AN INVESTIGATION OF THE ROLE OF THE SCANNING LASER OPHTHALMOSCOPE IN THE ASSESSMENT OF PATIENTS WITH MACULAR DISEASE

Submitted by

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for the degree of Doctor of Philosophy

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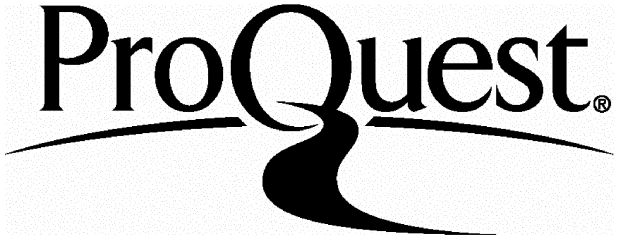
October 1994



ABSTRACT

Diseases of the macula are the primary cause of blindness in the western world. Given the current lack of effective medical treatment, there is a requirement for investigation of alternative therapeutic modalities. Traditionally, low vision services provide magnifying devices and advice on illumination. However, there have been claims that training is essential for successful rehabilitation.

Using the scanning laser ophthalmoscope (SLO), novel techniques have been developed for the investigation of visual function. Validation was undertaken on subjects with normal vision and patients with a variety of central field defects.

Microperimetry in patients demonstrated that visual function did not always correlate with fundus appearance. In normals, small inaccuracies of fixation were found to have no measurable influence on the reproducibility of scotoma maps.

Measurements of fixation indicated that the ability to maintain a steady eye position varied significantly between observers both with normal and low vision. Some patients had exceptionally poor fixation whilst in others it was normal.

To minimise the problems of target acquisition due to eye movements, a scrolling text system was developed. Assessment of reading performance at specific retinal locations demonstrated that the ability to recognise letters declined with increasing retinal eccentricity and decreasing text contrast. Patients were notably worse at reading tasks than normal observers.

Longitudinal evaluation of visual function was undertaken on patients entered into a low vision training programme. Most patients self-selected a single eccentric retinal location for viewing and no suggested alternative locus could be identified that provided superior performance. Although training improved visual performance, it probably resulted from enhancement of patients' psychological status and skill acquisition.

This study has demonstrated the usefulness of the SLO in the functional evaluation of vision and its potential for optimising the use of residual vision in patients with macular disease.

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ACKNOWLEDGEMENTS

For enlightenment, guidance and patience I owe a great debt of gratitude to my supervisors John Marshall and Fred Fitzke. I am very appreciative of their continued help and encouragement.

In addition I would like to thank:

George Timberlake for advising

Robert Kempson for assistance with statistical analysis

Chris Jubb and Ann Patmore for technical advice

Consultants at Moorfields Eye Hospital and St Thomas' Hospital for allowing access to their patients

The patients for their effort and interest

Staff and friends at Institute of Ophthalmology, Moorfields and St Thomas' Hospitals, in particular Janet Silver and June Krafft, for their help

My family and Dominic McHugh for their support and encouragement.

I am grateful to the Royal National Institute for the Blind and the British Retinitis Pigmentosa Society for funding this work.

OBJECTIVES

The primary aim of this study was to examine the concept that low vision training influences the reading ability of patients with macular disease.

This concept was evaluated in relation to the following objectives:-

1) To utilise the scanning laser ophthalmoscope to investigate visual performance at different retinal locations in normal observers and patients with macular disease;

2) To develop a system to present stimuli, including text, to chosen retinal locations and to evaluate the effects of eye movements;

3) To develop stimuli to minimise the effects of eye movements;

4) To assess the role of the scanning laser ophthalmoscope in direct visualisation of the fundus with superimposed visual stimuli for determining the existence and distribution of residual visual function in patients with macular diseases.

PART 1: INTRODUCTION

1.1 Macular Disease

1.1.1 Macular disease and the nature of vision loss

The term macular disease encompasses a group of conditions with different and, in most cases, poorly understood aetiologies. Such conditions may be divided into two main categories: acquired and hereditary diseases. A feature common to all these disorders is the degradation of central vision and in some, metamorphopsia and loss of colour vision are also apparent (Swann and Lovie-Kitchin, 1990; 1991).

