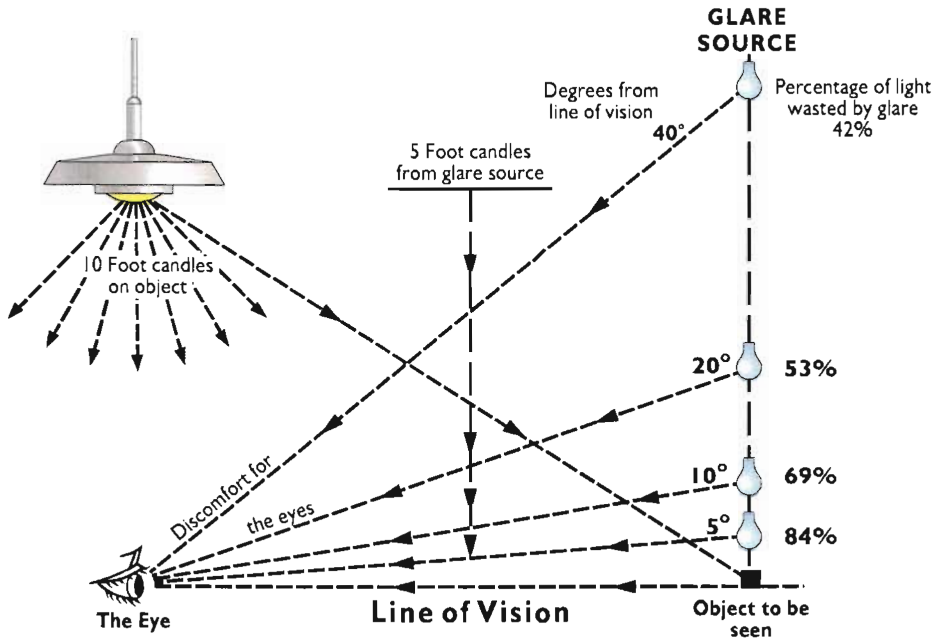



**Figure 26 The effect of glare in the central visual field (Sharp 1951:197)**

The surround is the remainder of the large visual field. The surround can be divided into two portions for purposes of lighting design; the 30 degree zone or immediate surround, and the remainder or remote surround as shown in figure 27. There should be a high difference in brightness between the object of regard and its background, but the difference in brightness between this background and the surround should be low. It is important for good vision that the brightness of the background should not be more than three times the brightness of the 30 degrees or near surround and the brightness should not be greater than ten times the brightness of the remote surround. If the surround, or any object in it, has a brightness greater than the background it will result in a reduction of visual efficiency. In practice there is almost always some brightnesses within the field of view in excess of object or background brightness. Therefore, the degree of skill in the lighting design determines in large measure how small the brightness differences will be (Sharp 1951: 194-197, Hewitt & Vause 1966:9).

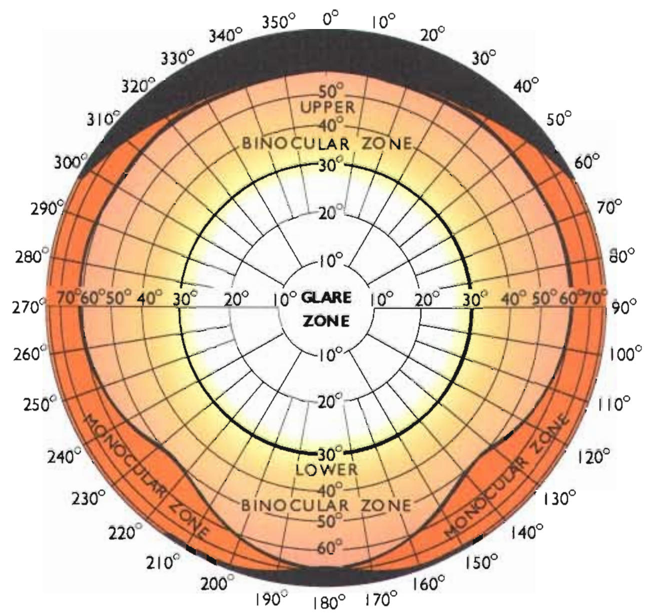



**Figure 27 The visual field (Sharp 1951:195)**

Generally, glare is not due to excessive apparent brightness of the total field of view (called 'too much light') but to the presence in this field of local areas where the luminance is much higher than the average ambient luminance. Therefore, the luminance of artificial lighting equipment must be kept down within ordinary angles of view so that it does not unduly exceed the luminance of surrounding areas of the panorama (Hewitt & Vause 1966:14).

## 3.7 Fundamental external vision factors

The eyes see a visual task because it has size, brightness, and contrast with reference to the background. The element of time also plays a role as the process of vision is not instantaneous (IES 1968:2-6, Sharp 1951:198). These four factors will be discussed separately:

- **Size**

With two objects of unequal size, the larger will subtend more retinal area than the smaller. If it was of the same brightness, the larger will introduce more light energy into the retina and it will therefore be easier to see. This is not true if the two objects are of unequal brightness. If the smaller object can have its brightness increased to the point where it will introduce as mush light energy into the eye as the larger object, then both may be equally visible. When both objects are black, it must appear against a lighter background in order to be seen. Then the pattern on the retina will be one of darkness surrounded by light. Once again the larger object is easier to see. But if the background of the smaller object is increased in brightness, it may be as visible as the large object against its lower brightness background (Sharp 1951:198).

- **Brightness**

The photochemical process of the retina is set into motion by the light energy. The greater the energy, within certain maximum values, the better the eyes will perform. This energy consists of the sum total from object and background. It can be a light object against a darker background or a dark object against a lighter background. No matter what the combination, that which introduces the greater light energy constitutes the better seeing environment (Sharp 1951:198).

- **Contrast**

Contrast is a shortened term for brightness contrast. If an object and its background have the same brightness and colour, it will be invisible no matter how much light is transmitted to the retina. There must be a brightness difference between the elements of the pattern in order to establish a pattern on the retina. For example, if the printing on this page had exactly the same reflectivity as the paper, it would not be visible no matter how much light was directed to it or reflected by it. See the example in figure 28. The basic formula for the numerical determination of contrast is as follows:

$$\text{Contrast} = C = \frac{B_1 - B_2}{B_1} \qquad (13)$$

Where $B_1$ = brightness of background

$B_2$ = brightness of object (Sharp 1951:198-199)

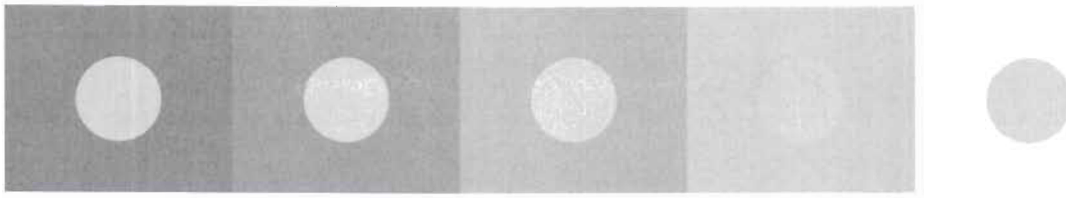


**Figure 28 Illustration of simultaneous contrast (Kaiser 2002b)**

The round dots in figure 28 are all exactly the same colour grey. The circle on the extreme right was created and then copied to each of the darker rectangles. Clearly, the lightness of the background effects the way in which the centre grey dot is perceived. This effect is called simultaneous contrast (Kaiser 2002b).

- **Time**

It takes time to see, especially when a series of visual tasks must be seen sequentially (IEC 1968:2-6, Sharp 1951:199). For objects of low brightness more time is required for accurate focusing than for ones of higher brightness. The light energy must first be transformed into the electrical impulses that travel along the optic nerve to the brain. The brain must then process these impulses and achieve recognition. The speed of vision is however subjected to considerable control through the manipulation of the factors of size, contrast and brightness (Sharp 1951:199).

## 3.8 Summary

Light is very important for vision, and an important aspect of vision involves the eyes. The human visual system is very complex but is limited to only a small portion of the electromagnetic spectrum. All visual information is received and transformed by different parts of the eye. The eye is very dynamic in the sense that it adjusts to prevailing conditions in order to optimize the visual process. The binocular field of vision gives a greater picture and immediate surround subtends a 30 degree circular zone about the line of vision. Glare is usually caused by excessive brightness difference within this field of vision. When the eyes are exposed to light, the light energy is transformed into electric energy and then sent to the brain, this process is based on biochemistry. The brain is therefore the place where actual seeing takes place. The visual pathway in the brain will be discussed in the next chapter.

# CHAPTER 4 – VISUAL PATHWAY IN THE BRAIN

## 4.1 Introduction

Of all the information sent to the brain more than 90 percent is visual; and 40 percent of all nerve fibres are connected via the retina to the brain. The eyes register $\pm$ 600 visual messages per second, therefore, it is important for humans to take advantage of the brain's enormous capacity for visual processing. The brain receives vital information via the eyes, concentrating on essential elements like contrast between light and darkness, tint, colour and size (Vermeulen 2000:6). The eyes are responsible for receiving and transforming radiant energy. The transformed radiant energy is transmitted to the brain, where vision occurs. This involves the central nervous system and is a subjective sensation (Sharp 1951:189). Therefore, it is clear that it is not the eyes that see, but the eyes are merely tools that make seeing possible.

## 4.2 Structure of the brain

The various regions of the brain all have specific functions. Billions of neurons and glia covers the surface of the cerebrum and together it forms the cerebral cortex. The cerebral cortex appears greyish brown in colour and is also called the 'grey matter' (neurons with no myelin). Beneath the cerebral cortex or surface of the brain, connecting fibres between neurons form the 'white matter' (myelinated neurons that enter and leave the cortex) (Freudenrich 2004b, NeuroSurgeryToday.org 2003). The human brain has six basic regions as shown in figure 29.

- **Brain stem** – situated deep in the brain and leads to the spinal cord, responsible for basic life functions such as breathing, heart rate and blood pressure.
- **Cerebellum** – responsible to co-ordinate voluntary body movement and balance.
- **Corpus callosum** – a bundle of nerve fibres connecting the two brain hemispheres.
- **Hypothalamus** – regulates hunger, thirst, sleep, sexuality and emotions.

- **Neocortex** – the thinking or learning brain.
- **Thalamus** – a central relay station for incoming sensory pathways except smell (Jensen 1996:28, Lehr 2004, Freudenrich 2004b, NeuroSurgeryToday.org 2003).

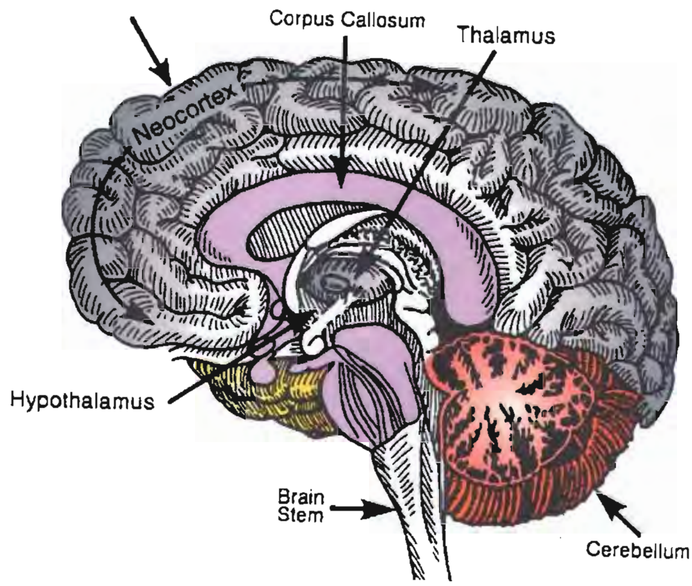



**Figure 29 A section through the human brain (Jensen 1996:28)**

Inside the brain there are basically three different functional systems:

- The neocortex or neo-mammalian brain.
- The limbic or early mammalian brain.
- The brain stem or reptilian brain (Howard 1994:34).

### 4.2.1 The neocortex or mammalian brain

The cerebrum is the largest part of the human brain. The term cerebrum is often used to describe the entire brain. All the centres that receive and interpret sensory information, initiate movement, analyse information, reason and experience emotions, are located in different parts in the cortex. The cortex dominates the exterior surface of the brain (Freudenrich 2004c). The word 'cortex' means 'bark' (of a tree) in Latin and resembles the meaning of the word as it makes up the outer layer of the brain. The neo-cortex is the outer layer of the cerebrum where synthesis and major thought processes occur (Hannaford 1995:71).

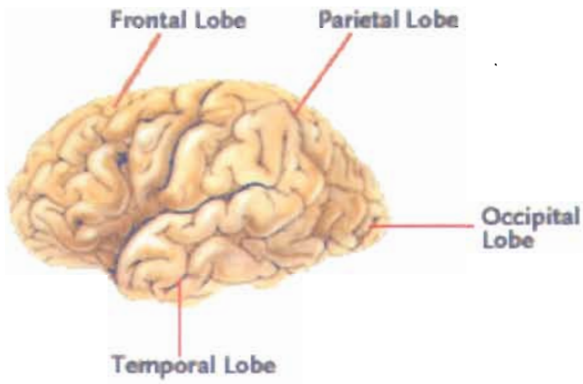



**Figure 30 The neocortex (Annenberg/CPB Learner.org 2001)**

The surface area of the brain is about 1 500 $cm^2$ to 2 000 $cm^2$, that can be compared to about one to two pages of a newspaper. In order for this surface area to fit into the skull, the cortex is folded forming bumps or bulges (gyri) and grooves (sulci) (Freudenrich 2004c). The singular for gyri is gyrus and for sulci it is sulcus. Therefore, the surface of the brain appears wrinkled as shown in figure 31.

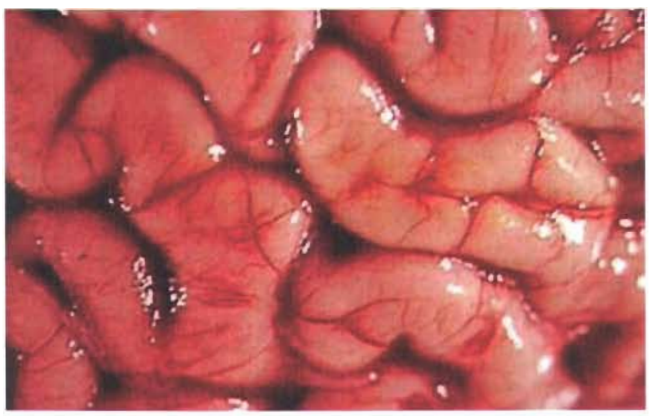


**Figure 31 Gyri and sulci on the surface of the brain (Stensaas & Millhouse 2002)**

The cerebral cortex has small grooves (sulci), larger grooves (fissures) and bulges between the grooves called gyri. All the bulges and grooves on the surface of the brain help to isolate very specific regions of the brain. These different regions are important for thought, voluntary movement, language, reasoning, perception, visualising, reading, and translating. (Chudler 1999c, Fourie 1998:14, Freudenrich 2004c, Hannaford 1995:71, Howard 1994:35, Jensen 1996:22, NeuroSurgeryToday.org 2003).

### 4.2.2 The limbic or early mammalian brain

This system is involved in emotions. In recent years evidence has shown that the limbic system and the right hemisphere are interrelated and that it functions in close co-operation. There is a close association in the processing and storage of memories, and is closely cooperating in different aspects of visual processing (Nadel & Moscovitch 1997:218). Included in this system are the hypothalamus, part of the thalamus, amygdala (active in producing aggressive behaviour) and hippocampus (plays a role in the ability to remember new information). The amygdala is located within the temporal lobe and controls social and sexual behaviour and other emotions (NeuroSurgeryToday.org 2003). The emotional aspects of experiences are linked to a person's memories via the amygdale. When the amygdale is stimulated it will cause muscles to tense up, blood pressure and heart rate will change and hormones will be released among other bodily and brain responses (Le Doux 1998:203). The hippocampus is also located in the temporal lobe and is responsible for the formation of memories (NeuroSurgeryToday.org 2003).

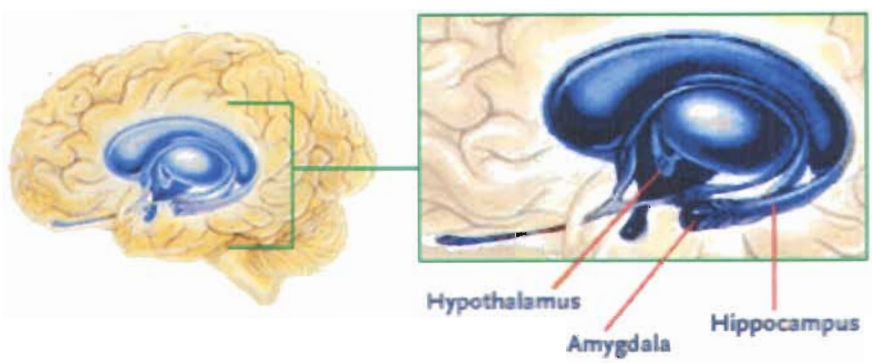



**Figure 32 The limbic system (Annenberg/CPB Learner.org 2001)**

The hypothalamus is situated just below the thalamus and monitors all internal information. The hypothalamus is a small structure containing nerve connections that send messages to the pituitary gland. The hypothalamus handles information that comes from the autonomic nervous system. It plays a role in controlling behaviour such as eating, sexual behaviour and sleeping, regulates body temperature, emotions, secretion of hormones and movement (Chudler 1999c, Davidmann 1998:3, Fourie 1998:14, Hannaford 1995:51-55, Howard 1994:34, Jensen 1996:22, Kapp 1991:212, NeuroSurgeryToday.org 2003).

### 4.2.3 The brain stem or reptilian brain

Lower animals do not think much, but are concerned with everyday business of gathering food, eating, drinking, sleeping, reproducing and defending. Humans perform these functions as well, and therefore also have a reptilian brain (Freudenrich 2004b). This forms part of the instinctive brain and it also controls some emotions (Buzan 1988:21). The brain stem is situated in front of the cerebellum and may be considered as a stem or structure that holds up the cerebrum. The brain stem consists of three structures: the midbrain, pons, and medulla oblongata. It acts as a relay station, passing messages back and forth between various parts of the body and cerebral cortex. Many primitive functions that are essential for survival are located here. Ten of the twelve cranial nerves that control hearing, eye movement, facial sensations, taste, swallowing and movement of the face, neck, shoulders and tongue muscles, originates in the brain stem (NeuroSurgeryToday.org 2003).

The midbrain is approximately two centimetres long and is the part of the brain stem where the two hemispheres of the cerebrum are attached, tying all three parts of the brain together. The midbrain contains nuclei that link the various sections of the brain involved in motor functions (cerebellum, basal ganglia, cerebral cortex), eye movements and auditory control (Freudenrich 2004b). The pons contains nuclei that relay movement and position information from the cerebellum to the cortex. It also contains nuclei that are involved in breathing, taste and sleep (Freudenrich 2004b). The pons is approximately five centimetres long and is formed by the cross-fibres situated in the anterior of the brain stem; it forms the bridge joining the cerebellum or small brain with the spinal cord and the midbrain. The pons relays all voluntary motor impulses coming from the cortex to the cerebellum for co-ordination and then to the neocortex for interpretation. The medulla oblongata is approximately eight centimetres long and forms the pathways for almost 90 percent of the approximately one million fibres in the body. The medulla contains nuclei for regulating blood pressure and breathing, as well as heart rhythms and swallowing and nuclei for relaying information from sense organs that comes from the cranial nerves.

The thalamus has a part in each of the hemispheres, situated just below the corpus callosum. The thalamus serves as a relay station for almost all information that comes and goes to the cortex. It plays a role in pain sensation, attention and alertness (NeuroSurgeryToday.org 2003). The thalamus relays the incoming sensory pathways to the appropriate areas of the cortex, determines which sensory information actually reaches consciousness and participates in motor-information exchange between the cerebellum, basal ganglia and cortex. The thalamus promotes or retains impulses to and from almost all parts of the central nervous system (Chudler 1999c, Davidmann 1998:3, Fourie 1998:13, Hannaford 1995:32, Howard 1994:34, Jensen 1996:27, Kapp 1991:212, NeuroSurgeryToday.org 2003).

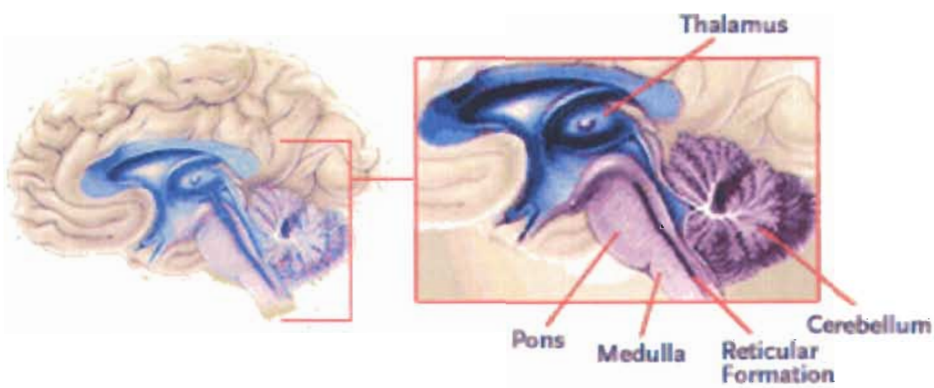



**Figure 33 The brain stem (Annenberg/CPB Learner.org 2001)**

### 4.3 Functions of the different parts of the brain

When viewed from the top, a large groove (inter-hemispheric fissure) separates the brain into left and right halves, refer to figure 34.

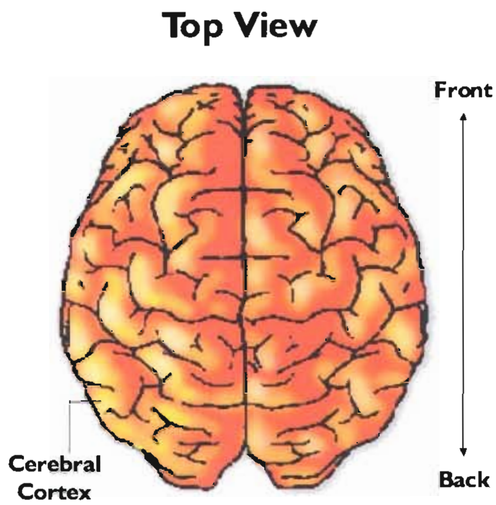



**Figure 34 Top view of the two hemispheres (Chudler 1999c)**

The halves communicate through a tract of white-matter fibres called the corpus callosum. The corpus callosum joins the two sides of the brain at the bottom, and passes messages from one half of the brain to the other (Freudenrich 2004b). Refer to figure 35.

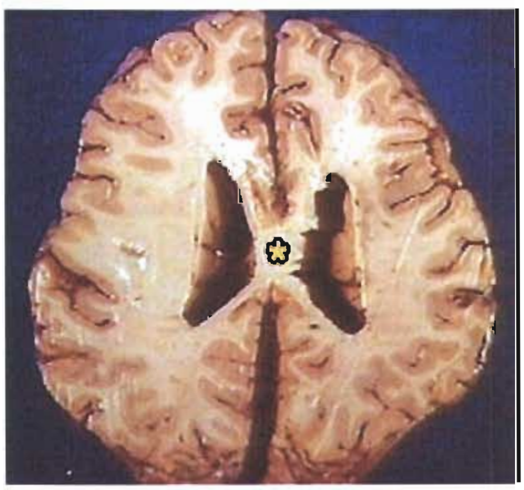


**Figure 35 Location of the Corpus callosum as indicated by the yellow dot (Stensaas & Millhouse 2002)**

The cerebral hemispheres have several distinct fissures. By looking at these fissures on the surface of the brain, the brain can effectively be divided into pairs of lobes. Lobes are simply broad regions of the brain. The brain may be divided into pairs of frontal, parietal, temporal and occipital lobes as illustrated in figure 36. Again, each lobe may be divided into areas that serve specific functions. There are very complex relationships between the lobes of the brain and therefore it never functions alone (NeuroSurgeryToday.org 2003).