The visual defect can vary from a slight disturbance to total extinction of central vision depending on the type and extent of the macular disorder. In most macular conditions peripheral retina is unaffected and visual function remains good (Sunness et al, 1985). However, paramacular retina may have a loss of sensitivity (Brown and Lovie-Kitchin, 1987). Residual vision depends upon the shape, size, density and location of the retinal lesions.

At present, the therapeutic options for macular disease are limited. In the absence of an effective treatment modality, patients must attempt to maximise their residual visual potential. Low vision rehabilitation therefore has an important role in patient management.

1.1.1.1. Acquired macular disease

Of this group of conditions, senile or age-related macular disease (ARMD) is the most common. Its aetiology is unknown but is related to age (Vinding et al, 1992). Other risk factors have been studied (Kahn et al, 1977; Delaney and Oates, 1982; Ferris, 1983; Blumenkranz et al, 1986) and there have been suggestions that it may have a genetic predisposition (Hyman et al, 1983) and that environmental factors such as light exposure (Marshall, 1987; Young, 1988), cigarette smoking and personal characteristics may be involved (Hyman et al, 1983). It is a bilateral condition, the average age of onset in the first eye being 65 years, with a 12% annual incidence of second eye involvement (Kanski, 1989). The demographic distribution of ARMD shows some individuals presenting with this condition in

their 40s. In general, in individuals presenting under the age of 55 the term juvenile ARMD is used.

Microscopic age-related changes occur before any clinical abnormality becomes manifest. These changes include an accumulation of lipofuscin within the retinal pigment epithelium (RPE) and thickening and hyalinisation of Bruch's membrane (Sarks, 1976). The earliest clinical signs are the appearance of small, discrete drusen which are focal collections of hyaline material located between the basement membrane of the RPE and inner collagenous layer of Bruch's membrane. Drusen are thought to form as a result of a gradual accumulation of molecular debris in this region due to incomplete phagocytosis of rod and cone membranes by the RPE (Marshall, 1987). Although these early changes may have little affect on vision, they may be precursors to conditions which may produce serious visual deterioration (Sunness et al, 1989). Such conditions are:

a) non-exudative "dry" ARMD or

b) exudative "wet" ARMD.

a) Non-exudative ARMD

This condition is also known as atrophic ARMD, or geographic atrophy. It is characterised by areas of atrophy of the RPE and neurosensory retina. The choriocapillaris is also involved and in advanced stages larger choroidal vessels become visible ophthalmoscopically within the lesion.

There is no medical treatment for this disease (Bressler et al, 1988). Because progression is slow and inexorable over a number of years, there is often time for the patient to adjust to the gradual decrease in detailed central vision. This time course also facilitates the rehabilitation of such patients by the use of magnifying devices of progressively increasing power.

b) Exudative or neovascular ARMD

The various manifestations of this condition include choroidal neovascularisation, serous or haemorrhagic detachment of the RPE, fibrovascular

disciform scarring and vitreous haemorrhage (Bressler et al, 1988).

In neovascular ARMD it is thought that as a result of the build up of extracellular material beneath the RPE, macrophages are attracted into this region. In order to enter Bruch's membrane degradative enzymatic activity takes place and a pathway is created for blood vessels to proliferate from the choriocapillaris. Such vessels may come to lie within Bruch's membrane, beneath the RPE or between the RPE and neurosensory retina. These vessels are known as choroidal neovascular membranes (CNVM) or subretinal neovascular membranes (SRNVM).

Visual loss is usually severe and rapid (days or weeks). If a neovascular membrane (NVM) is detected early during its development and if the NVM is at some distance from the fovea laser photocoagulation may be beneficial (Moorfields Macular Study Group, 1982; Jalkh et al, 1983; Coscas and Soubrane, 1983; Macular Photocoagulation Study Group, 1982 and 1986a). Even when treatment is successful some visual deficit will persist from the disease and more will have been created by the treatment. In addition, the high recurrence rate of new vessel formation, means that visual prognosis in the long-term may be poor (Moorfields Macular Study Group, 1982; Macular Photocoagulation Study Group, 1986b; Soubrane et al, 1990). Therefore, visual rehabilitation remains the only practical help for the majority of patients.

Another type of acquired macular disease, which is more rare than ARMD, is macular hole (Kornzweig and Feldstein, 1950; Gass, 1987). The second eye is affected in about 10% of cases (Kanski, 1989). The neurosensory retina in the foveal region is thin and it is therefore susceptible to hole formation. Most holes are idiopathic in nature, but myopia (Kanski, 1989) and trauma (Frangieh et al, 1981) are associated findings. Macular holes may be classified into different types and stages ranging from an impending hole to a full-thickness hole with fluid rim (see Gass, 1990). Visual deterioration is usually rapid but limited. The subsequent central field defect will depend upon the type and exact location of hole and the amount of fluid in the surrounding retina (Smith et al, 1990; Acosta et al, 1991;

Kothe et al, 1992). Most holes in the macular region are considered inoperable, although recent studies suggest that surgery may be helpful in some cases (Kelly and Wendel, 1991; Mein and Flynn, 1991).

1.1.1.2 Hereditary macular disease

Unlike the acquired forms of macular disease, juvenile macular disorders occur relatively infrequently and have a strong genetic basis. The more common conditions include cone dystrophy, Stargardt's dystrophy/fundus flavimaculatus and Best's disease.

In cone dystrophy the appearance of the macula is typically described as a "bull's eye" as it has a distinct colour distinguishing it from the rest of the fundus (see Gass, 1987). This appearance is thought to be due to selective atrophy of the RPE cells. Most cases are sporadic, but when familial they are usually autosomal dominant. Visual loss begins in the first to third decades of life although in the severe form the macular changes are more extensive at an earlier age (Kanski, 1989). Visual performance is often better in decreased illumination, when cone photoreceptors are supplemented by rods functioning at their optimal level (Sloan, 1969).

Stargardt's dystrophy and fundus flavimaculatus are usually considered variants of the same disorder (see Gass, 1987). Stargardt's begins with a non-specific mottling at the fovea, this later extends to an oval lesion approximately 1.5 disc diameters in size with a beaten bronze appearance. In most patients the condition is autosomal recessive but it can also be dominantly inherited. Loss of central vision usually begins in the first to second decade of life due to atrophic changes in the choriocapillaris and RPE and associated atrophy of the photoreceptors. This disease process is confined to the macula and does not progress outside this region, even with advanced age. With fundus flavimaculatus yellow flecks of hyaline material are prominent throughout the posterior poles of both eyes. New flecks usually appear to be dense with distinct edges whereas older flecks resorb and

appear ill-defined and softer. Vision tends to remain better relative to Stargardt's dystrophy and patients may remain asymptomatic until the foveola becomes involved.

Best's disease has autosomal dominant inheritance and recent research has shown the defect to be located on chromosome 11 (Stone et al, 1992). The disease has several phases and variable manifestations, for example, the lesions may be unilateral or bilateral, single or multiple and central or eccentric (see Gass, 1987). The condition is characterised by yellow spots, thought to be an abnormal accumulation of lipofuscin granules within the RPE. These so called "egg yolk" lesions are 0.5 to 3 disc diameters in size but vision at this stage is often normal. Acuity begins to decrease at a later stage when the egg yolk begins to break up and assumes a "scrambled egg" appearance.

1.1.2 Epidemiology

The Department of Health and Social Security (DHSS) compiles registers of visually handicapped persons in the United Kingdom. In England in 1988, 126,828 people were on the blind register and 79,048 were on the partially-sighted register (DHSS, 1989).

These figures are known to be a gross underestimation of the actual incidence of visual disability in the general population (Cullinan, 1977; Bruce et al, 1991; Robinson et al, 1994). A Royal National Institute of the Blind report, based on field work, estimated that in Great Britain the number of people aged 16 or over who were eligible for blind and partially-sighted registration was 319% and 839% higher than the official Department of Health figures (Bruce et al, 1991). As all DHSS figures relate to registration, part of the underestimate may result from a reluctance of ophthalmologists to register patients and part may be due to resistance by patients to a perceived stigma of registration. Inadequacies in the registration process and suggestions for improvement have been discussed by Wormald and Evans (1994). The total number of individuals eligible for registration in Great Britain in 1987 was estimated to be 959,000 (Bruce et al,

1991).