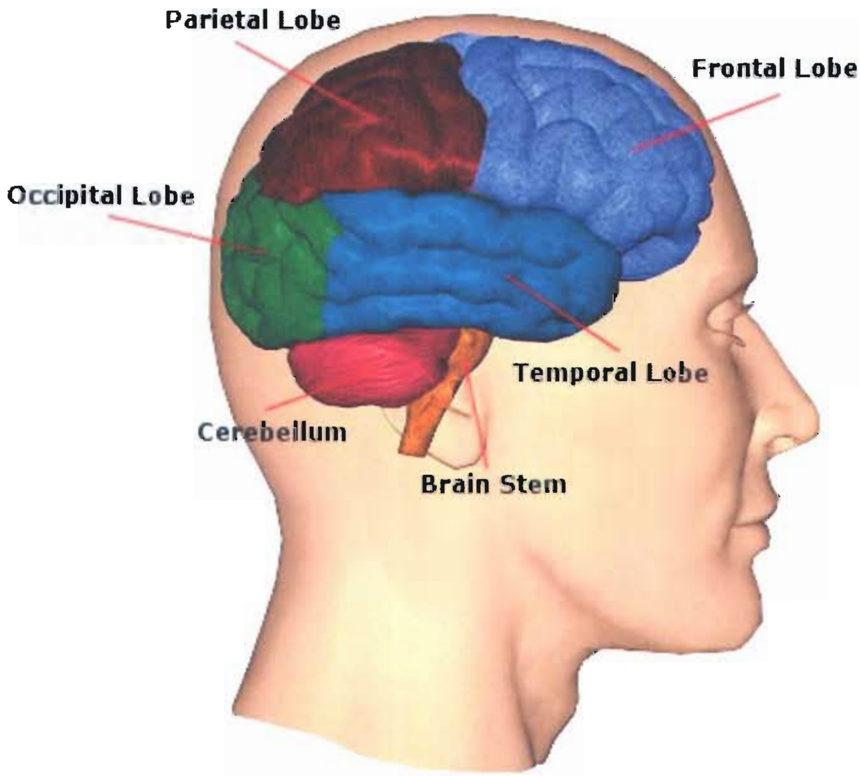



**Figure 36 Map of the brain functions (Lehr 2004)**

- **Frontal lobe**

This part of the brain is located most anterior, right under the forehead (Lehr 2004). It is responsible for the elaboration of thinking, programming individual needs and emotion (Cardoso 1997). This area of the neo-cortex is the primary motor area and controls specific muscles in the body. This area also enables a person to behave in accordance with the rules of the society. The frontal lobe is also responsible for pattern recognition and simultaneous processing of information, high level planning and fine motor control (Le Doux 1998:77, Hannaford 1995:76, Kapp 1991:219).

- **Parietal lobe**

This part of the brain is located near the back and top of the head (Lehr 2004). It is responsible for the sensation of pain, touch, taste, temperature, pressure, in other words all sensory areas. Stimulation of certain regions of this lobe in conscious patients produces taste sensations. It is also related with mathematics and logics (Le Doux 1998:77, Hannaford 1995:75, Kapp 1991:220, Cardoso 1997).

- **Temporal lobe**

This area is referred to as the language module and is located on the side of the head, just above the ears (Calvin 1997:79, Lehr 2004). It is primarily related with auditory sense, allowing the recognition of specific tones and sound intensity (Cardoso 1997). This area is also for olfactory functions that refer to the sensation of smell (Amen 1998:188, Le Doux 1998:77, Hannaford 1995:75). The temporal lobe plays an integral part in memory, emotional stability, learning, and socialisation. Remembering what was read as well as language processing problems relies heavily on the temporal lobe (Amen 1998:187,194). Tumor or accidental lesions in this area promote auditory damage or deafness (Cardoso 1997).

- **Occipital lobe**

This area of the neo-cortex is responsible for the processing of visual information and is called the visual cortex (NeuroSurgeryToday.org 2003). It is situated most posterior right at the back of the head (Lehr 2004). Sensory impulses from the eyes are interpreted into shape, colour and movement. What is seen is then evaluated and related to past and present visual experience and recognition (Le Doux 1998:77, Hannaford 1995:74, Kapp 1991:221). It also interprets the upside-down images of the world that are projected onto the retina by the lens of the eye (Freudenrich 2004c). Damage to this area results in partial or complete blindness (Cardoso 1997).

- **Cerebellum**

This area is located at the base of the skull, beneath the occipital lobes. The cerebellum is folded into many lobes and lies above and behind the pons. This part of the brain is involved with coordination of voluntary movement, balance and equilibrium and some memory for reflex motor acts. It is connected with the frontal lobe area where planning of order and timing of future behaviour occur (Freudenrich 2004c, Hannaford 1995:99, Lehr 2004, NeuroSurgeryToday.org 2003). Sensory input is received from the spinal cord, motor input from the cortex and basal ganglia and position information from the vestibular system. This information is then integrated in the cerebellum that influences outgoing motor pathways from the brain to coordinate movements (Freudenrich 2004c).

- **The reticular activation system**

The reticular activation system (RAS) is situated in the midbrain, pons, medulla and part of the thalamus. Impulses are carried from the medulla oblongata and pons to the neocortex by the RAS that acts as a nerve reticulum (NeuroSurgeryToday.org 2003). The RAS is activated by the vestibular system, which controls the sense of movement and balance, and is activated by movement. The RAS is also referred to as the 'gatekeeper' as it acts like a control centre. When two or more messages are received simultaneously, the RAS will decide which one is most urgent and will send it through to the right destination (Hannaford 1995:32-35). It controls the level of wakefulness, as it sends 'wake-up' signals to the higher parts of the brain, the attention given to what happens in the surrounding world and a person's sleeping pattern (NeuroSurgeryToday.org 2003).

## 4.4 The nervous system

The understanding of how the basic functional cell of the nervous system (neuron) works is fundamental to all processes such as sensation. The resting membrane potential is a stable electrical charge of approximately -65 to -70 millivolts of the internal side of the cell in relation to the external side. It forms the basis of bioelectricity, that is, the generation and use of electrical energy by cells such as the neuron to perform its functions of storage and transmission of information (Cardoso & Sabbatini 1999).

### 4.4.1 The neuron

Neurons are responsible to gather information of the internal state of a person and the external environment, evaluate the information and then coordinate activities that are appropriate to the situation and to the person's current needs. All this information is processed by an event called a 'nerve impulse'. The transmission of a coded signal from the given stimulus along the membrane of the neuron, from the point that it was stimulated, is called a nerve impulse. The nerve impulse processing that is involved can be divided into two types, namely electrical and chemical. The differences between the two types are that electrical events propagate a signal within a neuron, and chemical processes transmit the signal from one neuron to the other or to a muscle cell (Cardoso 1998).

Messages for any action from the brain are carried out through an electrical impulse or through communication waves between the billions of neurons. Any request for action from the brain is carried out through electrical impulse. Electrical impulses flow from the cell body of the sending neuron through the axon to the terminal where a chemical process occurs (Chudler 1999a:12, Chudler 1999b:7, Le Doux 1998:139, Howard 1994:36). During interaction between neurons a chemical process occurs at the end of the axon, called synapse. Touching intimately against the dendrite of a neighbouring cell, but without any physical continuity between the cells, the axon releases chemical substances called neurotransmitters, which are attached to chemical receptors in the membrane of the following neuron (Cardoso 1998). If enough transmitters bind to the receptors of the receiving neuron, electrical impulses will fire and move down the axon, which will contribute to the firing of the next neuron and the next one, until more than 10 000 other cells are fired simultaneously. The space where the axon of one neuron establishes a connection with the dendrite of another neuron is called the synapse, or synaptic gap (Chudler 1999a:12, Chudler 1999b:7, Le Doux 1998:139, Howard 1994:36).

All stimuli of the environment cause sensations such as pain and other feelings. Thought, programming of motor and emotional responses, cannot be understood without knowledge of the fascinating process of communication between neurons. The brain is a collection of about ten billion interconnected neurons. Neurons are specialised cells that use biochemical reactions to receive, process and transmit information. These specialisations include a cell membrane, which convey nerve signals as electrochemical pulses, the dendrite which receives and delivers the signals, the axon acting as the conducting cable of electrical signals, and points of synaptic contacts, where information can be passed on from one cell to the other (Cardoso 1998, Fraser 1998). Neurons have the ability to gather and transmit electrochemical signals. Neurons share the same characteristics and have the same parts as other cells, but the electrochemical aspect lets it transmit signals over long distances (Freudenrich 2004a). The neuron as illustrated in figure 37 consists of the following: a cell body, a nucleus, dendrites, axon, myelin and a pre-synaptic terminal.

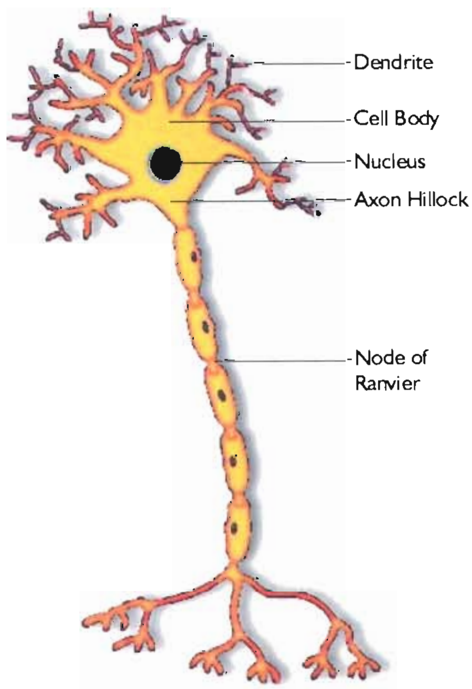



**Figure 37 The neuron (Lundbeck Institute 2002)**

#### 4.4.1.1 The cell body

This is the main part and has all of the necessary components of the cell, such as the nucleus (contains DNA), endoplasmic reticulum and ribosomes (for building proteins) and mitochondria (for making energy). When the cell body dies, the neuron dies (Freudenrich 2004a).

#### 4.4.1.2 The dendrites

The thick extensions of the cell body are called dendrites. These small, branch-like projections of the cell make connections to other cells and allow the neuron to communicate with other cells or to perceive the environment. One or both ends of the cell can have dendrites (Freudenrich 2004a). Most neurons have multiple dendrites, which are short and typically highly branched (Lundbeck Institute 2002). Dendrites gather information and conduct impulses towards the cell body (Hannaford 1995:20). Dendrites are incoming communication links that delivers messages to the cell body. These messages are then taken away from the cell body via the axon to the pre-synaptic terminal also known as outgoing communication links, by an electrochemical process called neurotransmission (Chudler 1999a:7, Howard 1994:36).

#### 4.4.1.3 The axon

The axon is a long, thin, cable like fibre that conducts nerve impulses along the length of the cell, away from the cell body to another neuron, muscle or a gland (Freudenrich 2004a, Hannaford 1995:20).

#### 4.4.1.4 The glial cells

Glial cells are an important component in the central nervous system. Glial cells do not have a direct role in neurotransmission, but do play a supporting role that helps define synaptic contacts and maintain the signalling abilities of neurons. The total number of glial cells is about three times more than the neurons. Glial cells are smaller than neurons and do not have dendrites and axons. The glial cells are responsible for modulating the rate of nerve impulse propagation and controlling the uptake of neurotransmitters (Lundbeck Institute 2002).

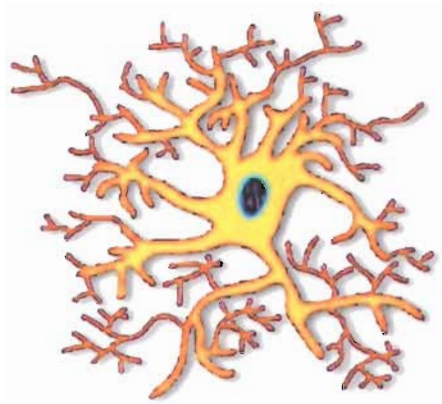


**Figure 38 The glial cell (Lundbeck Institute 2002)**

**4.4.1.5 The myelin**

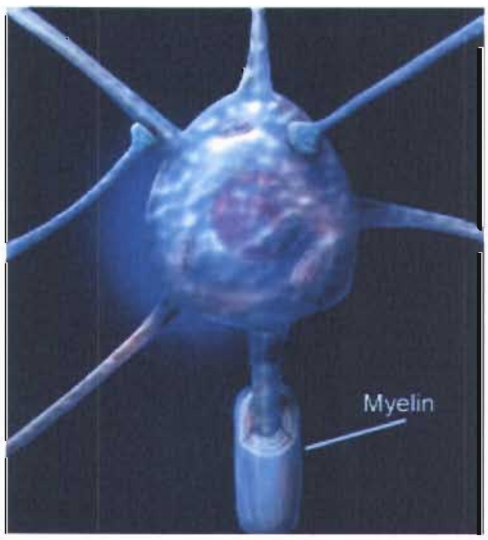



**Figure 39 Myelin on the axon of a neuron (Lundbeck Institute 2002)**

Myelin is the soft, white, partially fatty material which makes up the sheath surrounding a nerve axon. It insulates the axons and enables signals to be conducted at a faster rate (Lundbeck Institute 2002). By repeatedly activating a neuron a multi-layered, white phospholipid segment called myelin is formed over the axon. The more the neuron is activated the more myelin is laid down and the transmission and processing speed increases (Hannaford 1995:20). Axons can be covered with a thin layer of myelin, like an insulated electrical wire, but it depends on the type of neuron. Neurons covered with myelin are typically found in the peripheral nerves (sensory and motor neurons), while non-myelinated neurons are found in the brain and spinal cord (Freudenrich 2004a).

#### 4.4.1.6 The synapses

The synapse, as illustrated in figure 40, is the place where neurons make electrochemical contact. It forms bridges that carry impulses from one neuron to another (Ayres 1983:44). A neotransmitter is a chemical messenger that passes signals between neurons, and thus allows the body to function properly. Electrical signals are converted to chemical signals at the synapse. This is known as neurotransmission at the synapse (Lundbeck Institute 2002).

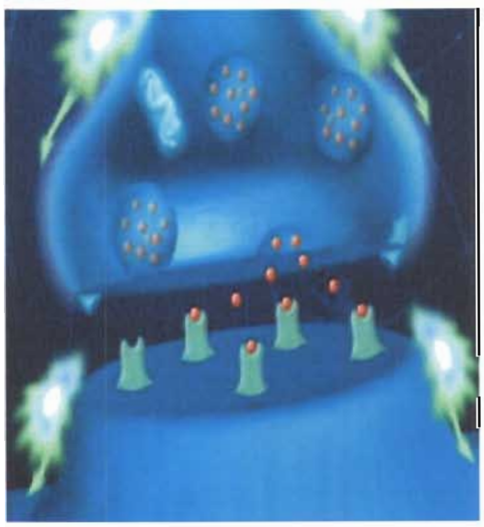


**Figure 40 Neurotransmission at the synapse (Lundbeck Institute 2002)**

When neurotransmitters bind to the receptors on the other side of the synapse, it can cause either an excitation or an inhibition of cells (Le Doux 1998:218). Molecules inside the neurons are constantly moving around, manufacturing the neurotransmitters within the cell body and transporting it down to the area where it can be used in communication across the synapses (Le Doux 1998:154).

#### 4.4.1.7 The synaptic cleft

The synaptic cleft is a sub-microscopic space (typically 50 nm wide) between the neurons, a nerve impulse is transmitted by a neurotransmitter across this space. The neurotransmitter molecules diffuse across the synaptic cleft and combine with receptor post-synaptic endings resulting in an electrical response in the post-synaptic neuron (Chudler 1999b:9, Lundbeck Institute 2002). In order for the synaptic cleft to work properly it should always be clean and in a good condition (Howard 1994:37).

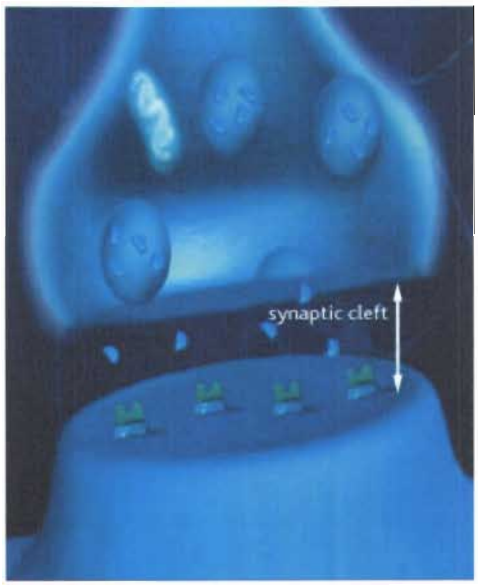



**Figure 41 The synaptic cleft (Lundbeck Institute 2002)**

### 4.4.2 The biological neuron

The human brain is made up of billions of nerve cells called neurons. These neurons engaged in transmitting the specialised electrical messages that enables the mind and body to sense and respond to stimuli encountered each moment of every day. Neurons that are part of the greater information processing system are more flexible than the most advanced computer. Alone, a neuron is an adaptive computer that is constantly changing with new input (Hannaford 1995:24).

A neuron's dendritic tree is connected to neighbouring neurons. When one of these neurons fire, one of the dendrites will received a positive or negative charge. The strengths of all the received charges are added together through the processes called spatial and temporal summation. Spatial summation is when several weak signals are converted into a single large one, while temporal summation converts a rapid series of weak pulses from one source into one large signal. The aggregate input is then send to the soma or cell body. The soma and the enclosed nucleus do not play a significant role in the processing of incoming or outgoing data, but are responsible for continuous maintenance to keep the neuron functional. The axon hillock is the part of the soma that is concerned with the signal. When the aggregate input is greater than the axon hillock's threshold value, the neuron will fire, and an output signal is transmitted down the axon. The output signal is always constant irrespective of the fact that the input was just above the threshold, or a hundred times as great. The many divisions in the axon will not affect the output strength, it reaches each terminal button with the same intensity it had at the axon hillock (Fraser 1998).

The physical and neurochemical characteristics of each synapse will determine the strength and polarity of the new input signal. This is where the brain is most vulnerable. Changing the constitution of various neuro-transmitter chemicals can increase or decrease the amount of stimulation that the axon will have on the neighbouring dendrite (Fraser 1998).

A short description of the operating principles of a neuron follows, refer to figure 42.

The neurons receive nerve signals from the axons of other neurons, and most of these signals are delivered to the dendrites (1). The signals that are generated by a neuron are carried away from the cell body (2), where the nucleus is contained (2a), which in turn is the core of genetic information. The axons (3) are the main conducting unit of the neuron and the axon hillock (2b) is the site where the cell's signs are initiated. Schwann cells (6) are not part of a nerve cell, but are a type of glial cell. These cells perform the important function of insulating axons by wrapping the membranous processes around the axon in a tight spiral, forming a myelin sheath (7), a fatty, white substance which helps axons transmit messages faster than axons without myelin. The myelin is broken at various points by the nodes of Ranvier (4). Branches of the axon of one neuron (pre-synaptic neuron) transmit signals to a neighbouring neuron (post-synaptic cell) at a place called the synapse (5). The branches of a single axon can form synapses with as many as thousand other neurons (Cardoso 1998).

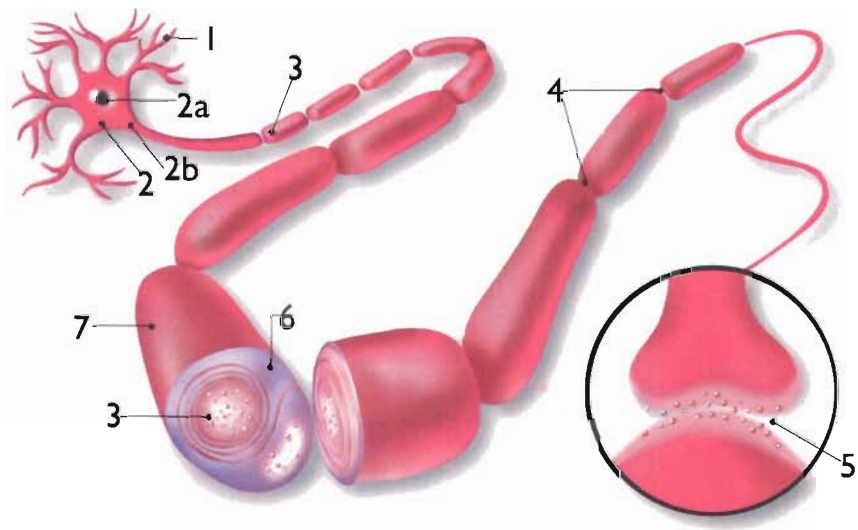



**Figure 42 The structure and operating principles of a neuron (Cardoso & Sabbatini 1999)**

## 4.5 The senses

Humans experience the environment via the eyes, ears, taste buds, nose and skin, and from the body via nerve receptors on each muscle and organ (Hannaford 1995:31). Every muscle, joint, bit of skin, and organ in the body sends sensory input to the brain. Sensations are therefore the 'food' given to the nervous system, without it the nervous system cannot develop adequately (Ayres 1983:33). Knowledge from the outside world triggers the senses; the information is then sent to the brain via neurons and neurotransmitters. This knowledge is then processed by the brain and sent back to the senses via neurons and neurotransmitters so that the body can respond to it (Fourie

1998:5). Information is absorbed by taking in sensory data from the messages sent to the brain via different nerves (Vermeulen 2000:5). Memory is the end result of good-quality sensory perception (De Jager 2001:58).

### 4.6 The sense of seeing

Previous research programmes have shown that the human eye is the most important sensory organ in the body (Rowell 2002:9). Massive amounts of information from eye retinas are processed rapidly by the brain (Deckert n.da). The multitude of nerve impulses received from the photoreceptor cells in the retina is assimilated in the brain to form an image (Scott 2003). In order for this to happen there are thousands of parallel paths in each layer of sensor cells that allow information to be partially processed in the path from the eye to the brain. Once the information is in the brain the final images are processed and then samples of the scenes may go into the memory (Deckert n.da).

#### 4.6.1 The visual pathway

The visual pathway begins at the photoreceptors in the retina and ends at the visual cortex of the cerebral hemispheres (Scott 2000). The visual sense relies entirely on reflected light (BioMedia 2003). Light rays reflected by objects enter the eyes, form an image and transmit information to the brain for processing (BioMedia 2003, Montgomery 1994). In some sensory pathways in the body, there is at most one synapse between a receptor and a sensory neuron that delivers information to the central nervous system (CNS). In the visual pathway, the message must cross two synapses (photoreceptor to bipolar cell and bipolar cell to ganglion cell) before it continue towards the brain. The synaptic delay is because of the extra synapse, but it provides an opportunity for the processing and integration of visual information before it leaves the retina (Kimball 2003a, Scott 2000).

#### 4.6.1.1 Retinal processing

Inside the retina, each photoreceptor monitors a specific receptive field. The retina contains about 130 million photoreceptors, 6 million bipolar cells, and 1 million ganglion cells. There is a great amount of convergence at the beginning of the visual pathway; but regardless of the amount of convergence, the ganglion cells each monitor a specific portion of the visual field. There is a difference in the degree of convergence between the number of rods and cones (Scott 2000). There are almost one thousand rods that pass information via its bipolar cells to a single ganglion cell. The ganglion cells monitoring the rods are pretty large and are called M cells, or magno cells (Scott 2000). These cells have large dendritic arrays and receive information from a large radius of bipolar cells. M-cells are found in the peripheral retina and are not colour sensitive, relative insensitive to detail and coarse grained (Molavi 1997a).