Macular disease is the most common cause of untreatable visual loss in the elderly (Lovie-Kitchin et al, 1982; Chan and Billson, 1991). On the DHSS register in 1981 for the newly blind category (i.e. prevalence), diseases of the macular and posterior pole accounted for 8% of cases in the age group under 65 years, 36% in the age group 65 to 84 and 51% in the over 85s (DHSS, 1988). The incidence of blindness from birth to 10 years of age is 4 per 100,000. This rises to 5300 per 100,000 over the age of 65. Given that in the UK blindness is predominantly a problem of the elderly it is not surprising that ARMD is the single greatest cause of untreatable blindness. One of the most comprehensive sets of epidemiological data on ARMD comes from the Framingham Eye Study (Khan et al, 1977; Leibowitz et al, 1980). The overall prevalence of ARMD was found to be 9%, with a prevalence rate of 2% in the age group 52 to 64, rising to 11% at age 65 to 74 and 28% at 75 to 80 (Kini et al, 1978).

As discussed by Marshall (1985), both the numbers and proportions of elderly people in western societies is dramatically increasing (Office of Population Censuses and Surveys, 1983) and by the end of this century 15.5% of the population will be over 65 years of age. The number of sufferers of ARMD is bound to increase unless novel treatment regimes or prophylactic measures become available.

While hereditary retinal dystrophies account for a very small number of total cases of visual loss in the community, they represent a significant proportion of cases in the younger age group. Two and a half percent of individuals on the newly blind register in 1981 suffered from these conditions; the distribution across the age groups was: 9% aged below 65, 1% 65-84 and 0.5% over 85.

In summary, a substantial proportion of the population suffer from macular disease. In the absence of effective treatment, patients must attempt to maximise their remaining visual potential. A better understanding of residual vision in macular disease is required so that rehabilitation may provide maximum benefit.

1.2 Evaluation of Macular Disease

Clinical evaluation of a patient with macular disease requires appraisal of symptoms and history, visual function and appearance of the fundus. Imaging techniques and psychophysical and electrophysiological tests may aid diagnosis and indicate the visual potential of the remaining retina.

1.2.1 Imaging

The ocular structures can be viewed with a direct or indirect ophthalmoscope or a slitlamp biomicroscope. Fundus photography can be performed if a record of the image is needed. The major problem associated with instruments designed to examine the inside of the eye is that a large amount of light must be incident upon the fundus in order that a useful image can be obtained from the small amount that is reflected back out of the eye. Conventional instruments therefore demand a large pupil to achieve maximum retinal illuminance. The high light levels of these methods may cause the patient discomfort and even potential damage (Delori et al, 1980).

One concept of limiting retinal exposure during ophthalmoscopic examination is to use a small intense beam of light and to scan the beam across the retina. The earliest instrument to examine the fundus using such a scanning spot of light was reported by Ridley (1952). The patient viewed a cathode ray tube and the scanning spot illuminated the retina. A second cathode ray tube, synchronised with the first, reproduced the fundus image. Although initially unreliable, the inventor recognised the potential of such an instrument.

In 1980, a scanning laser ophthalmoscope (SLO) was demonstrated (Webb et al, 1980; Webb and Hughes, 1981; Webb, 1983). This device produced continuous, real-time images of the ocular fundus on a TV screen. It was designed as a recording ophthalmoscope and as such could produce fundus images by using 1000 times less light than conventional indirect ophthalmoscopy (Mainster et al, 1982).

Optically it is fundamentally different from standard imaging instruments, e.g.

cameras and indirect ophthalmoscopes (Woon et al, 1990). It also has the advantages that low light levels mean virtually no patient discomfort and the use of a small beam means that the effects of opacities in the media are minimised (Webb et al, 1981).