Information on general form, motion and on shadows under dim light conditions is provided by these cells. All the convergence occurs at the beginning of the visual pathway, therefore, when an M cell becomes active, it indicates that light has arrived in a general location rather than in a specific spot. Ganglion cells vary its activity respective to the pattern of activity in the sensory field. This field is generally circular, and a ganglion cell usually responds to stimuli that arrive in the centre of that field rather than light striking on the edge of the field. On-centre and off-centre neurons, meaning exactly what the name implies, indicate which portion of this sensory field is being illuminated (Scott 2000).

Cones, unlike rods, show very little convergence and are typically a 1:1 ratio with ganglion cells. Ganglion cells that monitor cones are called P cells, or parvo cells. These cells are smaller but more numerous than the M cells, it is active in bright light and provides the information from the edges, fine detail and from colour. Because there is only a little bit of convergence occurring, the activation of the P cell indicates that light has come from one location, the opposite of the M cells activation. As a result of this specific arriving location, cones provide more information about images than rods. As an example it will be explained in photographic terms. Pictures formed by rods have a grainy and coarse appearance and the details of that picture are blurred. The cones produce a fine-grained picture that is sharp and very clear (Scott 2000).

### 4.6.1.2 Central processing of visual information

Axons from the entire ganglion cell population converge onto the optic disc, enter into the wall of the eye, and head to the diencephalon as the optic nerve. Each of the optic nerves, one from each eye, reaches the diencephalon at the optic chiasm, a partial crossing of axons. After the chiasm, the rearranged combinations of ganglion cell axons are called the optic tract (University of Toronto 2003). At this point inside the brain the fibres proceed to the lateral geniculate nucleus (LGN), where the nerve fibres from the inside half of each retina cross to the other side of the brain, but the nerve fibres from the outside half of the retina stay on the same side of the brain. This happens to both optic nerves entering into the chiasm. Refer to figure 43.

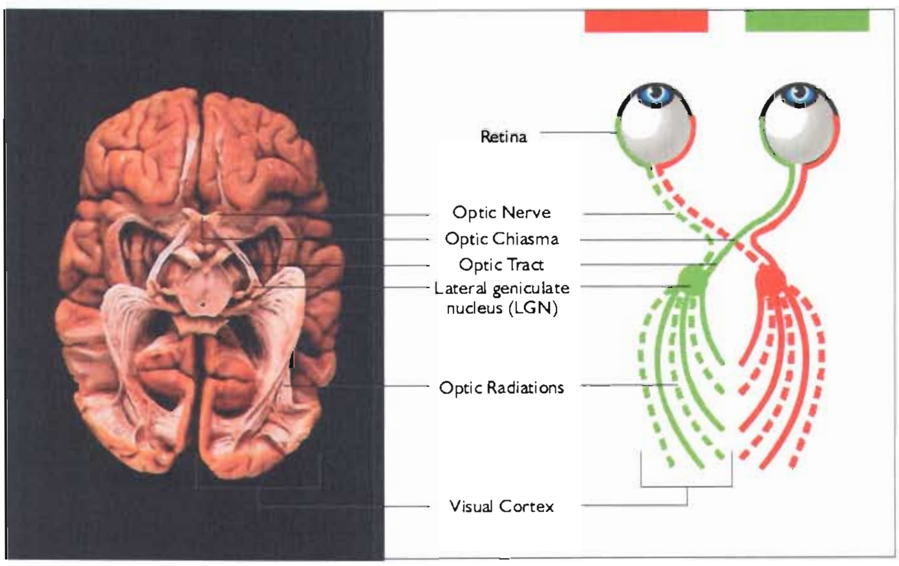



**Figure 43 Illustration of the central processing of visual information (Kaiser 2002a, Terence *et al* 2004)**

All signals entering the brain from the optic nerves enter the LGN and undergo some processing before moving on to the various visual areas of the cerebral cortex (Fraser 1998). The LGN is really part of the thalamus, nothing gets into the cortex without synapsing in the thalamus first. The LGN acts as a switching and processing centre that relays the visual information to reflex centres in the brain stem as well as to the cerebral cortex. From the LGN, the fibres eventually reach the occipital lobe, at the back of the brain. This is where vision is interpreted and is called the primary visual cortex, also known as $V_1$, striate cortex or area 17. From there, some of the visual fibres go to other parts of the brain to help control eye movements, response of the pupils and iris and some signals go to 'higher' areas of the cortex that process more global aspects of what is seen such as shape, colour or motion (Bianco 2004, Kaiser 2002b, Montgomery 1994, Molavi 1997a, Scott 2000, University of Toronto 2003).

#### 4.6.1.3 The visual pathway from the front of the eye to the back of the brain

In order to consolidate the route of the visual stimuli it is summarised as follows with reference to figure 44.

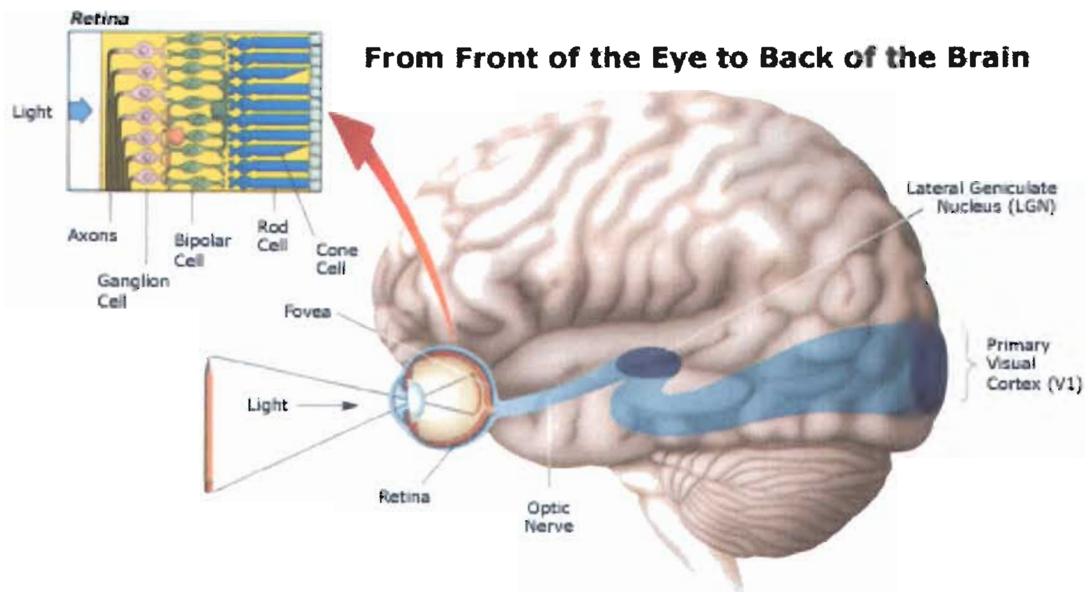



**Figure 44 An illustration of the location of $V_1$ (Montgomery 1994)**

As light rays are reflected from an object, for example a pencil, it enters the eye by passing through the lens. An inverted image of the pencil is then projected by the lens onto the retina at the back of the eye. Signals are produced by photoreceptor cells called rods and cones (Montgomery 1994). The information then leaves the eye by way of the optic nerve. There is a partial crossing of axons at the optic chiasm. After the chiasm, the axons are called the optic tract. The optic tract wraps around the midbrain to get to the lateral geniculate nucleus (LGN), where all the axons must synapse. From there, the LGN axons fan out through the deep white matter of the brain as the optic radiations, which will ultimately travel to the primary visual cortex, at the back of the brain (Molavi 1997b). Signals representing particular characteristics of the pencil then travel to selected areas of the primary visual cortex (V1), which curves around a deep fissure at the back of the brain (Montgomery 1994). An expanded view of the primary visual cortex ($V_1$) is shown in figure 45 and gives the location of several important visual areas. The left part of the figure shows a top view of one hemisphere of the brain and the right part shows a side view (University of Toronto 2003).

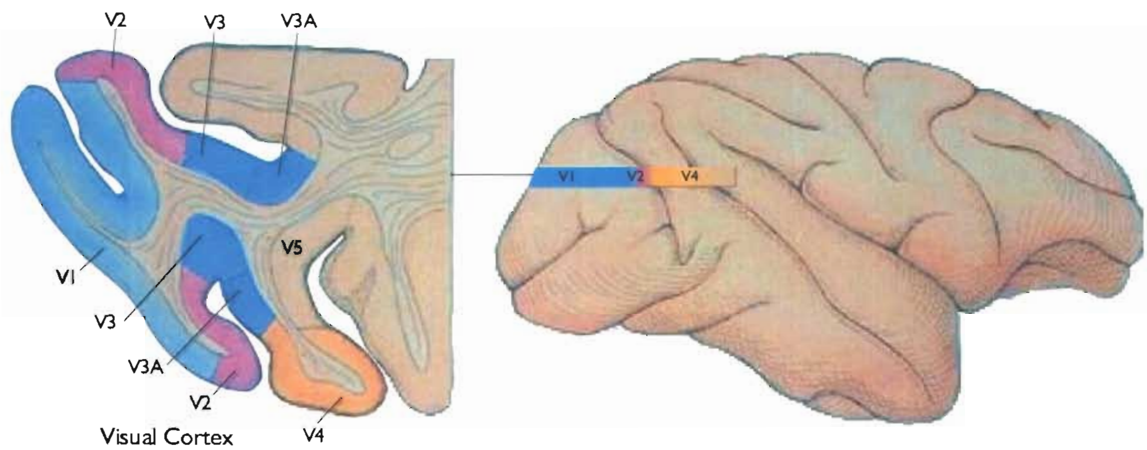



**Figure 45 Schematic illustrations of several important visual areas (University of Toronto 2003)**

The axons of the neurons in the LGN are sent directly to the primary visual cortex (V1, striate cortex or area 17). The path of this visual information courses through the white matter of the temporal and parietal lobes (Molavi 1997b). Area V1 is also layered like the LGN. After the axons reach V1 it terminates primarily in a sub-layer of cortex, the

LGN inputs primarily to layer four. There are about a hundred million cells in V1 of each hemisphere; with so much information organization is critical. Because of this; different kinds of information are stored separately. For example the parvocellular input is stored to a lower subdivision of layer four in V1 and the magnocellular input to an upper subdivision of layer four in V1 (Molavi 1997b). The layers of V1 are specialised, layer four has been expanded into four sub-layers namely, 4A, 4B, 4Ca and 4Cb. From figure 46 it can be seen that layer 4A is a dark layer while layer 4B is very pale because it is full of myelin. Layer 4B is visible without a micro-scope and form the line of Gennari. This white stripe is what gives V1 the other name of striate cortex. Layer 4C is important because most of the input from the LGN is received there. The transition area between V1 and V2 is where stripe 4B suddenly disappears into a more compact layer four. The LGN axons enter into layer 4C. As the signals from the LGN are transmitted to upper layers of the cortex, the information from the eyes are mixed and binocular vision is created, but in layer 4C the two eyes are still separate (Molavi 1997b).

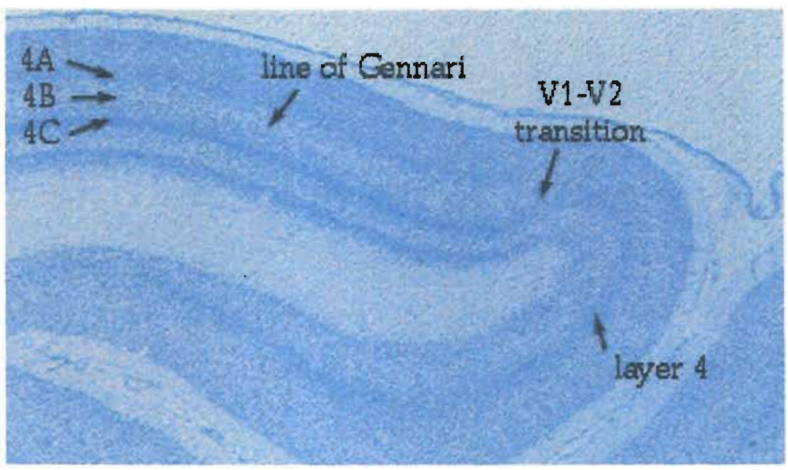



**Figure 46 Showing different layers in V1 (Molavi 1997b)**

### 4.7 Electro-chemical function

The human body is one of the most complex electrical systems. All sensory information is changed into electrical signals and passed to the brain via nerve fibres (Dennison 1981:80). The human brain's electrical rhythms range from one to twenty-five per second; compare this to the heart that beats about once every second (Jensen 1996:41). A low frequency electromagnetic field is produced by the body. When the brain is involved in different tasks it exhibits different chemico-electric frequencies (Executive edge: A personal mental power tool 1999:56). A great deal of history is involved in the definition, naming and use of these frequency bands, it is named using Greek letters. The brainwaves from slowest to fastest are called delta, theta, alpha, beta and gamma. Hans Berger, the discoverer of the EEG in humans, observed all the frequency bands known today, except the 40 Hz 'gamma' band, and described many of its basic properties (Collura 1997, Newman 2000) as discussed in the next chapter.

### 4.8 Summary

Since more than 90 percent of all information sent to the brain is visual it is important to understand the visual pathway in the brain as this is where actual seeing takes place. By investigating the structure of the brain it was determined that the part of the brain responsible for processing visual information is situated in the occipital lobe. The visual senses rely heavily on reflected light. An image formed by light rays that are reflected by objects enters the eye and are transmitted to the brain where it is processed. Sensory information is changed into electrical signals that are transmitted to the brain via nerve fibres. Each activity by the brain exhibits different electrical rhythms. By evaluating the activity of the brain caused by visual stimulus, it is presumed that it would be measurable by evaluating brain frequencies involved with the particular activity. The method of measurement will be discussed in the next chapter.

# CHAPTER 5 – THE ELECTROENCEPHALOGRAM (EEG) AND THE EXPERIMENTAL LAYOUT

## 5.1 Introduction

EEG is an acronym for Electroencephalograph. This is a recording ('graph') of electrical signals ('electro') from the brain ('encephalo'). The recordings are made on chart paper that moves underneath pens that are connected to galvanometers that read the electrical signals from electrodes appropriately placed on the scalp. The electrodes only receive electrical signals naturally generated by the brain. The electrical signals are then amplified and displayed on a computer, or other suitable instrument (Collura 1997, Biocybernaut Institute 1997). Very small charges pass between the nerve cells, accompanied by changes in electrical potential (Davidmann 1998:6). It consists of waves that vary in time, much like a sound signal, or a vibration. As such, it contains a frequency component that can be measured and analyzed, and these frequency components have interesting and valuable properties which will be discussed as part of this chapter (Collura 1997, Biocybernaut Institute 1997).

## 5.2 The history of the discovery of the Electroencephalogram

Dr. Hans Berger, an Austrian psychiatrist was the first to record electroencephalographs from humans. After gaining a doctorate at the University of Jena in 1897, Berger conducted experiments with animals which were inconclusive by 1910, but after World War I, Berger decided to look for the EEG in the human brain. In the early years of the 1920's Berger obtained results for the first time in subjects who had skulls with gaps under the skin where bone was missing. Recordings were made on moving photographic paper with a wavy spot of light. This was how Berger found the regular waves at about 10 cycles per second and named it the Alpha waves because it was the first waveforms isolated in the human EEG (BioCybernaut Institute 1997).

Berger published a paper in 1929 based on the research and announced that it was possible to record the feeble electric currents generated on the human brain, without opening the skull, and to depict it graphically onto a strip of paper (Sabbatini 1997).

**Figure 47 Dr. Hans Berger (BioCybernaut Institute 1997)**

Berger named this new form of recording the electroencephalogram (EEG), and this activity changed according to the functional status of the brain such as sleep, anaesthesia and in certain nervous diseases such as epilepsy (Sabbatini 1997).

This discovery laid the groundwork to the field that today is known as clinical neurophysiology (Sabbatini 1997). Berger's electrodes were too large to make detailed topographical studies of the EEG, but a British scientist, Walter, proved that a larger number of electrodes, having a small size, could be pasted onto the scalp to get readings of the electrical activity of the brain. By using this to build bi-dimensional maps of the EEG activity over the brain surface, Walter invented the toposcope in 1957. It was very complex and expensive and therefore did not achieve commercial success or widespread use. The topographic study of brain electrical activity was born again only when fast desktop computers became available in the 1980's. At the end of the 1980's the use of computers made it possible to record a great number of digitized channels of EEG simultaneously, and a new technique for EEG brain topography was developed (Sabbatini 1997). Figure 48 gives an example of the EEG topographic map.

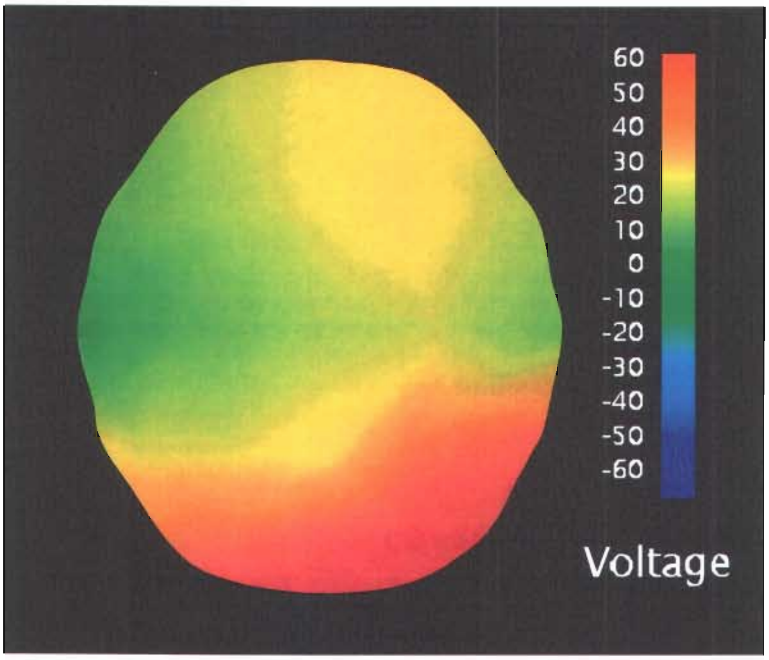



**Figure 48 EEG topographic map (Sabbatini 1997)**

## 5.3 The brain is electric

Technical developments in the field of electrical measurement and recording in the last quarter of the 19th century made possible one of the greatest triumphs of modern neuroscience, the discovery that the human brain has a continuous electrical activity, and that it can be recorded (Sabbatini 1997). Figure 49 illustrates what can be seen if it was possible to perceive and capture a still image of the electrical information 'flowing' from the scalp. The squiggly line represents EEG from a single point on the scalp, such as the EEG acquired from a single electrode. An 'isosurface' is a graphical rendering technique available to make a series of twenty or so squiggly lines, representing electrical data from the scalp, appear more readable to the neuro-diagnostic technician. The squiggly line and the isosurface itself are colour coded with red corresponding to higher values in microvolt and blue as the lower values across a range of about 10-100 microvolt peak-to-peak for a normal EEG. In reality, the electrical activity extends only a short distance (a few millimetres) from the scalp before it becomes undetectable. This image is simply intended as a sort of conceptual graphic for understanding these isosurfaces (Sale 1996).

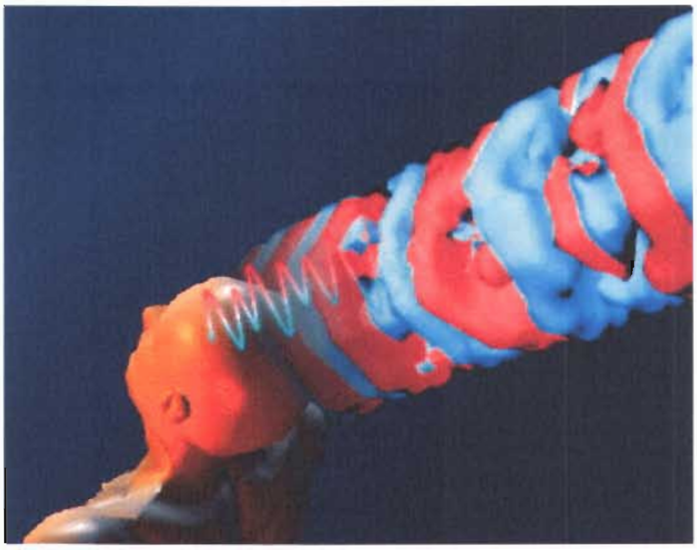


**Figure 49 Electrical information 'flowing' of the head (Sale 1996)**

## 5.4 How brain rhythms are generated

Brainwaves come from cells in about the top quarter inch of the cerebral cortex, from millions of cells working together. The EEG can be compared to a symphony, which is a complex mixture of sounds changing in time and place (Newman 2000).

Populations of cells generate rhythms when it is depolarized in synchrony. This activity occurs primarily in the upper four layers of the outer layers of the cerebral cortex. When an EEG rhythm is present it indicates that there is some brain activity occurring in terms of millions of cells acting together, in a synchronized fashion. The observed brainwave frequencies must be thought of as a by-product of normal brain function, but not a brain signal in itself. The brain does not communicate using the EEG; rather, it is a secondary measure such as vibration measured from a machine. Therefore, the brain does not produce alpha waves for any purpose. It is produced as a result of certain types of brain activity, which can be recognised and taken advantage of, by learning what it represents (Collura 1997).

There are over 100 billion cells in the brain, organized into many different regions, all doing different things, all acting simultaneously. The brain is not a computer; it is actually an assemblage of millions and billions of computers. Therefore, at any time and any particular location, the brain may produce a combination of frequencies. Variations in time and space (seen as different places on the scalp) are important to understand. EEG signals are seen to grow larger and smaller, in time, generally showing moment-to-moment variation of all times. Alpha is almost always seen in spindles and bursts of from about 1/5 second, up to one or two seconds in length, and almost never as a continuous wave. It is the production of more, or larger, bursts of rhythmic activity that is associated with it being a higher 'amount' of that component. Beta, for example, may occur in very small bursts, of 1/10 second or less, so that it comes and goes very rapidly (Collura 1997).

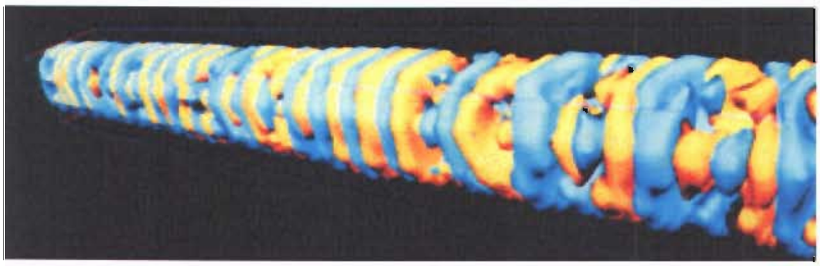


**Figure 50 Raw Alpha Waves (Sale 1996)**

Figure 50 shows alpha waves acquired from a human subject, relaxed, eyes closed, comprising roughly three to four seconds of activity. This particular subject had especially clean and strong alpha activity with closed eyes (Sale 1996).

Spatial distribution can be seen in all components. Since the brain consists of broadly identifiable areas frontal, parietal, occipital (visual), temporal (hearing, language), rhythms are seen to be associated with the particular involved area. Electrode placement is therefore important when measuring particular rhythms. The basic EEG rhythms are summarized briefly in the tables to follow, and are discussed with regard to the typical distribution on the scalp, subject states, tasks and physiological correlates. It should only be taken as a general 'roadmap' (Collura 1997).

## 5.5 Brain wave frequencies

### 5.5.1 Delta waves (0.1 – 3 Hz)

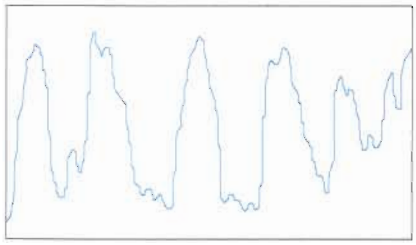


**Figure 51 Delta waves (Crossroads Institute n.d)**

The lowest frequencies are delta. Delta waves are involved with the ability to integrate and let go. It reflects the unconscious mind. It tends to be the highest amplitude and the slowest waves. Delta waves are increased in order to decrease the awareness of the physical world. Delta is also used to access information in the unconscious mind. Peak performers can decrease delta waves when peak performance is required (Crossroads Institute n.d).

**Table 6 Characteristics of Delta rhythms**

| DELTA (0.1 – 3 Hz) | |
|---|---|
| **Distribution** | Generally broad and diffused, may be bilateral, widespread |
| **Subjective feeling states** | Deep, dreamless sleep, trance, unconscious |
| **Associated tasks and behaviours** | Lethargic, not moving, not attentive |
| **Physiological correlates** | Not moving, low-level of arousal |

### 5.5.2 Theta waves (4 – 8 Hz)

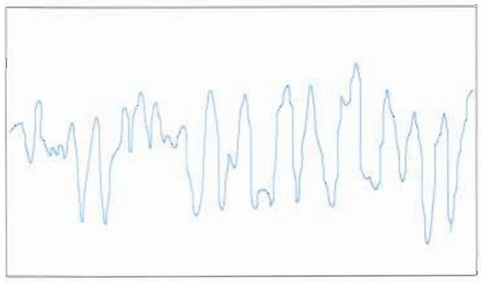


**Figure 52 Theta waves (Crossroads Institute n.d)**

The theta frequency is classed as slow activity. Theta waves are strong during internal focus and reflect the state between wakefulness and sleep. It relates to the subconscious. It is believed that theta reflect activity from the limbic system and hippocampal regions. Theta is observed in anxiety and in behavioural activation and inhibition. When the theta rhythm is functioning normal it mediates adaptive, complex behaviours such as learning and memory (Crossroads Institute n.d).

**Table 7 Characteristics of Theta rhythms**

| **THETA (4 – 8 Hz)** | |
|---|---|
| **Distribution** | Usually regional, may involve many lobes, can be lateralized or diffused |
| **Subjective feeling states** | Intuitive, creative, recall, fantasy, imagery, dreamlike, switching thought, drowsy |
| **Associated tasks and behaviours** | Creative, intuitive, but may also be distracted, unfocused |
| **Physiological correlates** | Healing, integration of body of mind |

### 5.5.3 Alpha waves (8 –12 Hz)

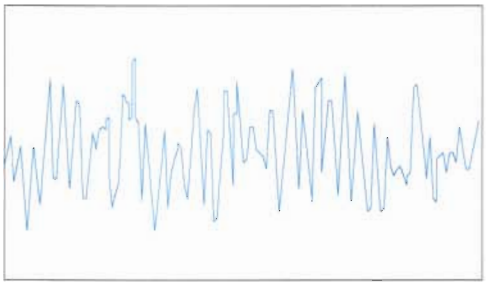


**Figure 53 Alpha waves (Crossroads Institute n.d)**

Good healthy alpha production promotes mental resourcefulness and enhances the overall sense of relaxation and fatigue. In this state any task is completed quickly and efficiently. Alpha appears to bridge the conscious and unconscious. Alpha rhythms are reported to be derived from the white matter of the brain which connects all parts with each other. Alpha is a common state of the brain and occurs whenever a person is awake, but not actively processing information. When alpha waves are within normal ranges good moods and a sense of calmness are experienced. These waves are the strongest over the occipital and frontal cortex (Crossroads Institute n.d).

**Table 8 Characteristics of Alpha rhythms**

| ALPHA (8 – 12 Hz) | |
|---|---|
| **Distribution** | Regional, usually involves entire lobe, strong occipital with eyes closed |
| **Subjective feeling states** | Relaxed, not agitated, but not drowsy, tranquil, conscious |
| **Associated tasks and behaviours** | Meditation, no action |
| **Physiological correlates** | Relaxed, healing |
| ***Low alpha (8 – 10 Hz)*** | Inner-awareness of self, mind/body integration, balance |
| ***High alpha (10 – 12 Hz)*** | Centering, healing, mind/body connection |

### 5.5.4 Beta waves

The beta band has a relative large range, and has been defined as anything above the alpha band:

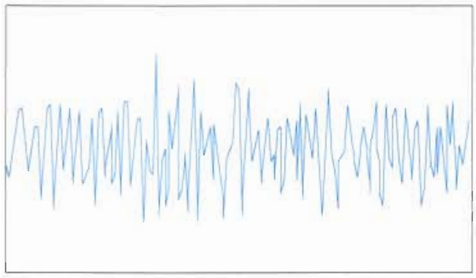


**Figure 54 Beta waves (Crossroads Institute n.d)**

Beta activity is a fast activity. It is usually seen frontally, on both sides in symmetrical distribution. This is the state that most of the brain is in when a person has open eyes, listening and thinking during analytical problem solving (Crossroads Institute n.d).

**Table 9 Characteristics of different Beta rhythms**

| BETA (above 12 Hz) | |
|---|---|
| ***LOW BETA (12 – 15 Hz)*** | |
| **Distribution** | Localised by side and by lobe (frontal, occipital, etc.) |
| **Subjective feeling states** | Relaxed, yet focused, integrated |
| **Associated tasks and behaviours** | Lack of focused attention |
| **Physiological correlates** | Is inhibited by motion |
| ***MIDRANGE BETA (15 – 18 Hz)*** | |
| **Distribution** | Localized, over various areas, may be focused on one electrode |
| **Subjective feeling states** | Thinking, aware of self and surroundings |
| **Associated tasks and behaviours** | Mental activity |
| **Physiological correlates** | Alert, active but not agitated |
| ***HIGH BETA (above 18 Hz)*** | |
| **Distribution** | Localized, may be very focused |

| | |
|---|---|
| **Subjective feeling states** | Alertness, agitation |
| **Associated tasks and behaviours** | Mental activity, e.g. math, planning, etc. |
| **Physiological correlates** | General activation of mind and body functions |

### 5.5.5 Gamma waves (40 Hz)

Gamma is the only frequency found in every part of the brain. The 40 Hz activity consolidates the required areas for simultaneous processing, when simultaneous information from different areas of the brain needs to be processed. A good memory is associated with well-regulated and efficient 40 Hz activity, but a deficiency creates learning disabilities (Crossroads Institute n.d).

**Table 10 Characteristics of Gamma rhythms**

| **GAMMA (40Hz)** | |
|---|---|
| **Distribution** | Very localized |
| **Subjective feeling states** | Thinking, integrated thought |
| **Associated tasks and behaviours** | High-level information processing |
| **Physiological correlates** | Associated with information-rich task processing |

(Collura 1997)

## 5.6 Measurement of EEG frequency bands

The EEG is usually taken by electrodes (small metallic discs) pasted by an electricity conducting gel to the surface of the scalp. A powerful electronic amplifier is used to increase several hundreds or thousands of times the amplitude of the weak signal (less than a few micro volts) that is generated in this particular place. A device called galvanometer, that has an ink-pen attached to its pointer, writes on the surface of the paper strip, which moves continuously at a fixed speed past it. The result is a wiggly 'wave'. A channel is usually made up from one pair of electrodes. EEG recordings can also have from 8 to 40 channels recorded in parallel; this is called multi-channel EEG recordings (Sabbatini 1997). Refer to figure 62.

## 5.7 Electrode placement on the head

The International 10-20 system is the most widely used method to describe the location of scalp electrodes. This system is designed so that the use of additional electrodes can be easily facilitated; the numbering of additional electrodes is built into the system. The system is based on the relationship between the location of the electrode and the underlying area of the cerebral cortex. Each site has a letter, to identify the lobe, and a number or another letter to identify the hemisphere location (Chudler 2004b, Niedermeyer & Da Silva 1983:41). Refer to figures 55 and 56 for examples of the layout of electrodes.

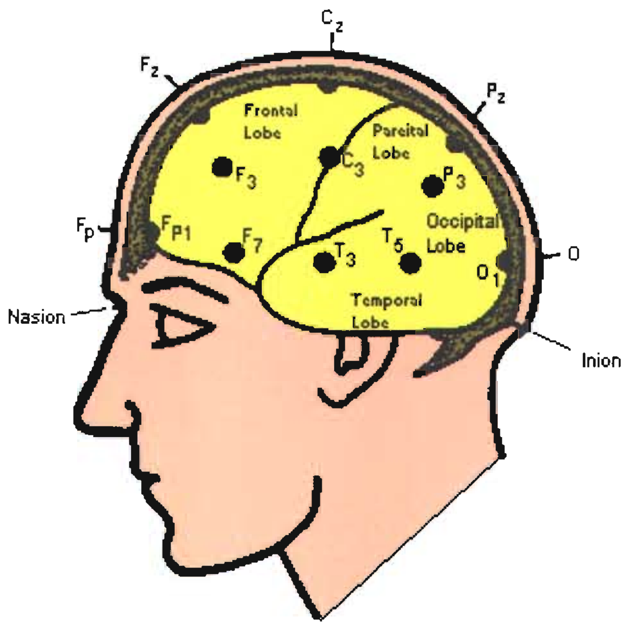



**Figure 55 Electrode placements on the different lobes of the brain (Chudler 2004b)**

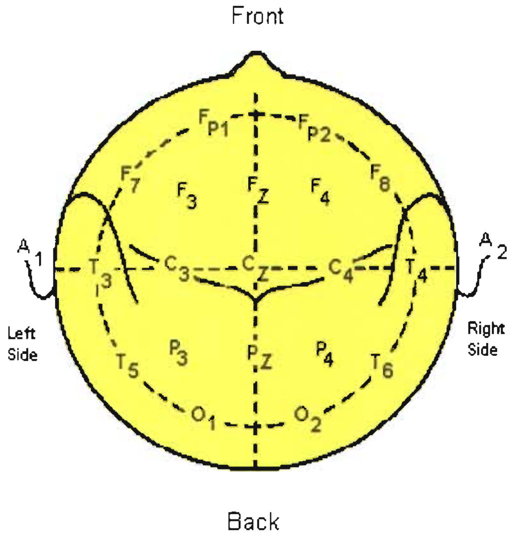



**Figure 56 The electrode placements on the two hemispheres of the brain (Chudler 2004b)**

**Table 11 Summary of the International 10-20 system for electrode placement (Chudler 2004b)**

| Letters used | Position on scalp |
|---|---|
| F | Frontal lobe |
| T | Temporal lobe |
| C | (There are no central lobe in the cerebral cortex, C is just for identification purposes) |
| P | Parietal lobe |
| O | Occipital lobe |
| Z | Electrode placed on the midline |
| Even numbers (2, 4, 6, 8) | Refers to the right hemisphere |
| Uneven numbers (1, 3, 5, 7) | Refers to the left hemisphere |
| Fp | Front polar |
| Nasion | Point between forehead and nose |
| Inion | Bump at the back of the scull |

With reference to figure 57:

- The smaller the number, the closer the position to the middle.
- The '10' and '20' (10-20) system refer to the 10 % and 20 % inter electrode distance (Chudler 2004b).

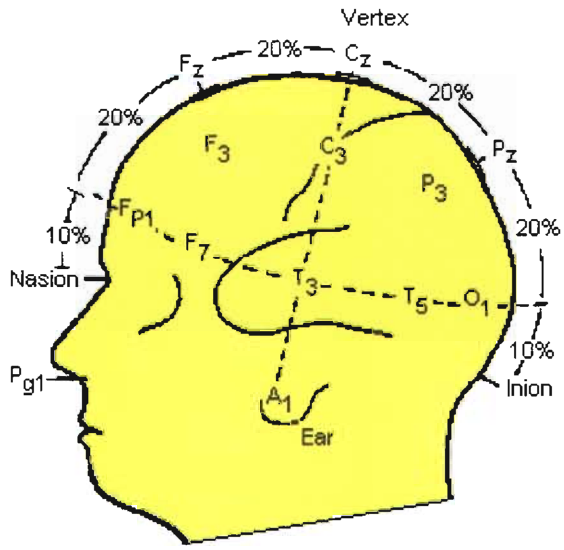



**Figure 57 The 10 % and 20 % inter electrode distance (Chudler 2004b)**

## 5.8 The experimental layout

### 5.8.1 Methodology

The main purpose of this experiment was to evaluate whether there would be any change indicated in the functional status of the brain activity when the observer was exposed to an unshielded light source. To achieve this, EEG measurements were taken across the area of the occipital lobes; this is where visual interpretation takes place. In order to conduct the experiment two observers were tested and are referred to as 'observer 1' and 'observer 2'. The observers were exposed to a bare incandescent lamp at regular intervals. The light source was placed about two meters in front of the observer and about 30 cm above the line of sight. Refer to figure 58 for a schematic layout of the experimental set-up. The stand on which the incandescent lamp was mounted, was adjustable in height in order to keep the distance above the line of sight the same for both observers.

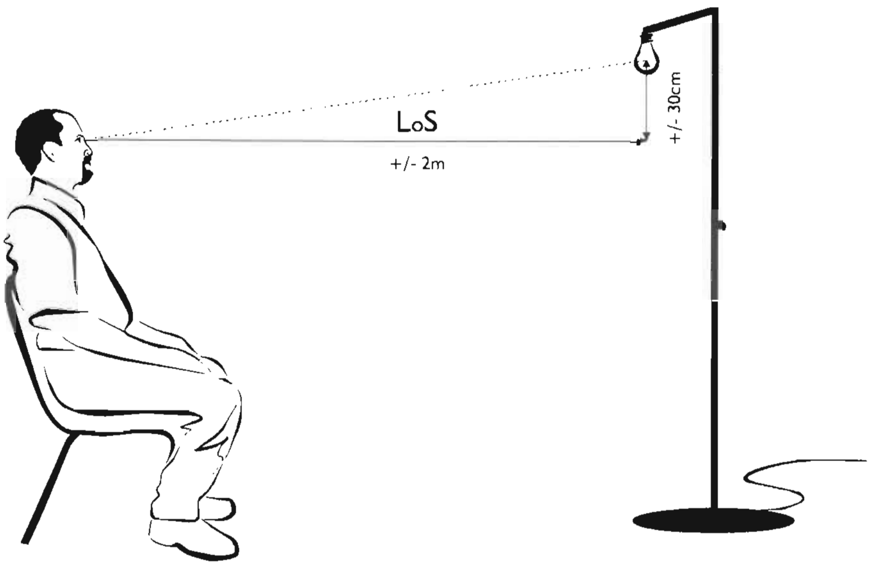



**Figure 58 Layout of experiment**

For reliable EEG readings, each observer's head was measured and then marked with a non-permanent pen in order to indicate the correct location of the electrodes on the observers scalp as illustrated in figure 59.

**Figure 59 Measuring observer's head for electrode placement**

The area on the skin under each electrode was wiped clean of all natural oiliness. The electrodes were covered with a conducting gel and placed into position. A piece of gauze was placed on top of each electrode and in combination with the conducting gel helped to keep the electrode in place. Refer to figure 60 for a picture of an observer with the electrodes attached to the scalp.

**Figure 60 Observer with electrodes attached to the scalp**

An example of the electrode readings as it appeared on the computer screen is shown in figure 62. There were twenty channels and the specific position of each electrode is indicated by the abbreviations as used by the International 10-20 system and is shown by the blue shaded area.

For this experiment the area of the brain where visual stimuli is being interpreted was of great importance and therefore the electrodes attached to the relevant areas on the scalp were evaluated. The channels representing the right hemisphere of the brain that were evaluated for any suppression of the alpha activity were numbers three, four, seven and eight and are indicated by the red shaded lines in figure 62.

For the left hemisphere of the brain, channels eleven, twelve, fifteen and sixteen were evaluated for any suppression in alpha activity and are indicated by the green shaded lines in figure 62. For the precise position of each electrode on the scalp of the two different brain hemispheres, refer to figure 61.

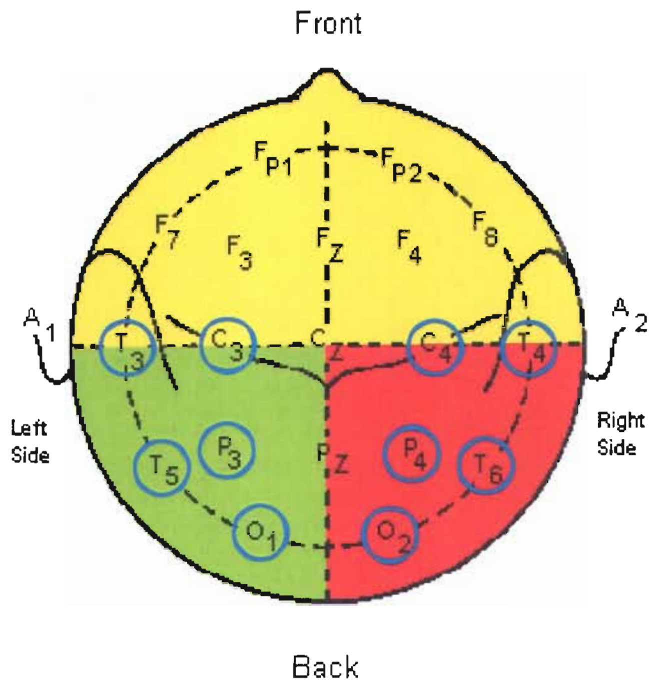



**Figure 61 Exact positions of the electrodes on the right and left brain hemispheres according to the International 10-20 system**

The asterisk-like lines at the bottom of each of the EEG results indicate the time when the light was switched 'on'. In order to determine the suppressing effect of the light source on the alpha activity for each observer it is necessary to evaluate the chosen channels for the period as indicated by the asterisk line. If any suppression of the alpha activity occurred, there will be a reduction in the amplitude of the wave for the duration of exposure to the light source. The complete set of results is available in annexure C, but for explanation purposes some of the results are discussed as part of this chapter.

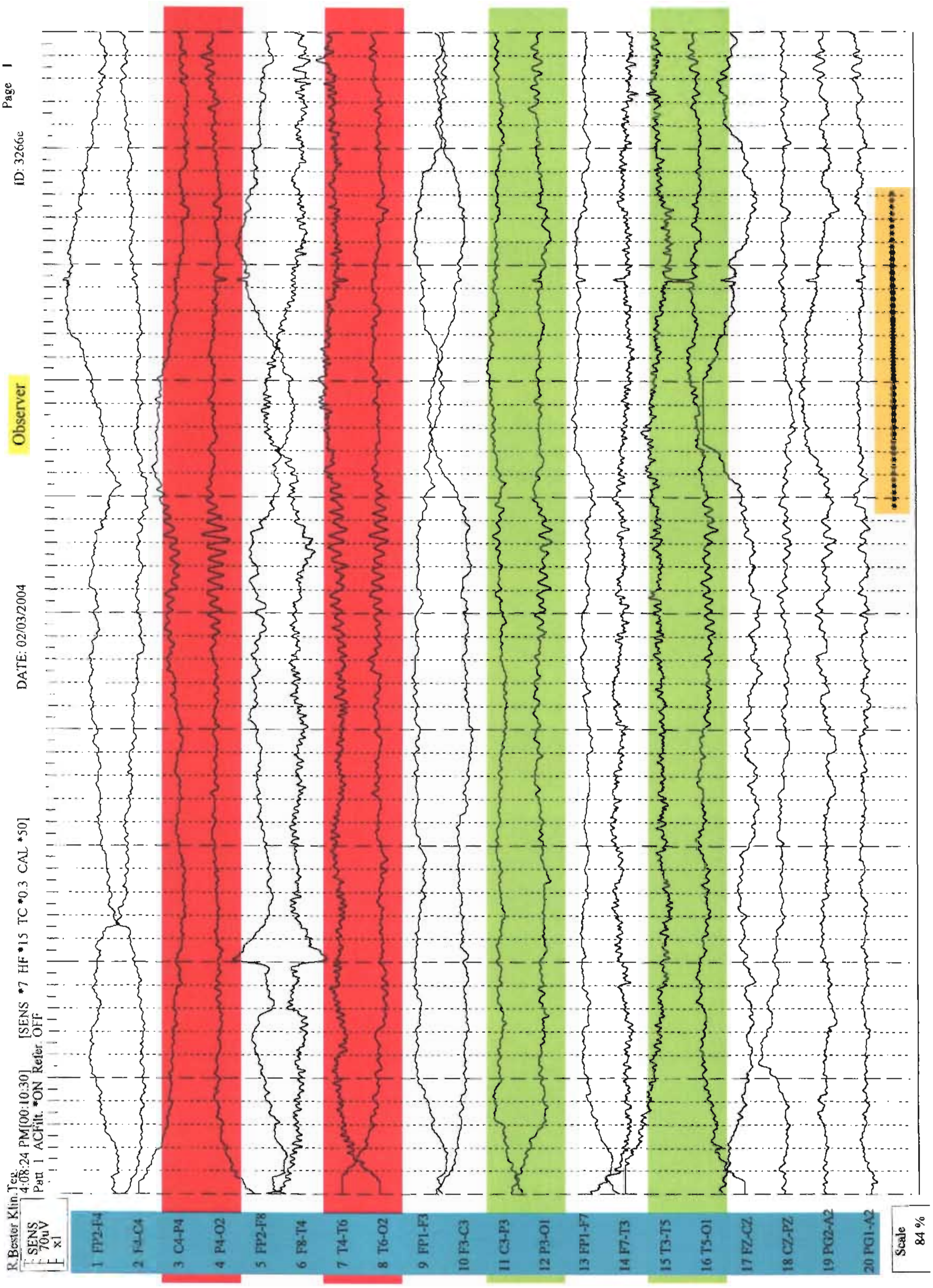



**Figure 62** **EEG result indicating channels used to evaluate the observer's responses**

### 5.8.2 Discussion of results

#### 5.8.2.1 Photosensitivity test

Not all individuals are equally sensitive to light and will therefore not react in the same way when exposed to bright light sources. Therefore, each observer was tested for photosensitivity with a photo-stimulator that operates like a strobe with variable frequency values. The greyish shaded areas as indicated on the following two results indicate the time of exposure to the strobe.

**Observer 1:**

With the frequency at 1 Hz the observer didn't show any response. The frequency was increased to 6 Hz before the observer showed any suppression of the alpha activity. The results of the photo-drive response test done at a frequency of 6 Hz can be seen in figure 63. This indicates that the observer does not have a high rate of light sensitivity. The results of the tests done at 1 Hz and 3 Hz can be seen in annexure C.

**Observer 2:**

The result of the photo-drive response test done at a frequency of 1 Hz is shown in figure 64. The result shows that observer 2 was much more photosensitive. The additional test done at a frequency of 11 Hz is shown in annexure C.