The SLO can be used to generate images at any level in the retina by the use of apertures. The shape and size of the aperture allows the system to operate in different modes, i.e. non-confocal, confocal and indirect (Webb and Delori, 1989; Woon et al, 1992). Early SLO models used the non-confocal mode (wide open aperture) where all light reflected out of the eye contributed to the TV image. Development of the confocal mode improved image contrast and provided axial resolution. Here a small aperture, located in the conjugate plane, allows light from only a thin slice of retina to reach the detector. The indirect mode of operation employs a different principle; instead of using an aperture, a central stop is introduced. In this case, only structures that cause light to be scattered outside the stop are imaged and these are seen as bright objects against a dark background.

During examination of the fundus, the wavelength of light selected will influence the structures imaged. Superficial retinal structures can be observed using shorter wavelength light (e.g. blue) while deeper lesions are imaged better with longer wavelengths (e.g. red or infrared). Typically, the laser in a SLO is a Helium-Neon (He-Ne, 633nm). This radiation is visible and the brightness of the raster during long testing periods can be tiring for the subject. As an alternative, an infra-red diode laser (IR) can be used to image the fundus using a wavelength that is barely visible to the subject, e.g. 780-830nm. This not only improves patient comfort but also maintains a large pupil diameter by minimising the retino-pupillary reflex. Imaging with IR light alone produces resolution comparable to He-Ne images (Fitzke et al, 1991), but retinal vessels have relatively reduced contrast (Plesch and Klingbeil, 1989). Elsner et al (1992) have used a 830 nm laser in a SLO to view deposits, hyperpigmented areas and other sub-retinal structures in patients suffering from ARMD.

Fundus angiography is a valuable technique for studying the retinal and choroidal circulations and for demonstrating disease processes affecting the fundus (Rosen, 1969; Schatz et al, 1978). This procedure has been used routinely for 30 years and has had a great impact on the treatment and management of patients. In this technique the dye sodium fluorescein is induced to fluoresce by an excitation beam of 490nm. The excitation beam is produced by filtering the emission of a flash lamp. Conventional fundus photography can be used to obtain images at 1 second intervals over a period of typically 25 seconds.

Limited work has been done using sodium fluorescein in conjunction with high performance video cameras and video angiography has not proved popular with clinicians. More recently, fluorescein angiography has been performed with a SLO incorporating an argon laser (Webb et al, 1982; Gabel et al, 1988). Resolution is equivalent to angiograms taken with a fundus camera and is sufficient for investigations of ocular haemodynamics (Rehkopf et al, 1990; Wolf et al, 1990; Tanaka et al, 1991; Lui et al, 1992). Again, due to the light efficiency of the system, the laser stimulating the dye to fluoresce produces relatively lower retinal irradiance and patients are more comfortable (Nasemann and Muller, 1990). Another advantage of using the SLO system is that images of the retina are recorded continuously on videotape at a rate of 24 frames per second.

One limitation of conventional angiography is that it uses an excitation wavelength of 490nm in the visible spectrum. This wavelength is absorbed strongly by the RPE and therefore insufficient radiation passes through in order to achieve useful fluorescence of the choroidal vessels. The possibility of using IR diode lasers in association with a dye that could be induced to fluoresce by IR radiation would minimise the problems caused by the RPE and allow observation of the choroidal circulation. A suitable dye, indocyanine green (ICG), was introduced for angiography in 1971 (Hochheimer, 1971). However, using conventional methods then available excessive amounts of light were necessary for excitation and fundus examination was limited to 10 seconds. In contrast, the SLO with its low light levels

has proved to be an excellent instrument for infrared angiography (Scheider et al, 1990).

1.2.2 Assessment of visual function

Individuals with macular disease can suffer a wide variety of visual impairment, from a slight disturbance to total extinction of central vision. In order to determine the extent of the deficiency and the utility of the residual vision a comprehensive assessment of visual function is necessary.

Common clinical tests include: distance acuity, near and/or reading acuity and visual fields. Such tests give a minimal measure of the patients' ability to perform visual tasks and they may not accurately define the visual status of the individual. In this study, to further investigate performance other more time-consuming and informative tests were deemed appropriate; these included tests with reduced contrast targets and assessment of fixation and the retinal location used for viewing.