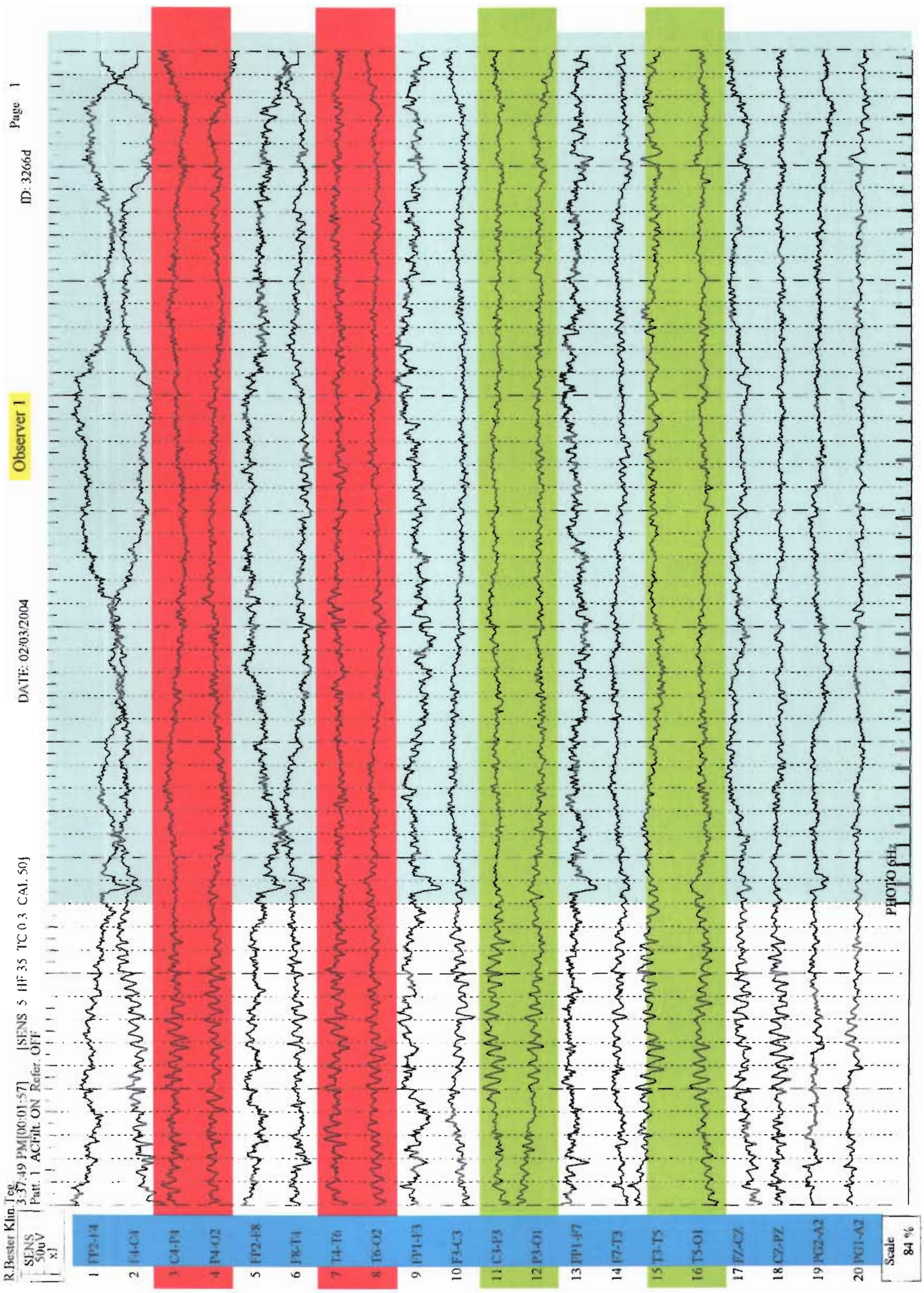



**Figure 63 Observer 1 – Result of photosensitivity test at 6 Hz**

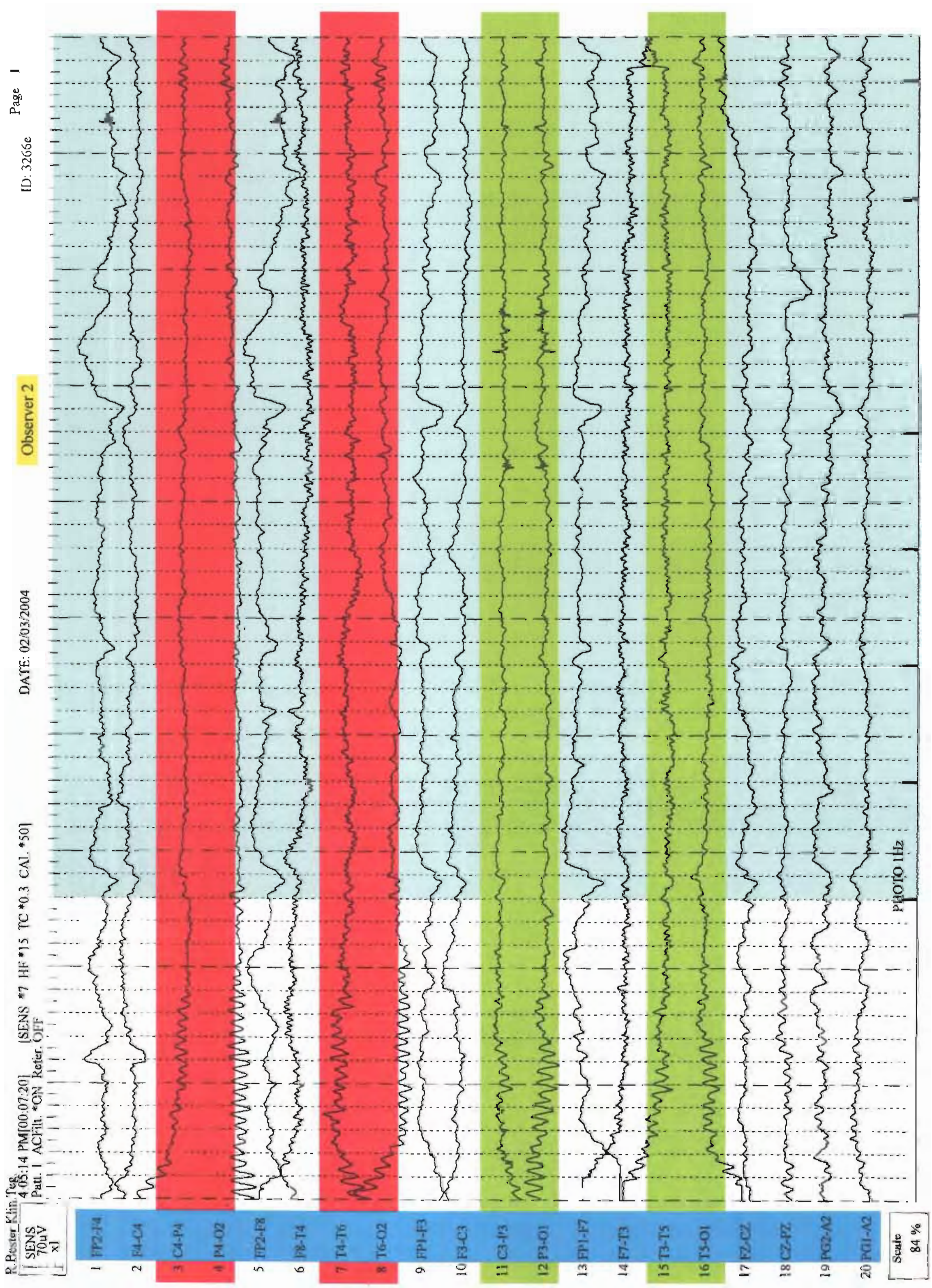



**Figure 64 Observer 2 – Result of photosensitivity test at 1 Hz**

#### 5.8.2.2 Eyes open during the test

When the observer's eyes were open during the test, it was more difficult to recognize alpha-activity suppression. As mentioned previously, most of the brain is in a Beta state when a person has open eyes; this explains the reason for the weaker alpha activity in the affected areas. The results were as follows:

**Observer 1:**

In general, observer 1 had a natural poor alpha activity and in addition a low photosensitivity. Conducting the test with open eyes aggravated the situation as the alpha activity decreased even more and complicated the process of detecting suppression in the alpha activity when the observer was exposed to the light source. The result of the test can be seen in figure 65.

**Observer 2:**

The fact that open eyes decreased the overall alpha activity was diminished as a result of observer 2 having a better general alpha activity and being more photosensitive. The result of the test can be seen in figure 66.

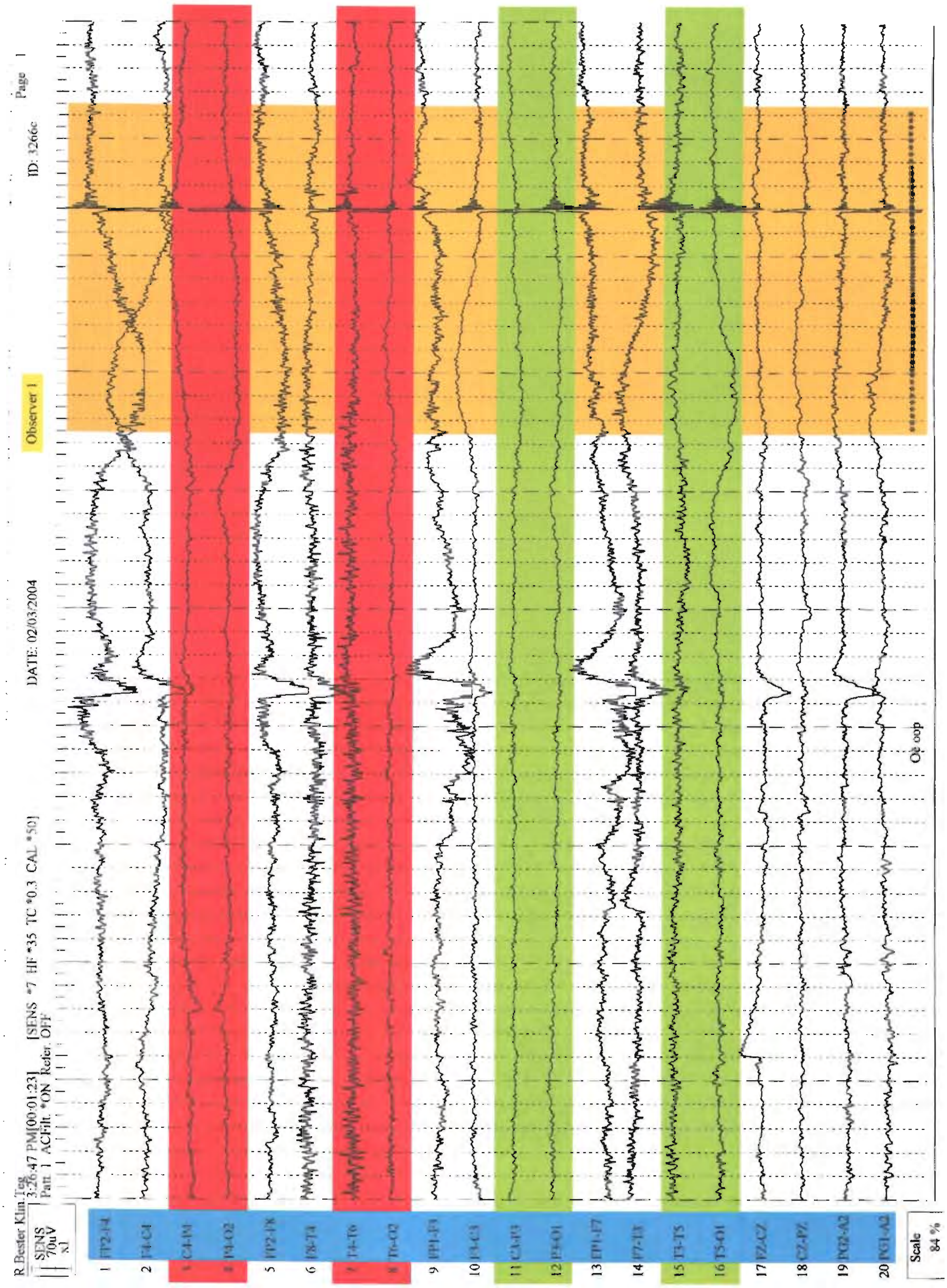


**Figure 65 Observer 1 – Results of test with eyes open**

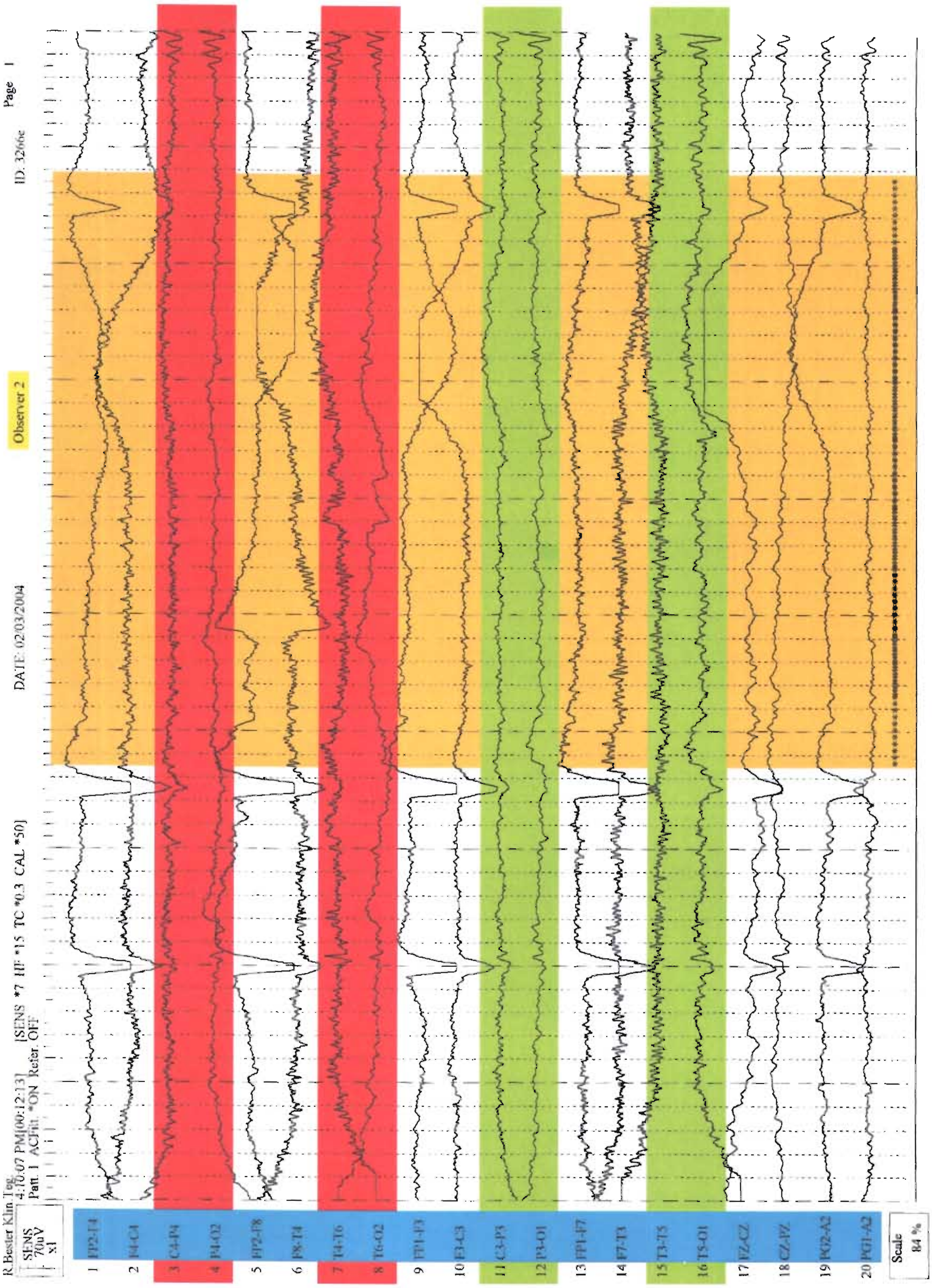



**Figure 66 Observer 2 – Results of test with eyes open**

#### 5.8.2.3 Eyes closed during the test

With reference to table 8, it is stated that the distribution of alpha waves are strong occipital when the eyes are closed, in collaboration with a relaxed feeling without being drowsy.

**Observer 1:**

With a general poor alpha activity it is not anticipated that closed eyes will have a vast influence on the magnitude of the alpha waves. It did however make the suppression in the alpha activity a little easier to notice. Refer to figure 67 for the result of the test.

**Observer 2:**

The result of the test is shown in figure 68. With the increased alpha activity the change in the waves are more noticeable. Unfortunately the observer started getting drowsy during the experiment and a stronger theta activity became visible. As mentioned before, theta waves reflect the state between wakefulness and sleep.

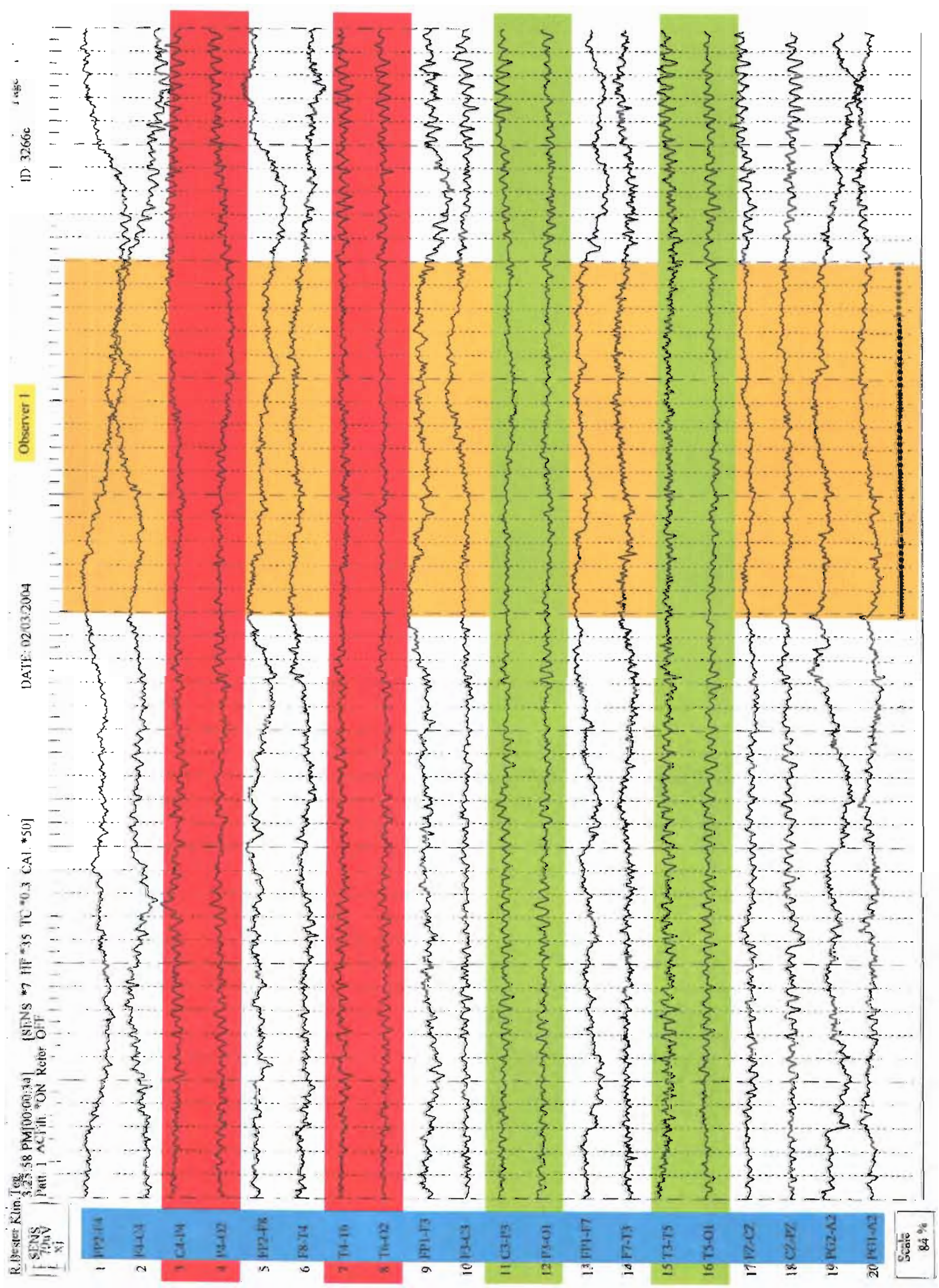



**Figure 67** **Observer 1 – Results of test with eyes closed**

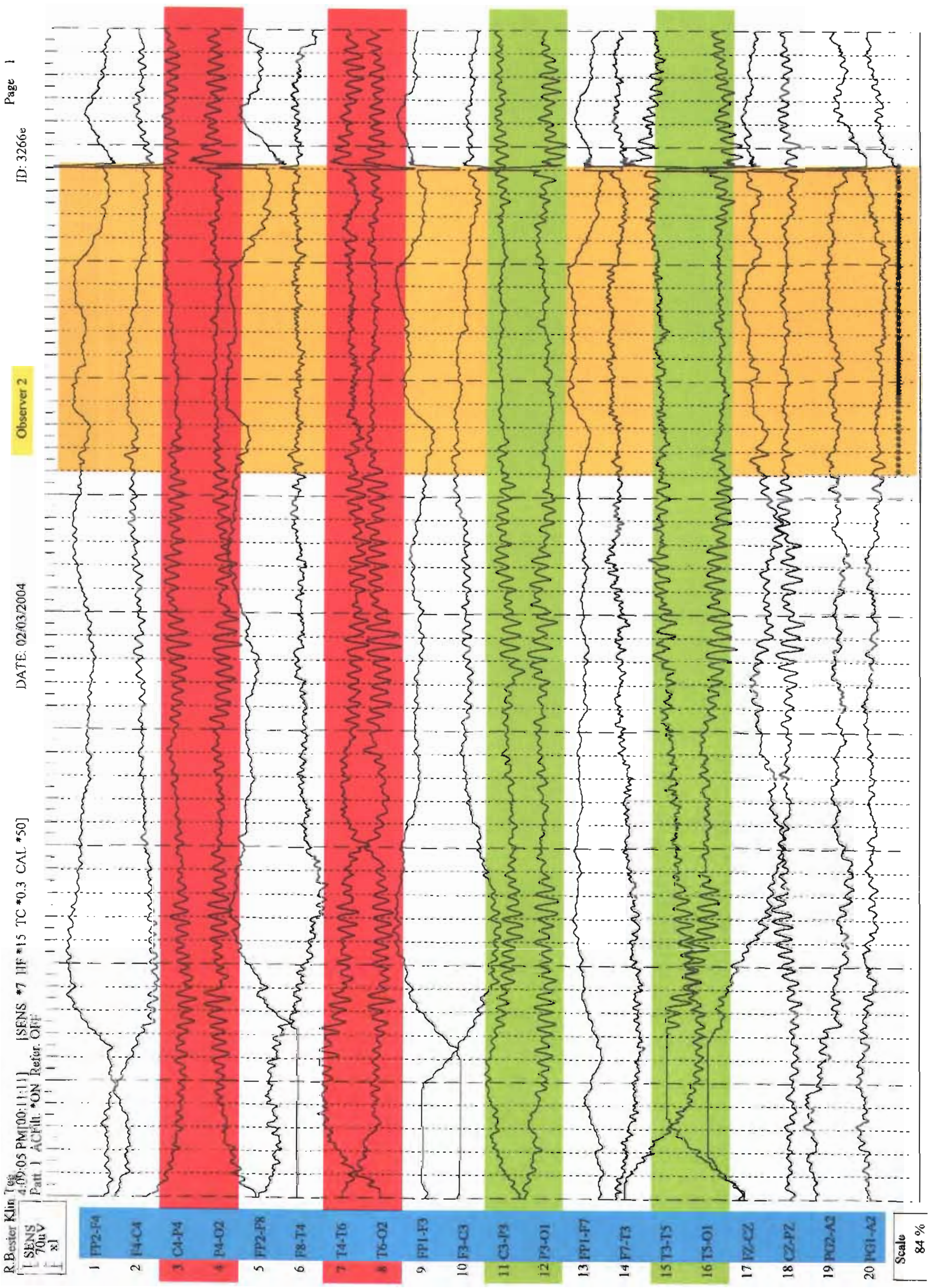



**Figure 68 Observer 2 – Results of test with eyes closed**

## 5.9 Summary

The experiments were conducted in order to determine whether it would be possible to measure any change in the functional state of the brain influenced by the visual response as a result of exposure to an unshielded light source. The alpha rhythm was evaluated for any change during exposure to the light source. The occipital lobes are the area of the brain responsible for the processing of visual stimuli. The electrodes connected in this area were monitored and the results showed that there was indeed a suppression of the alpha activity whenever the observers were exposed to the light source. When the observer's eyes were open it was more difficult to notice a suppression of alpha activity as the alpha rhythms decreased in size. This phenomenon can be explained by the fact that beta rhythms become more predominant when the eyes are open. However, when the observer's eyes were closed the alpha waves increased in size and it was much easier to notice suppression in the alpha activity.

# CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Findings and deductions

The main purpose of this research was to investigate a new method of discomfort glare evaluation. Any person experiencing discomfort when exposed to a glare source; do so as a result of visual stimuli. The first step of the investigation was therefore to study the route of the visual pathway. The eyes are the windows to the outside world, and the only means of visual representation; thus the process of seeing starts at the eyes. Because the eyes are merely tools making seeing possible; it was also important to evaluate the different functions of the brain. The place in the brain where visual interpretation takes place, the occipital lobe, was of particular importance and was investigated in depth. Transfer of information to the brain and the corresponding reactions from the brain, takes place through an electrochemical process between neurons. It was also determined that the brain has different frequency waves, each indicating a different state of activity.

The method of measuring these frequencies is by taking an EEG of the observer with electrodes placed on the appropriate points on the observer's head. The positioning of the electrodes was done according to the International 10-20 system. By conducting an experiment with an incandescent lamp that was switched on and off alternatively, the alpha activity of the observer's brainwaves located in the occipital region was monitored. By evaluating the results it is concluded that readings can be taken by using an EEG technique.

The results indicated that the observer with higher photosensitivity is more susceptible to exposure from a bright light just above the line of sight. The stronger the alpha activity of an observer the easier it is to see a change when the observer is exposed to a changing light source. When the observers were tested with closed eyes the change in alpha activity increased, but that is due to the fact that alpha frequency increases with closed eyes. With the observers eyes open it was more difficult to ascertain suppressions in the alpha activity. These results lay the groundwork for further intensive research on the topic of discomfort glare.

## 6.2 Conclusions and Recommendations

The process that takes place during the visual pathway from the eyes to the brain governs each individual's interpretation of what is seen. By analyzing the results of the EEG measurements of the different observers, it can be assumed that the subjective evaluation of the observers when exposed to discomfort glare, is based on the sensitivity of the visual system. Therefore, the difference in the sensitivity of visual systems of different individuals; can be taken as a possible reason for the vast variety of results from observers when exposed to discomfort glare. It is clear that each individual differs in sensitivity to the brightness of light as indicated by the photosensitivity test done on the observers. Another reason for differences is the quality of the alpha activity of individuals; this will influence the distinction between the reactions of the brain frequencies in the particular part of the brain where the activity takes place. For more conclusive and reliable readings it is suggested that the observers are tested beforehand in order to ascertain the level of photosensitivity, state of wakefulness and clean strong alpha activity.

It is recommended that individuals with clear, regular alpha rhythms take part in experiments, as it is the key element that indicates change of the functional status in the particular part of the brain. Another important factor to consider is to make sure that the observer is in a wide-awake state as sleepiness influences the outcome of the results, by referring to table 8, it can be seen that in order to have a good alpha activity it is essential to be relaxed but not drowsy. It is also important that the observers are photosensitive; this will ensure good results when EEG measurements are taken while the observers are exposed to a bare light source. In practice it is also individuals prone to visual sensitivity that will experience discomfort when exposed to glare in the visual field; and therefore, will determine the level of acceptable glare.

## 6.3 Fields for further studies

The system for evaluating the glare from large sources e.g. fluorescent lamp luminaires in typical applications has been internationally agreed upon. However, the glare from small sources e.g. incandescent lamps; has been the subject under dispute for many years. The late Dr. H.D Einhorn of Cape Town University was a forerunner in the research in this field. Fields for further proposed research will be a continuation of the work started by Einhorn. It is recommended that further studies into discomfort glare be conducted with special reference to the following aspects:

- **Personality types**

The influence of personality types on the level of discomfort experienced when exposed to a glaring source, some personality types have the tendency to be more inclined to discard frustrating or irritating actions. The reason for such investigation is that people have different pain or discomfort levels, the fact that observers are educated beforehand when evaluating a glare source is opposing the whole idea of determining a discomfort level. Hopkinson demonstrated that wide observer differences reduced in variability when suitable individual subjects were given experience in making glare judgements (Stone & Harker 1973:41). Methods like this result in observers indicating glare without experiencing discomfort and this leads to under-or over estimation of glare ratings.

- **Eye colour**

Eye colour is dependent on the amount of pigment present in the iris. The more pigment present the darker the eye colour, typically dark brown eyes. Lighter coloured eyes have less pigment and are typically blue in colour. People with lighter coloured eyes are much more sensitive to bright lighting conditions. The influence of eye colour will be a contributing factor towards the investigation into glare assessment results. An investigation of this nature is possible by making use of EEG measurements when individuals with different eye colour are exposed to photosensitivity tests using a strobe.

- **Intervals of exposure**

In a previous chapter it was indicated that observers found it much easier to appraise the sensation of discomfort when exposure of the light source was brief rather than prolonged. This however, makes EEG measurements more complex as the main purpose is to indicate changes in the alpha activity, therefore it would be preferable to make use of longer exposure times. With additional research on this topic a compromise can be suggested.

- **External factors influencing glare**

As mentioned previously, discomfort glare prediction systems indicate four factors influencing the degree of discomfort glare, namely: source luminance, background luminance, the solid angle subtended at the eye by the glare source and the position of the glare source relative to the line of sight. In order to investigate the effect of the varying external factors it is suggested that EEG measurements are taken continuously in order to determine the effect of the changes on the observer's visual sensitivity and emotional state.

- **Different brain frequencies**

To investigate the feasibility of measuring the degree of agitation experienced by an observer exposed to discomfort glare. With reference to table 9, a high Beta frequency indicates agitation and the distribution is shown as much focused. It would be ideal if a researcher could determine the level of frustration of an observer without depending on the observer's verbal statement on feelings of irritability, and short temperedness.

The result of such investigations will aid in setting an empirical relation between the glare sensation and the photometric and geometric characteristics of a lighting installation, in order to formulise a boundary between comfort and discomfort (BCD).

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ANNEXURE A

**Table 2 Luminance values (Fischer 1972:99)**

| *G* | *Quality Class* | *Value of 'in service' illuminance (lux) for which valid:* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1.15 | A | 2 000 | 1 000 | 500 | ≤ 250 | | | | |
| 1.5 | B | | 2 000 | 1 000 | 500 | ≤ 250 | | | |
| 1.85 | C | | | 2 000 | 1 000 | 500 | ≤ 250 | | |
| 2.2 | D | | | | 2 000 | 1 000 | 500 | ≤ 250 | |
| 2.55 | E | | | | | 2 000 | 1 000 | 500 | ≤ 250 |
| ***Diagram*** | ***Angle γ*** | ***Luminance limits (cd/m²):*** | | | | | | | |
| I | $45^0$ | $2.71x10^2$ | $5.08x10^3$ | $1.19x10^4$ | $3.49x10^4$ | $1.29x10^5$ | $5.96x10^5$ | $3.44x10^6$ | $2.46x10^7$ |
| | $75^0$ - $90^0$ | $1.25x10^3$ | $1.58x10^3$ | $2.18x10^3$ | $3.26x10^3$ | $5.31x10^3$ | $9.44x10^3$ | $1.82x10^4$ | $3.81x10^4$ |
| II | $45^0$ | $1.87x10^3$ | $2.82x10^3$ | $4.90x10^3$ | $9.88x10^3$ | $2.30x10^4$ | $6.24x10^4$ | $1.95x10^5$ | $7.00x10^5$ |
| | $75^0$ - $90^0$ | $0.94x10^3$ | $1.05x10^3$ | $1.22x10^3$ | $1.47x10^3$ | $1.85x10^3$ | $2.42x10^3$ | $3.29x10^3$ | $4.64x10^3$ |

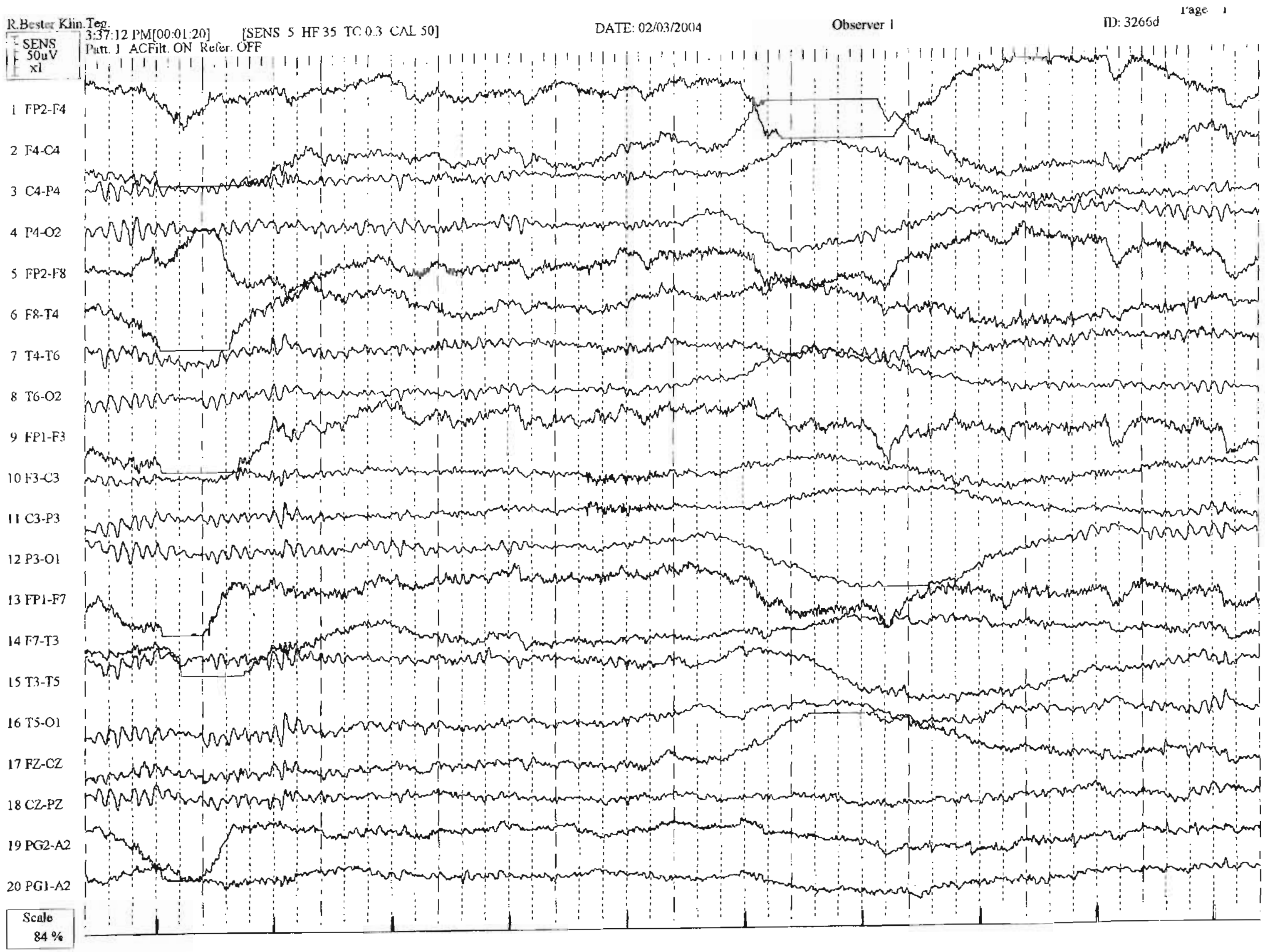
Table 3 Position indices (CIE 1995:4)

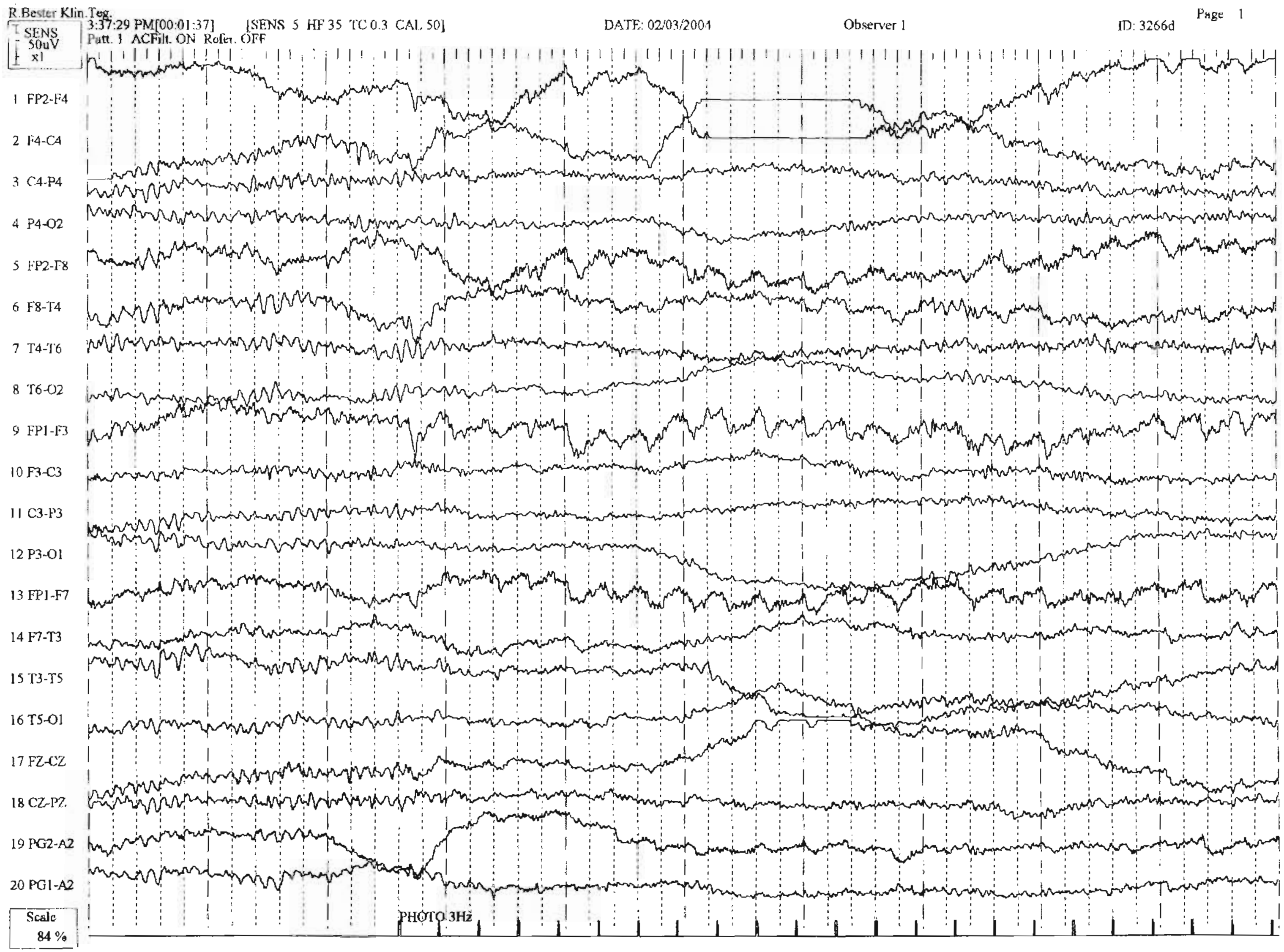
| T/R \ H/R | 0,00 | 0,10 | 0,20 | 0,30 | 0,40 | 0,50 | 0,60 | 0,70 | 0,80 | 0,90 | 1,00 | 1,10 | 1,20 | 1,30 | 1,40 | 1,50 | 1,60 | 1,70 | 1,80 | 1,90 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0,00 | 1,00 | 1,26 | 1,53 | 1,90 | 2,35 | 2,86 | 3,50 | 4,20 | 5,00 | 6,00 | 7,00 | 8,10 | 9,25 | 10,35 | 11,70 | 13,15 | 14,70 | 16,20 | - | - |
| 0,10 | 1,05 | 1,22 | 1,46 | 1,80 | 2,20 | 2,75 | 3,40 | 4,10 | 4,80 | 5,80 | 6,80 | 8,00 | 9,10 | 10,30 | 11,60 | 13,00 | 14,60 | 16,10 | - | - |
| 0,20 | 1,12 | 1,30 | 1,50 | 1,80 | 2,20 | 2,66 | 3,18 | 3,88 | 4,60 | 5,50 | 6,50 | 7,60 | 8,75 | 9,85 | 11,20 | 12,70 | 14,00 | 15,70 | - | - |
| 0,30 | 1,22 | 1,38 | 1,60 | 1,87 | 2,25 | 2,70 | 3,25 | 3,90 | 4,60 | 5,45 | 6,45 | 7,40 | 8,40 | 9,50 | 10,85 | 12,10 | 13,70 | 15,00 | - | - |
| 0,40 | 1,32 | 1,47 | 1,70 | 1,96 | 2,35 | 2,80 | 3,30 | 3,90 | 4,60 | 5,40 | 6,40 | 7,30 | 8,30 | 9,40 | 10,60 | 11,90 | 13,20 | 14,60 | 16,00 | - |
| 0,50 | 1,43 | 1,60 | 1,82 | 2,10 | 2,48 | 2,91 | 3,40 | 3,98 | 4,70 | 5,50 | 6,40 | 7,30 | 8,30 | 9,40 | 10,50 | 11,75 | 13,00 | 14,40 | 15,70 | - |
| 0,60 | 1,55 | 1,72 | 1,98 | 2,30 | 2,65 | 3,10 | 3,60 | 4,10 | 4,80 | 5,50 | 6,40 | 7,35 | 8,40 | 9,40 | 10,50 | 11,70 | 13,00 | 14,10 | 15,40 | - |
| 0,70 | 1,70 | 1,88 | 2,12 | 2,48 | 2,87 | 3,30 | 3,78 | 4,30 | 4,88 | 5,60 | 6,50 | 7,40 | 8,50 | 9,50 | 10,50 | 11,70 | 12,85 | 14,00 | 15,20 | - |
| 0,80 | 1,82 | 2,00 | 2,32 | 2,70 | 3,08 | 3,50 | 3,92 | 4,50 | 5,10 | 5,75 | 6,60 | 7,50 | 8,60 | 9,50 | 10,60 | 11,75 | 12,80 | 14,00 | 15,10 | - |
| 0,90 | 1,95 | 2,20 | 2,54 | 2,90 | 3,30 | 3,70 | 4,20 | 4,75 | 5,30 | 6,00 | 6,75 | 7,70 | 8,70 | 9,65 | 10,75 | 11,80 | 12,90 | 14,00 | 15,00 | 16,00 |
| 1,00 | 2,11 | 2,40 | 2,75 | 3,10 | 3,50 | 3,91 | 4,40 | 5,00 | 5,60 | 6,20 | 7,00 | 7,90 | 8,80 | 9,75 | 10,80 | 11,90 | 12,95 | 14,00 | 15,00 | 16,00 |
| 1,10 | 2,30 | 2,55 | 2,92 | 3,30 | 3,72 | 4,20 | 4,70 | 5,25 | 5,80 | 6,55 | 7,20 | 8,15 | 9,00 | 9,90 | 10,95 | 12,00 | 13,00 | 14,00 | 15,00 | 16,00 |
| 1,20 | 2,40 | 2,75 | 3,12 | 3,50 | 3,90 | 4,35 | 4,85 | 5,50 | 6,05 | 6,70 | 7,50 | 8,30 | 9,20 | 10,00 | 11,02 | 12,10 | 13,10 | 14,00 | 15,00 | 16,00 |
| 1,30 | 2,55 | 2,90 | 3,30 | 3,70 | 4,20 | 4,65 | 5,20 | 5,70 | 6,30 | 7,00 | 7,70 | 8,55 | 9,35 | 10,20 | 11,20 | 12,25 | 13,20 | 14,00 | 15,00 | 16,00 |
| 1,40 | 2,70 | 3,10 | 3,50 | 3,90 | 4,35 | 4,85 | 5,35 | 5,85 | 6,50 | 7,25 | 8,00 | 8,70 | 9,50 | 10,40 | 11,40 | 12,40 | 13,25 | 14,05 | 15,00 | 16,00 |
| 1,50 | 2,85 | 3,15 | 3,65 | 4,10 | 4,55 | 5,00 | 5,50 | 6,20 | 6,80 | 7,50 | 8,20 | 8,85 | 9,70 | 10,55 | 11,50 | 12,50 | 13,30 | 14,05 | 15,02 | 16,00 |
| 1,60 | 2,95 | 3,40 | 3,80 | 4,25 | 4,75 | 5,20 | 5,75 | 6,30 | 7,00 | 7,65 | 8,40 | 9,00 | 9,80 | 10,80 | 11,75 | 12,60 | 13,40 | 14,20 | 15,10 | 16,00 |
| 1,70 | 3,10 | 3,55 | 4,00 | 4,50 | 4,90 | 5,40 | 5,95 | 6,50 | 7,20 | 7,80 | 8,50 | 9,20 | 10,00 | 10,85 | 11,85 | 12,75 | 13,45 | 14,20 | 15,10 | 16,00 |
| 1,80 | 3,25 | 3,70 | 4,20 | 4,65 | 5,10 | 5,60 | 6,10 | 6,75 | 7,40 | 8,00 | 8,65 | 9,35 | 10,10 | 11,00 | 11,90 | 12,80 | 13,50 | 14,20 | 15,10 | 16,00 |
| 1,90 | 3,43 | 3,86 | 4,30 | 4,75 | 5,20 | 5,70 | 6,30 | 6,90 | 7,50 | 8,17 | 8,80 | 9,50 | 10,20 | 11,00 | 12,00 | 12,82 | 13,55 | 14,20 | 15,10 | 16,00 |
| 2,00 | 3,50 | 4,00 | 4,50 | 4,90 | 5,35 | 5,80 | 6,40 | 7,10 | 7,70 | 8,30 | 8,90 | 9,60 | 10,40 | 11,10 | 12,00 | 12,85 | 13,60 | 14,30 | 15,10 | 16,00 |
| 2,10 | 3,60 | 4,17 | 4,65 | 5,05 | 5,50 | 6,00 | 6,60 | 7,20 | 7,82 | 8,45 | 9,00 | 9,75 | 10,50 | 11,20 | 12,10 | 12,90 | 13,70 | 14,35 | 15,10 | 16,00 |
| 2,20 | 3,75 | 4,25 | 4,72 | 5,20 | 5,60 | 6,10 | 6,70 | 7,35 | 8,00 | 8,55 | 9,15 | 9,85 | 10,60 | 11,30 | 12,10 | 12,90 | 13,70 | 14,40 | 15,15 | 16,00 |
| 2,30 | 3,85 | 4,35 | 4,80 | 5,25 | 5,70 | 6,22 | 6,80 | 7,40 | 8,10 | 8,65 | 9,30 | 9,90 | 10,70 | 11,40 | 12,20 | 12,95 | 13,70 | 14,40 | 15,20 | 16,00 |
| 2,40 | 3,95 | 4,40 | 4,90 | 5,35 | 5,80 | 6,30 | 6,90 | 7,50 | 8,20 | 8,80 | 9,40 | 10,00 | 10,80 | 11,50 | 12,25 | 13,00 | 13,75 | 14,45 | 15,20 | 16,00 |
| 2,50 | 4,00 | 4,50 | 4,95 | 5,40 | 5,85 | 6,40 | 6,95 | 7,55 | 8,25 | 8,85 | 9,50 | 10,05 | 10,85 | 11,55 | 12,30 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 2,60 | 4,07 | 4,55 | 5,05 | 5,47 | 5,95 | 6,45 | 7,00 | 7,65 | 8,35 | 8,95 | 9,55 | 10,10 | 10,90 | 11,60 | 12,32 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 2,70 | 4,10 | 4,60 | 5,10 | 5,53 | 6,00 | 6,50 | 7,05 | 7,70 | 8,40 | 9,00 | 9,60 | 10,16 | 10,92 | 11,63 | 12,35 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 2,80 | 4,15 | 4,62 | 5,15 | 5,56 | 6,05 | 6,55 | 7,08 | 7,73 | 8,45 | 9,05 | 9,65 | 10,20 | 10,95 | 11,65 | 12,35 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 2,90 | 4,20 | 4,65 | 5,17 | 5,60 | 6,07 | 6,57 | 7,12 | 7,75 | 8,50 | 9,10 | 9,70 | 10,23 | 10,95 | 11,65 | 12,35 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |
| 3,00 | 4,22 | 4,67 | 5,20 | 5,65 | 6,12 | 6,60 | 7,15 | 7,80 | 8,55 | 9,12 | 9,70 | 10,23 | 10,95 | 11,65 | 12,35 | 13,00 | 13,80 | 14,50 | 15,25 | 16,00 |

# Results of photosensitivity tests on observers

**ANNEXURE C**

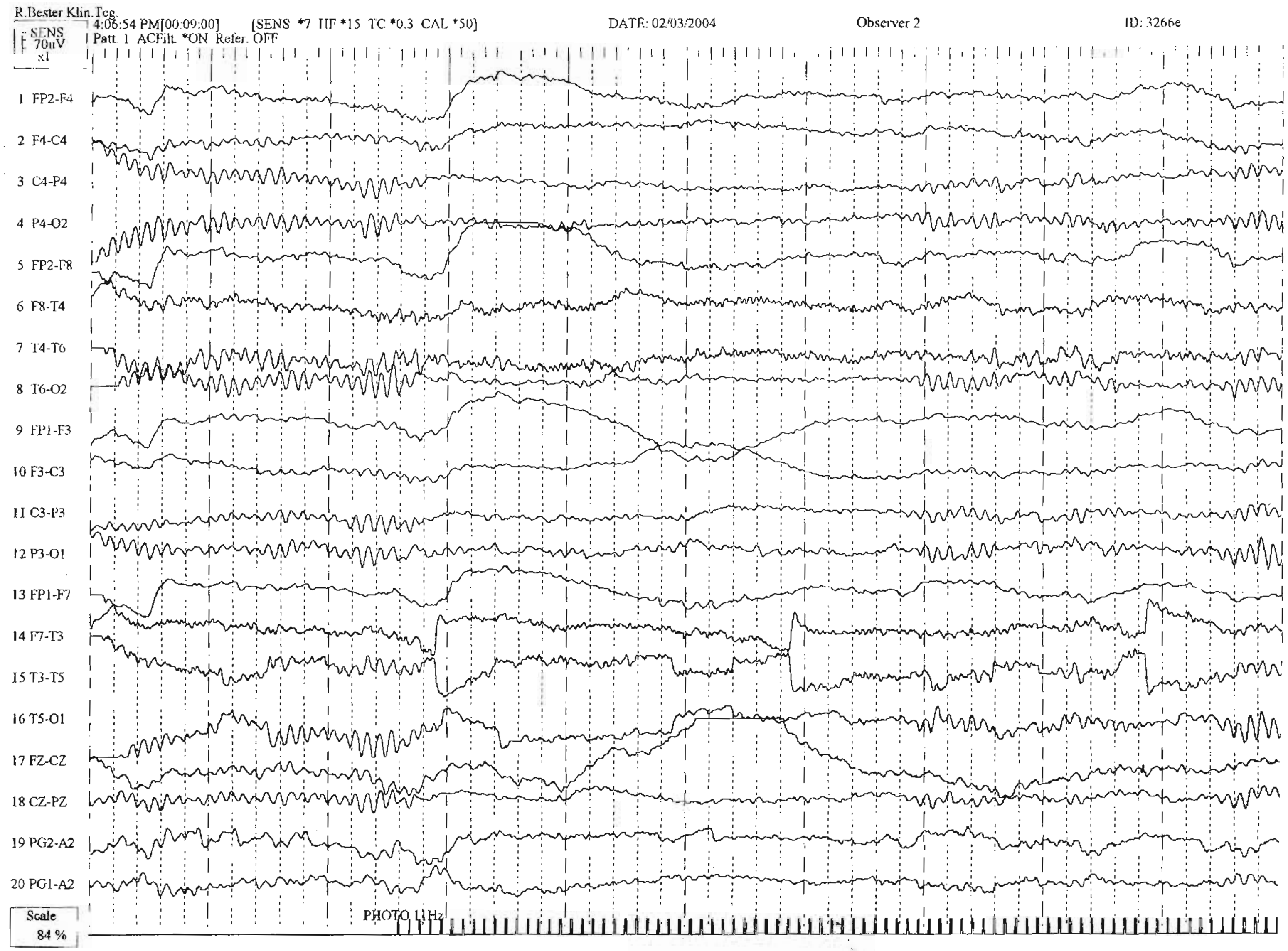
## Observer 1 – Photosensitivity test at 1 Hz