1.2.2.1 Visual acuity

In clinical practice, visual acuity is "determined from the size of the smallest line of letters or symbols on the test chart that can be read by the patient after any defects of focusing, other than aberrations, have been corrected" (Bennett and Rabbetts, 1989).

Many tests of distance visual acuity are available (Bennett, 1965; Bennett and Rabbetts, 1989). The most common, the Snellen chart, has a number of design deficiencies (Rubin, 1989). In contrast, the Bailey-Lovie chart has the important features appropriate for evaluating both normal subjects and those with impaired vision. Essentially, the test task is the same at each level on the chart. This is achieved by providing letters of equal legibility, the same number of letters on each row, uniform between-letter and between-row spacing and a logarithmic progression of letter size (Bailey and Lovie, 1976).

Tests of near acuity are used to assess reading vision. There is some debate about which form a reading chart should take (Rubin, 1989). Unrelated words that

do not form a sentence, e.g. Bailey-Lovie word reading vision chart, do not provide contextual information, hence the patient is less likely to guess correctly (Bailey and Lovie, 1980). However, meaningful text, e.g. the near vision reading chart recommended by the Faculty of Ophthalmologists, provides a task that relates to the patient's daily life.

Suitable illumination of the test chart is essential (Sheedy et al, 1984). Patients with ARMD often have optimal visual performance when the illumination is well above normal, conversely some patients, e.g. those with cone dysfunction, require lower luminance (Sloan, 1969).

The conventional tests of visual acuity hope to determine the best acuity an individual is capable of achieving. Therefore it is assumed that a patient with a field defect intuitively utilises optimally functioning retina when viewing the chart. However, these standard methods do not encourage use of different retinal areas, and the clinician has no control over the placement of the acuity target on the retina. Walsh et al (1984) addressed this problem by developing a "full-field" visual acuity test which consisted of a regular two-dimensional array of identical Snellen Es. Compared to standard testing, improved acuity was recorded in 90% of patients with macular degeneration. With the same test, Harris et al (1985) demonstrated that 70% of macular patients have potential for visual acuity at least two times better than previously measured by conventional means. Such results would imply that patients do not always intuitively find the best area of retina for acuity tasks. However, the test gives little indication to the examiner as to where the improved visual function is located.

A more informative method for investigation of visual acuity in defined retinal areas is acuity mapping with the SLO (Mainster et al, 1982; Timberlake et al, 1987a). In this procedure the information is encoded into the scanning laser beam such that visual stimuli are projected onto the patient's fundus. The operator can view simultaneously the fundus and the precise location of the target on the retina throughout the test. Different retinal loci can be selected by the operator without

the cooperation or the knowledge of the patient. Snellen Es and square Landolt Cs have been used in the SLO for both normal and low vision subjects (Mainster et al, 1982; Timberlake et al, 1987a). The subject responded to the orientation of the testing target by pressing a button representing the up, down, left or right position (Mainster et al, 1982).

Timberlake et al (1987a) used this method to produce acuity contour maps in normal subjects. Equipment constraints on the apparatus used resulted in the minimum size of acuity target available being equivalent to 6/18. Since this was not small enough to assess the threshold of acuity in the foveolar region, contrast was varied. By presenting targets of contrasts 99% (high contrast), 50% (medium) and 20% (low) for 0.5 seconds along eight major meridians, at eccentricities of 2, 6 and 10 degrees, isoacuity profiles were determined. With the low contrast targets marked meridional asymmetries were found with threshold acuity being better in the nasal and superior retina. The findings were similar with medium contrast targets but were not apparent with high contrast targets.

Visual acuity is limited by optical and anatomical features of the eye. Central vision is affected by optical degradation and is limited to about 60 cycles/degree (Campbell and Green, 1965; Campbell and Gubisch, 1966). Outside the central region visual resolution falls more rapidly than optical factors account for (Jennings and Charman, 1981). Variations in acuity with eccentricity are influenced by receptor density, receptive field size and the amount of visual cortex available. Anstis (1974) designed an acuity chart which compensated for these factors and presented the subject with equally readable letters at increasing eccentricities.