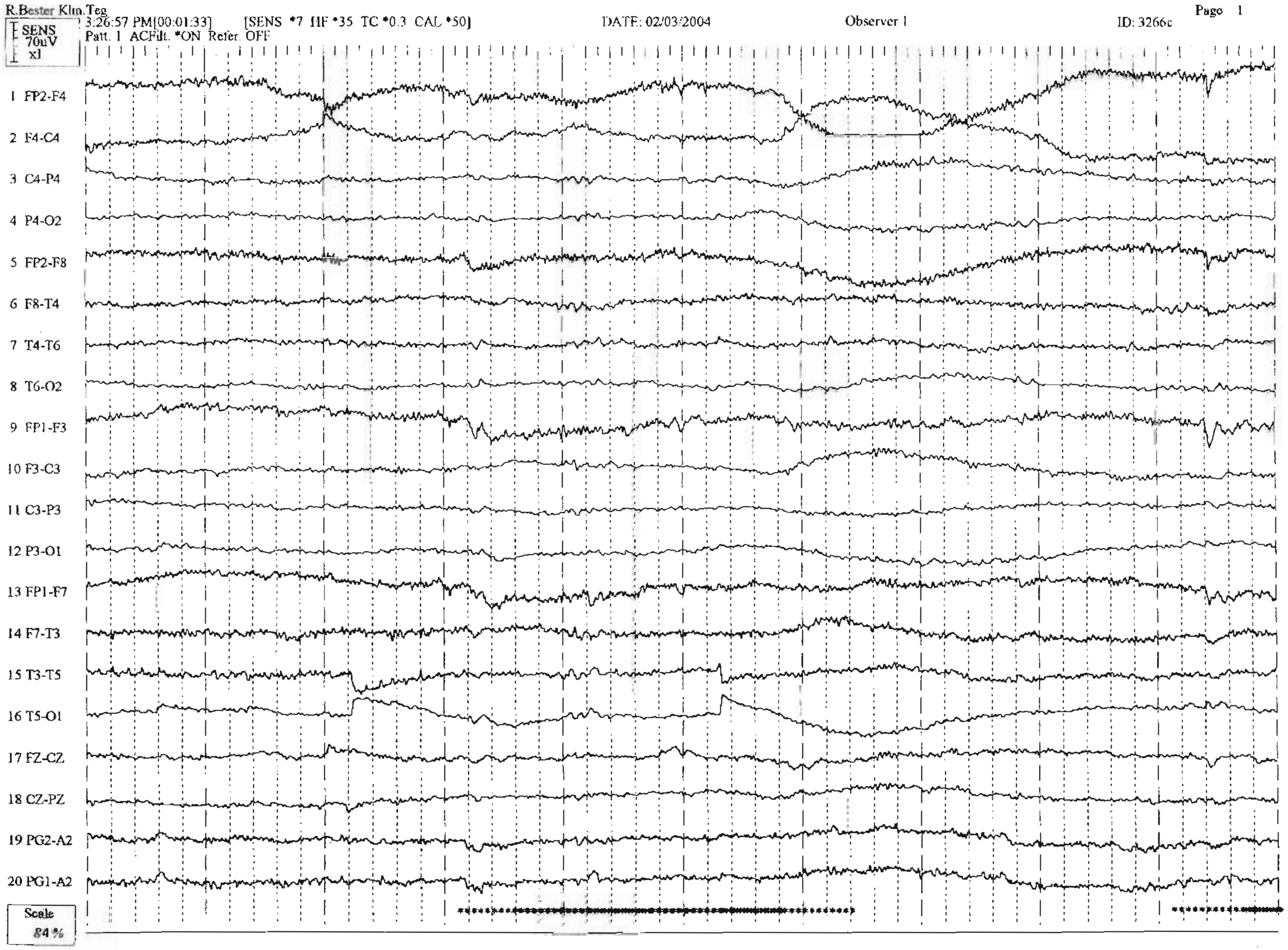

**Observer 1 – Photosensitivity test at 3 Hz**

# Observer 2 – Photosensitivity test at 11 Hz



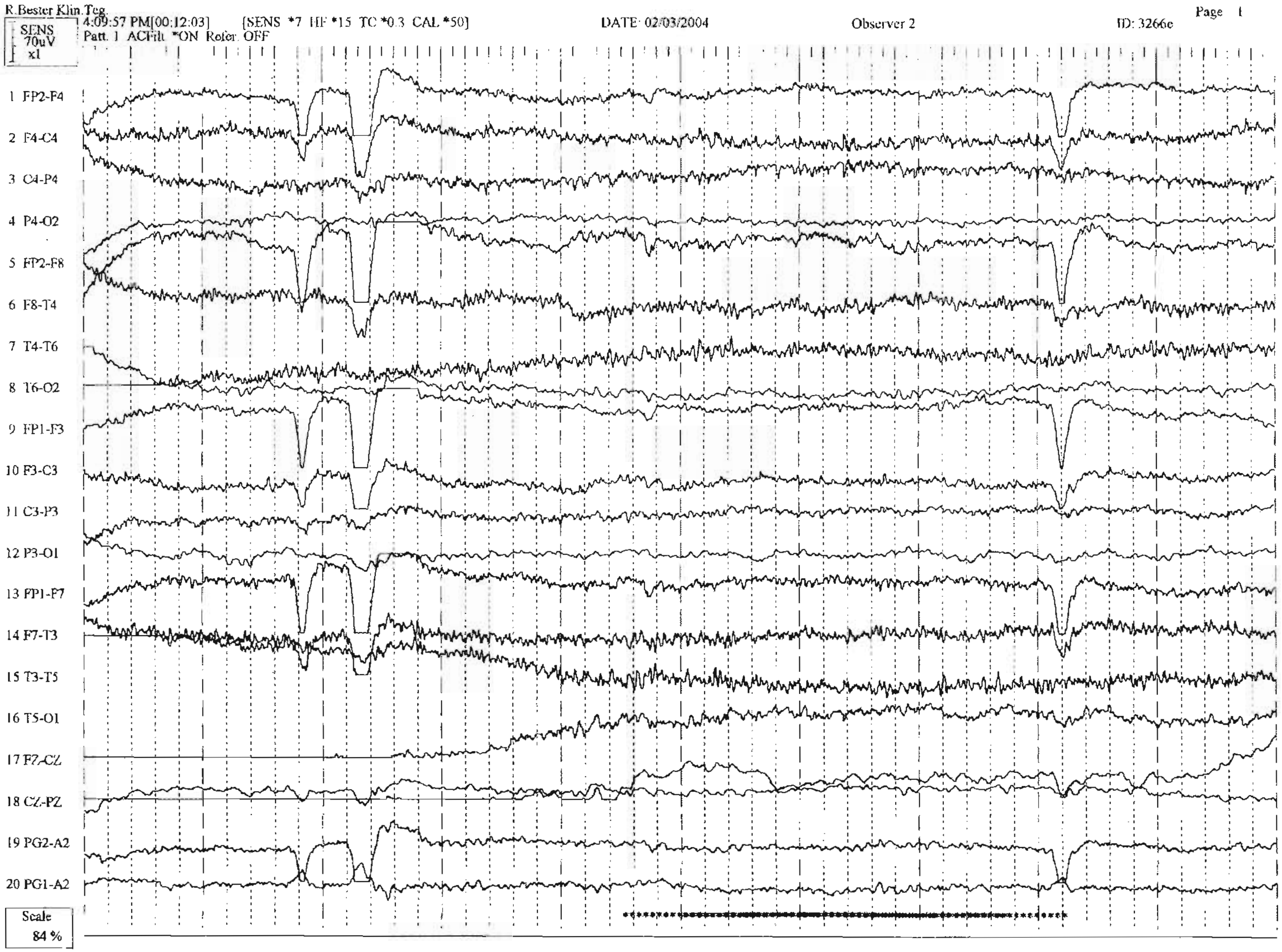
# Results of tests with eyes open

Observer 1 - Eyes open




ANNEXURE C

## Observer 2 - Eyes open






ANNEXURE C

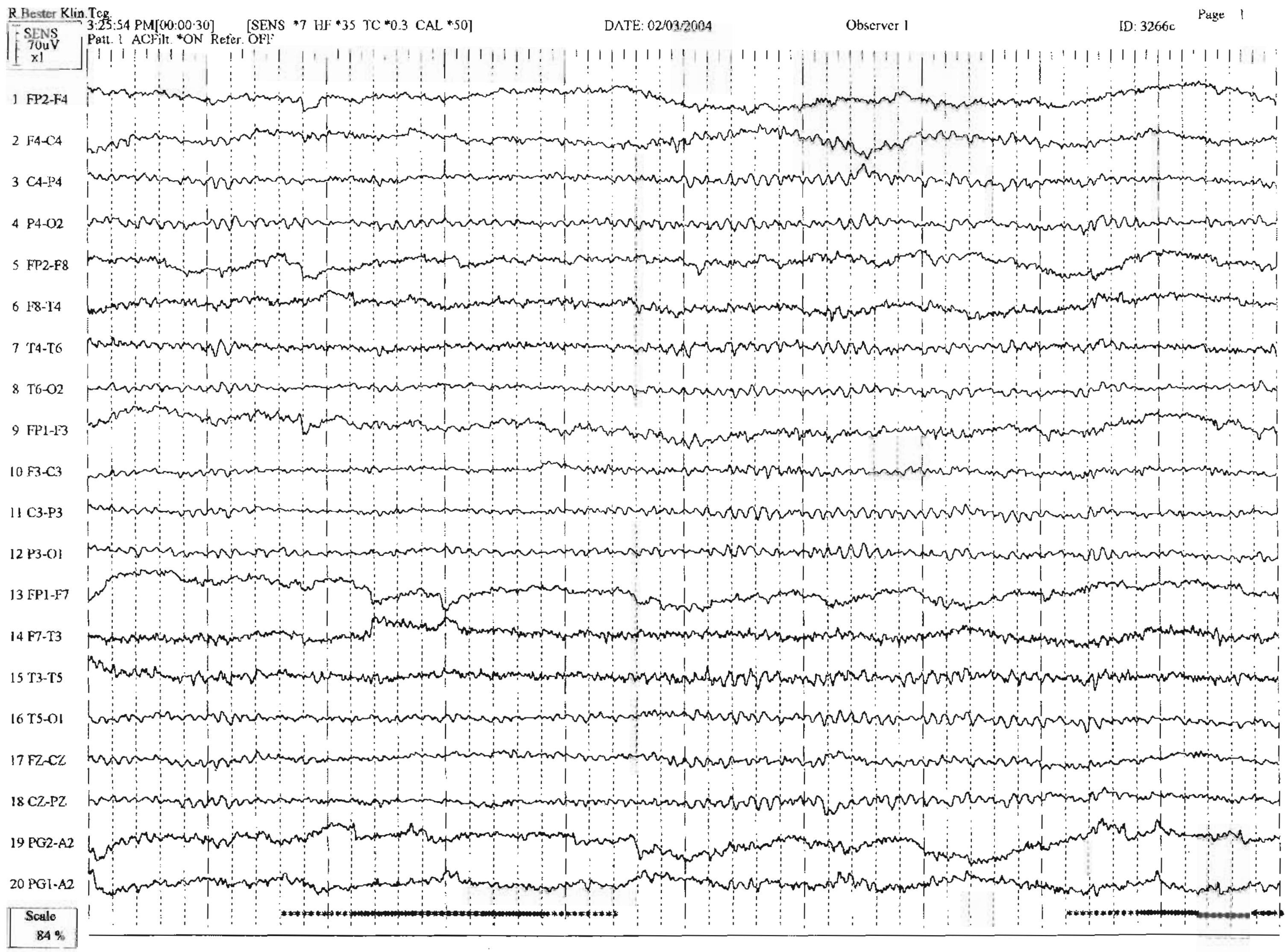
**Observer 2 - Eyes open**




**ANNEXURE C**

# Results of tests with eyes closed

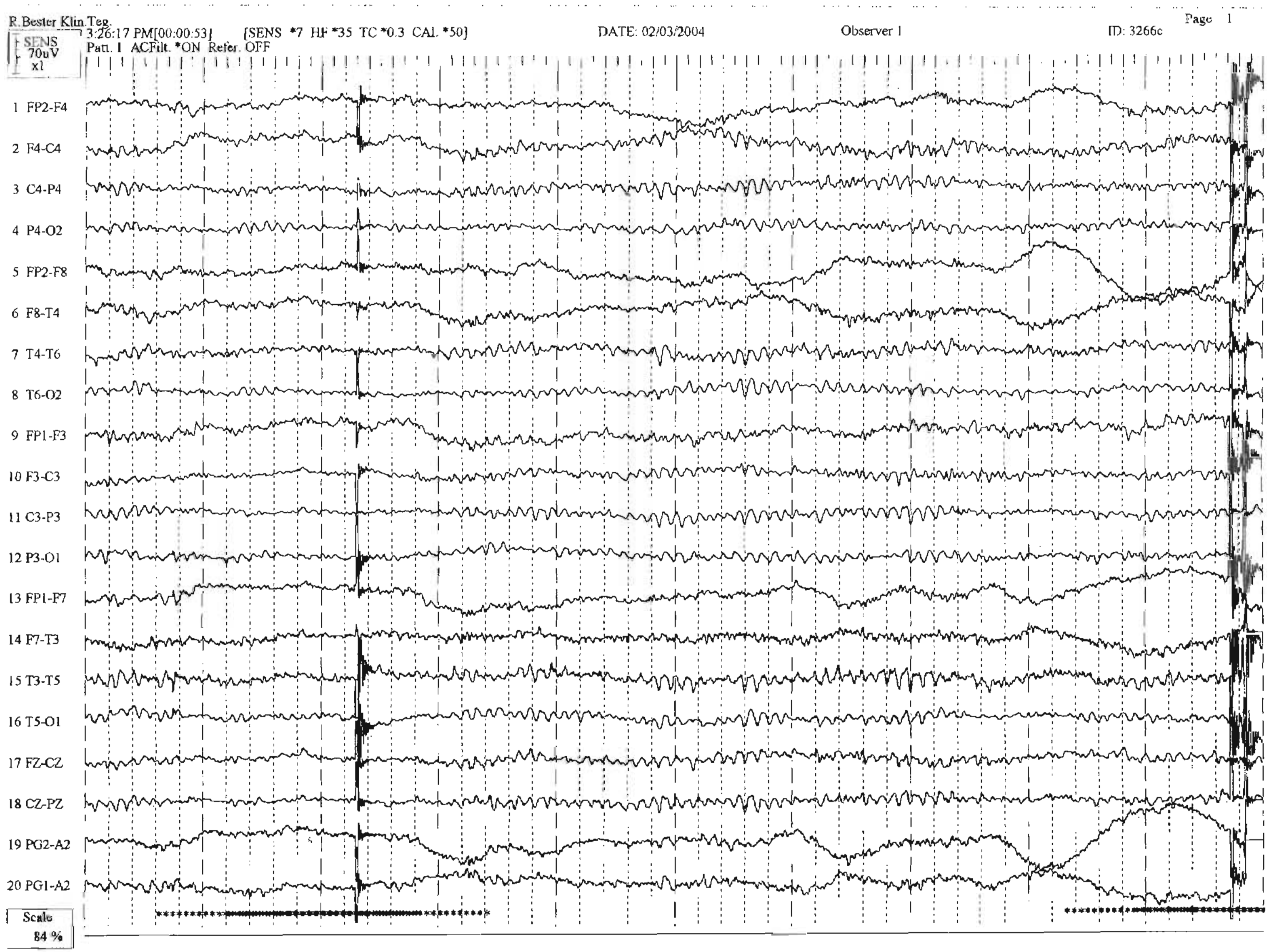
Observer 1 - Eyes closed





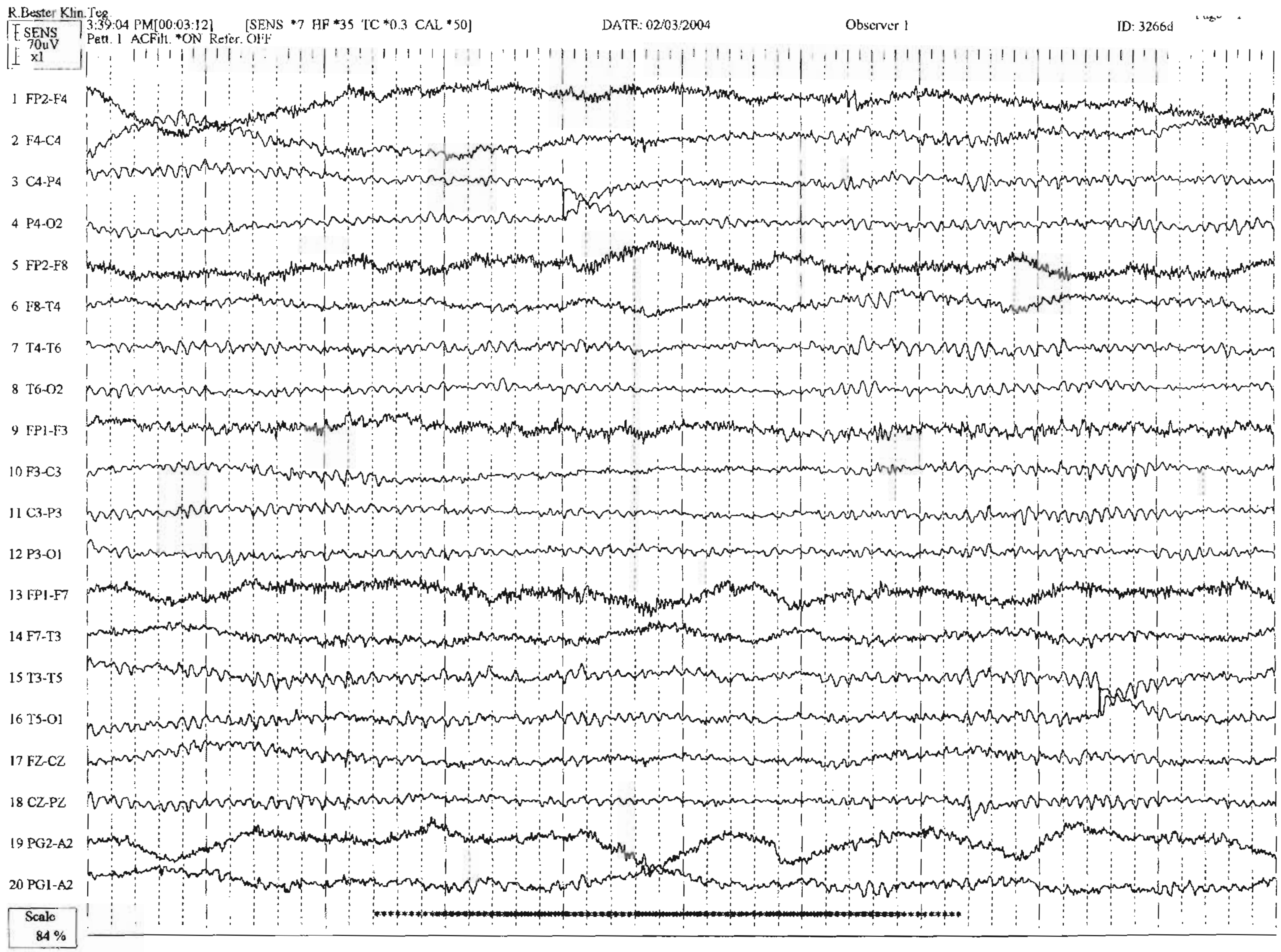

ANNEXURE C

Observer 1 - Eyes closed




ANNEXURE C

Observer 1 - Eyes closed

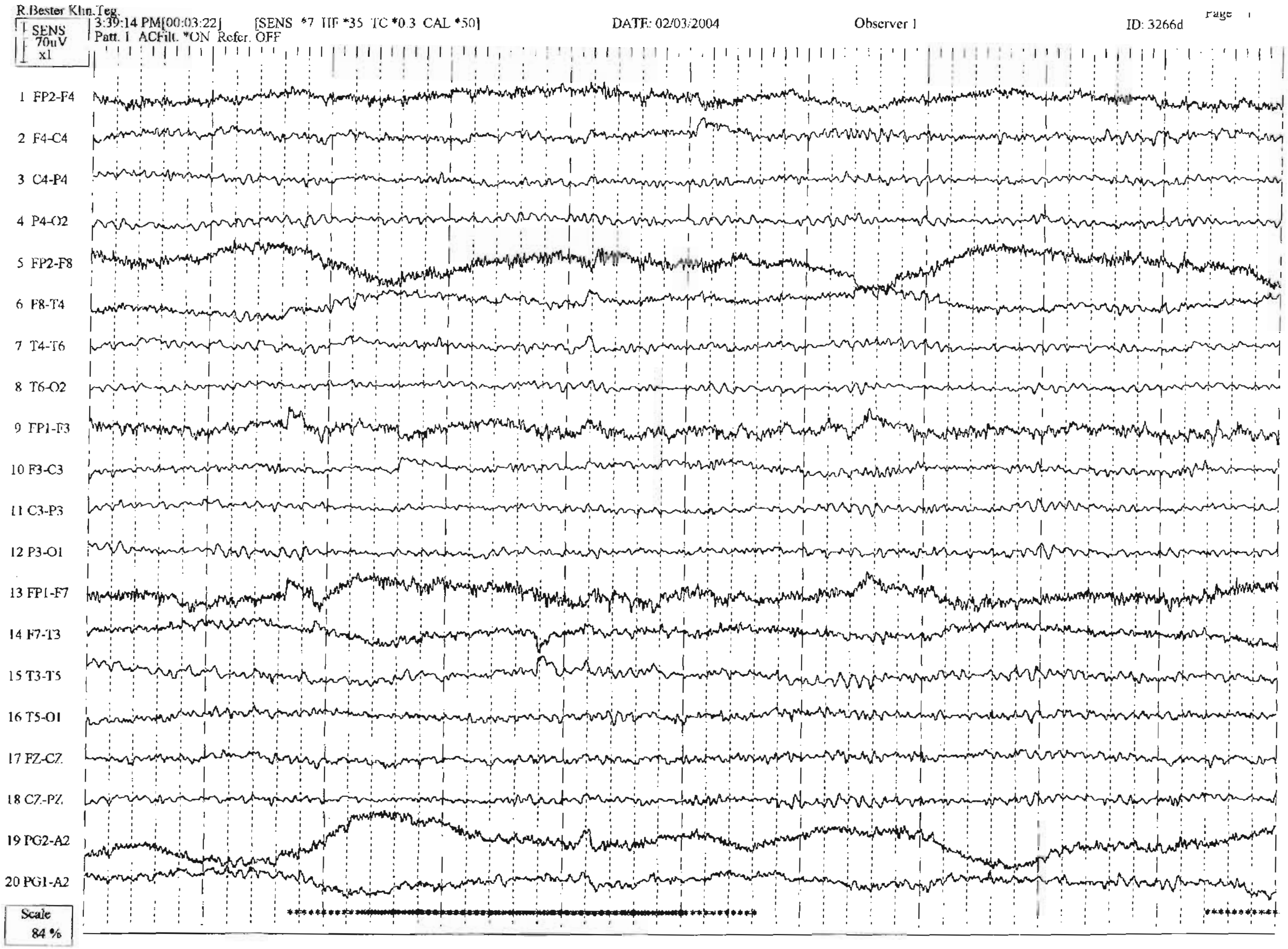





ANNEXURE C

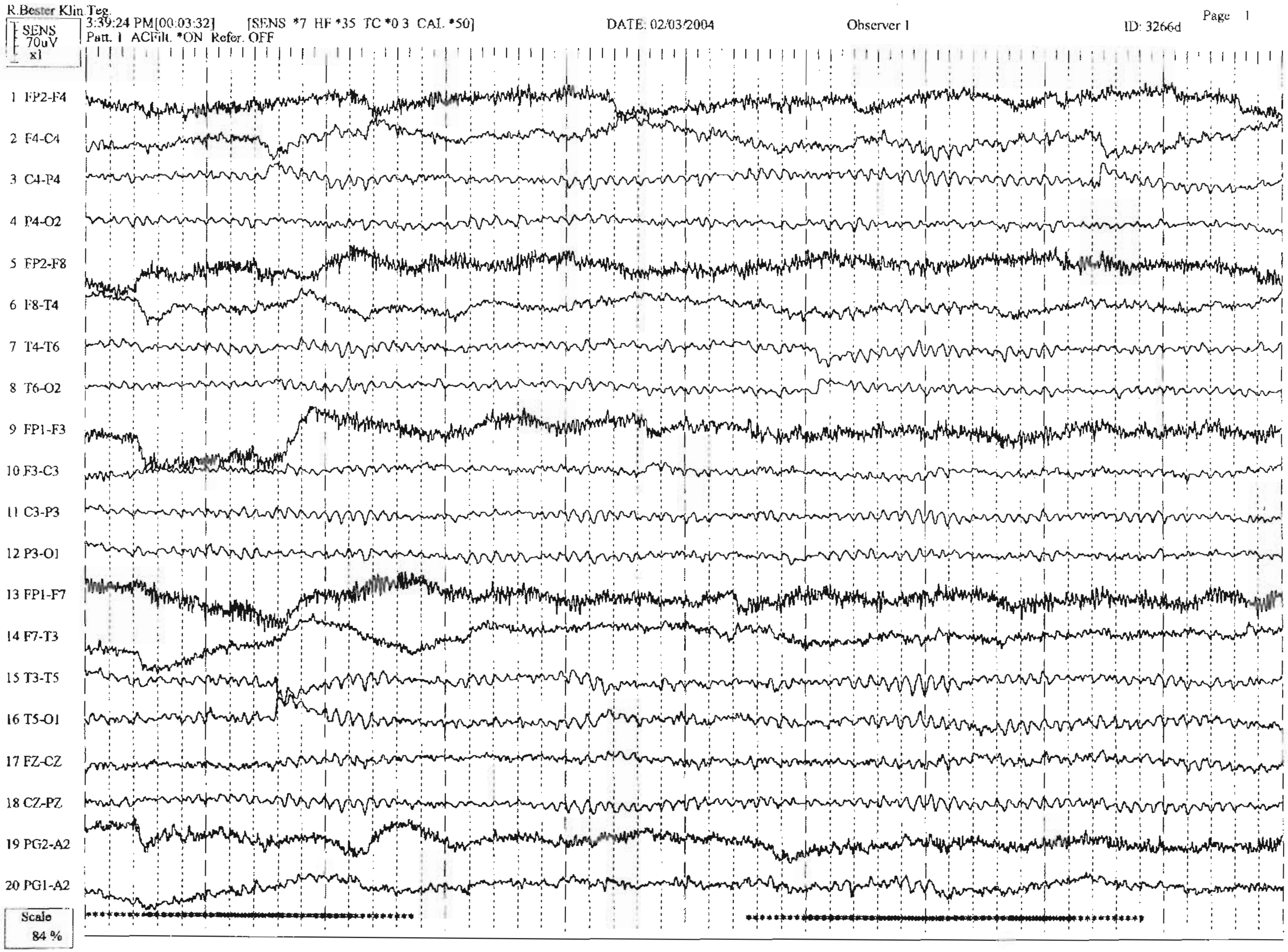
ANNEXURE C

# Observer 1 - Eyes closed

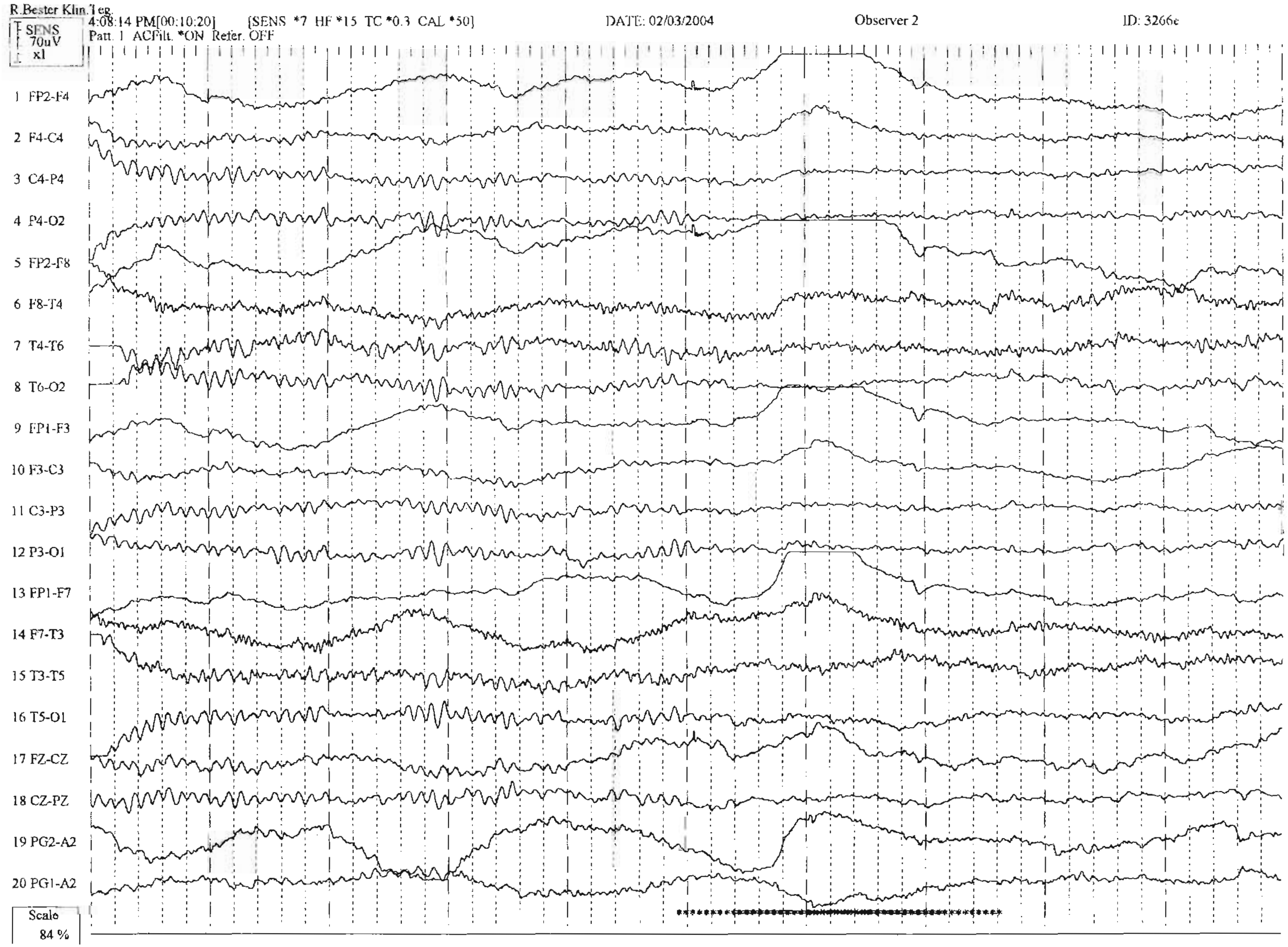


ANNEXURE C

# Observer 1 - Eyes closed



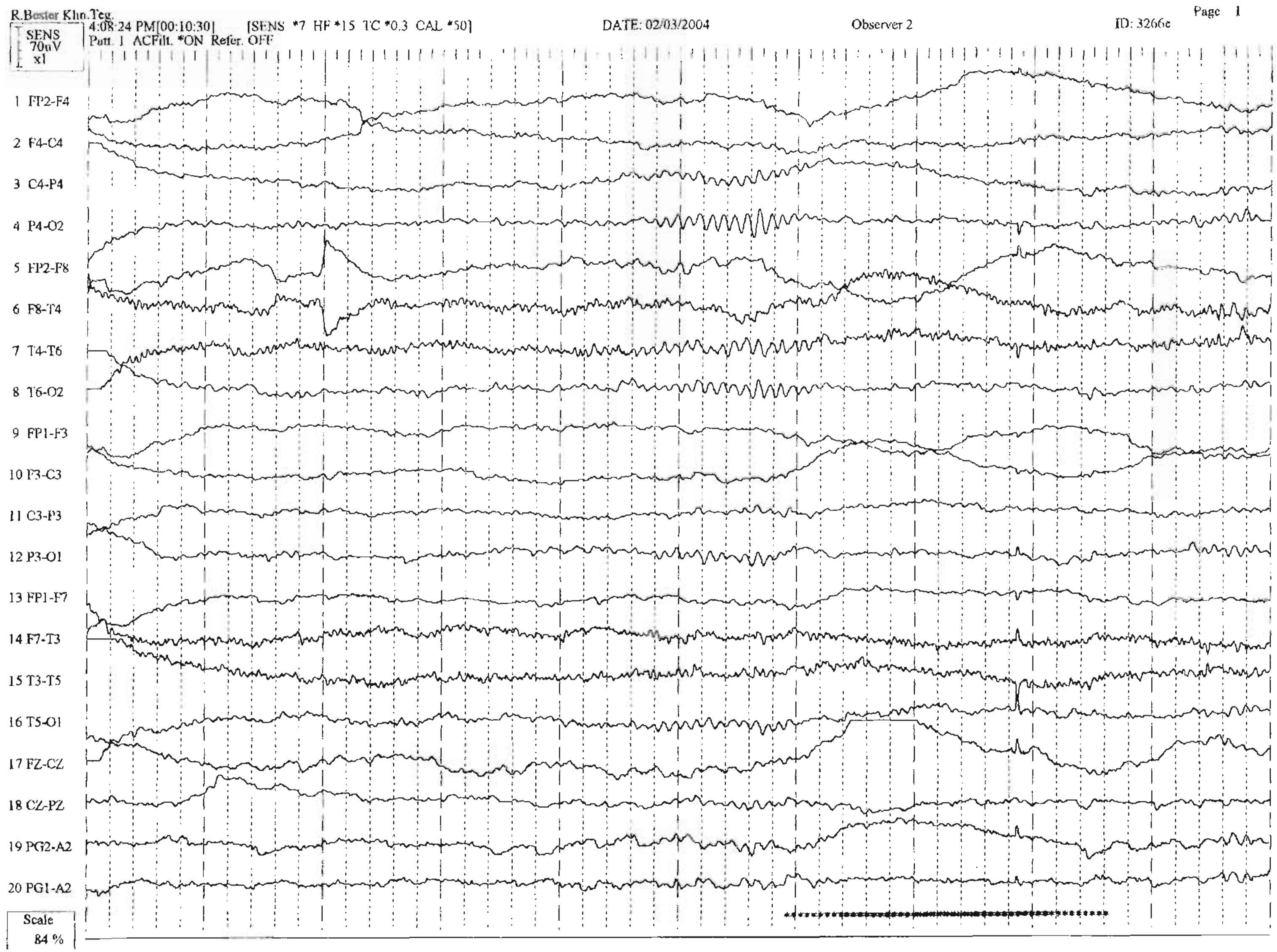
## Observer 2 - Eyes closed



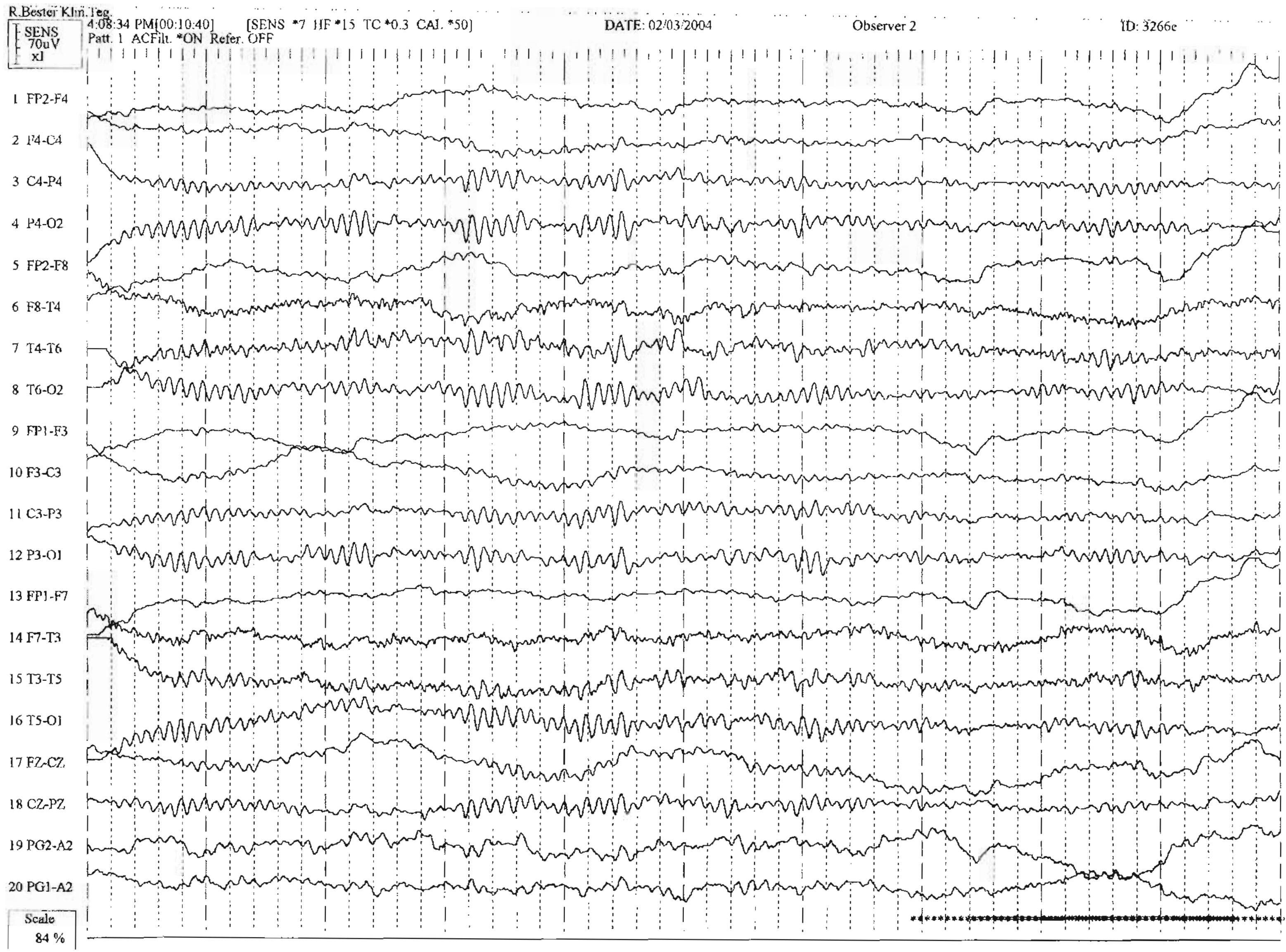

ANNEXURE C

# ANNEXURE C

## Observer 2 - Eyes closed

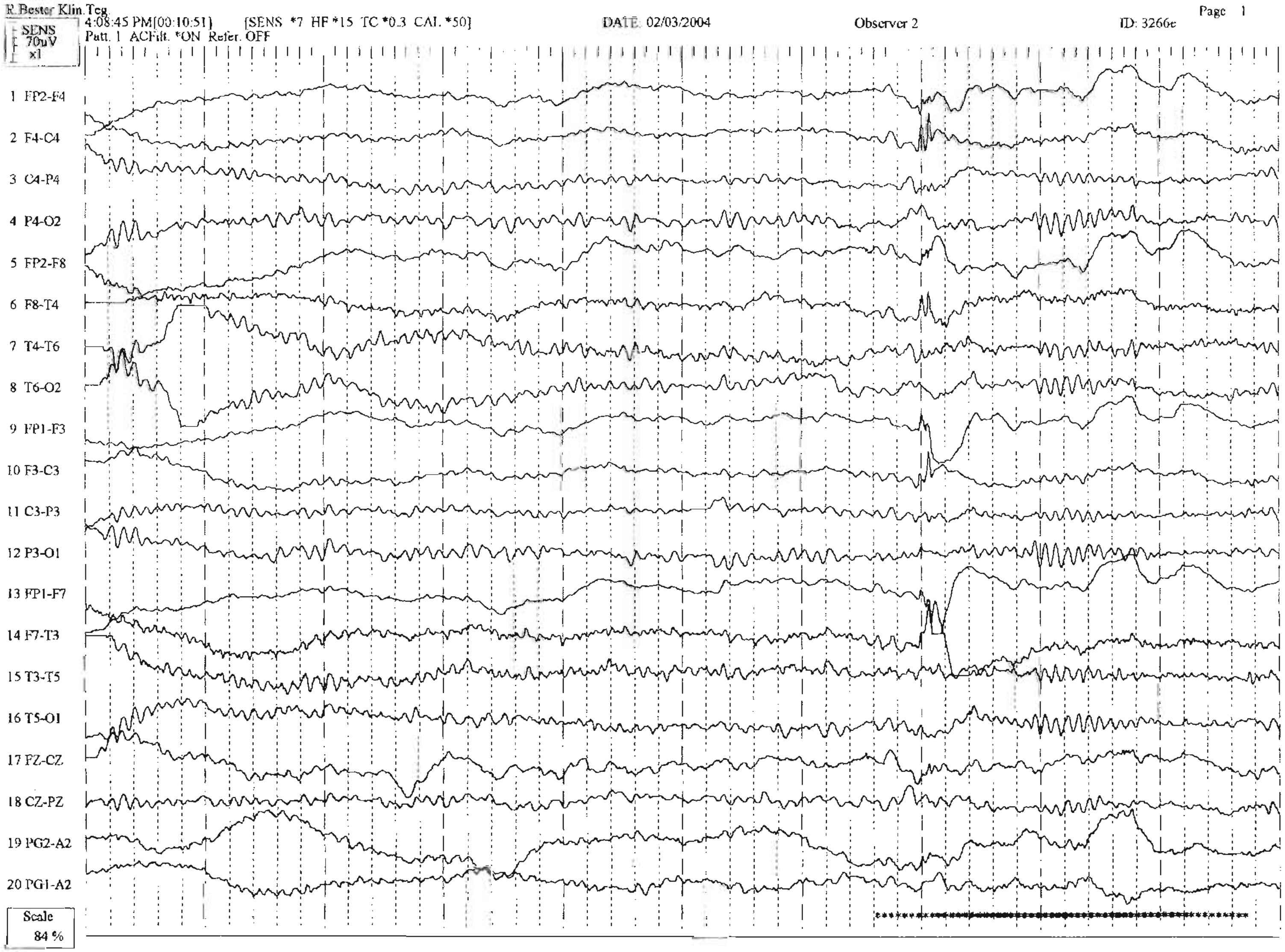


Observer 2 - Eyes closed




ANNEXURE C

Observer 2 - Eyes closed






ANNEXURE C