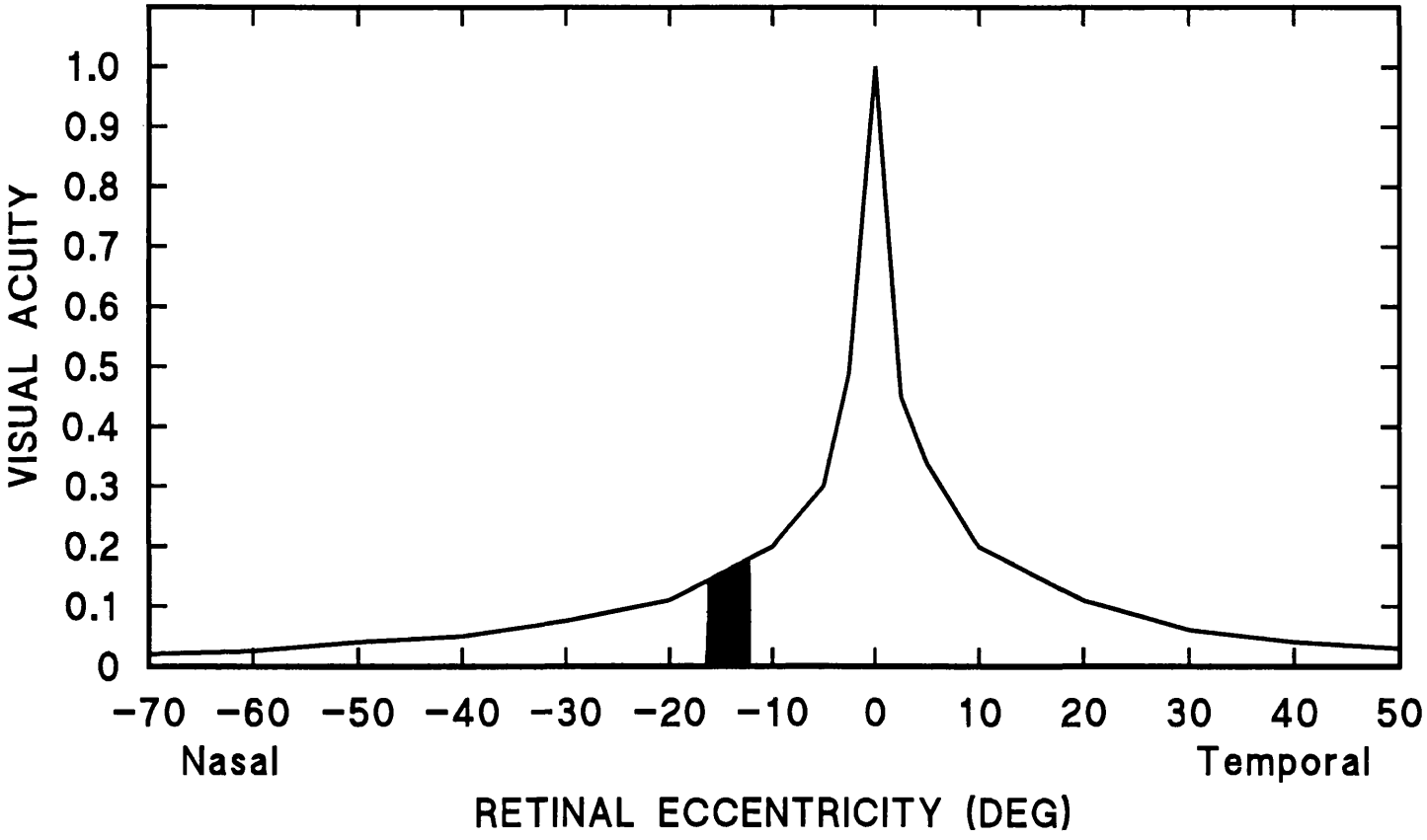
In his classic study, Osterberg (1935) showed that photoreceptor density peaks at the fovea and falls dramatically with eccentricity. More recent and extensive studies have provided a detailed account of human photoreceptor topography (Curcio et al, 1987; Curcio et al, 1990). Cone distribution is radially asymmetrical and isodensity contours are elliptical. Cone density is higher in the horizontal than the vertical and slightly higher in the midperipheral inferior compared to superior retina. Also,

density is greater in the nasal compared with the temporal retina. The horizontal elongation of the contour may appear in the fovea itself, whereas the nasotemporal asymmetry is not present until a more peripheral location is reached. A high degree of variability in maximum cone density at the fovea is apparent in normal young adult eyes (Curcio et al, 1987). Rod photoreceptor distributions are also asymmetrical; density is greater superiorly compared with inferiorly and temporally compared with nasally (Curcio et al, 1990).

Low convergence of foveal cones onto individual ganglion cells preserves high resolution in the fovea, but there are suggestions of meridional differences in cone convergence with increasing eccentricity (Curcio and Allen, 1990). Ganglion cell density is greatest in a horizontally orientated elliptical ring around the fovea. In peripheral retina, densities in the nasal area exceed those in the equivalent temporal area by over 300%; densities in the superior exceed the inferior by 60% (Curcio and Allen, 1990). The representation of the retina in the visual cortex is non-uniform; a solid degree of central retina is mapped to a much larger area of the cortex than a solid degree of peripheral retina (Daniel and Whitteridge, 1961; Rovamo and Virsu, 1979). It has been suggested that cortical magnification is proportional to ganglion cell density throughout the visual field (see Curcio and Allen (1990) for discussion).

These anatomical features can be related to visual performance. Visual acuity is maximal at the fovea and drops dramatically with increasing eccentricity (Ludvigh, 1941; Low, 1951; Randall et al, 1966). One of the earliest and most quoted studies is that of Wertheim (1894) whose results are illustrated in Figure 1. In addition, differences in meridional acuity exist. Acuity isopters are flattened horizontally and have the greatest extent in the temporal field (i.e. nasal retina) (Weymouth et al, 1928). These results are in agreement with cone and ganglion cell distribution. The results of Timberlake et al (1987a) agree by demonstrating maximum visual performance in nasal retinal regions. By using an interferometer, Anderson et al (1992) showed that nasal retina provides the best resolution acuity and such

FIGURE 1: THE RELATIONSHIP BETWEEN VISUAL ACUITY AND RETINAL ECCENTRICITY



From Wertheim (1894)

performance in the peripheral retina is limited by ganglion cell density. If the anatomical features are applicable to patients with macular disease then the most effective residual vision would be in the nasal retinal region.

As a clinical guide, acuity at the fovea is 6/6; at 1 degree eccentricity it is 6/9; at 1.5-2 degrees it is 6/12 and at 3-5 degrees it is 6/18 (Bennett and Rabbetts, 1989). These values may not be necessarily applicable to the diseased eye.

1.2.2.2 Low contrast targets

Visual acuity tests measure resolution of small, high contrast targets, but provide little information about the patient's ability to see low contrast patterns, for example, faces. Contrast sensitivity measurement has become important because it provides vital information for predicting performance on everyday visual tasks (Bennett and Rabbetts, 1989). Indeed, contrast sensitivity functions may predict mobility performance (Marron and Bailey, 1982) and may give a good indication of potential reading speed in low vision patients (Rubin, 1986).

Contrast sensitivity has been shown to vary with eccentricity (Rijsdijk et al, 1980). Sensitivity contour maps in normal subjects show a more rapid decrease for all spatial frequencies in the vertical than in the horizontal. Also, sensitivity in the upper half of the field is less than in the lower half of the field.

Contrast sensitivity in normal subjects declines with increasing age, particularly in the intermediate and higher frequencies (Sekuler et al, 1982). The relative importance of potential causes such as decrease in retinal irradiance induced by reduction in pupil diameter and increased absorption by the ocular media, are discussed by Weale (1992). Abnormally high loss of contrast discrimination has been reported in patients with macular disease (Loshin and White, 1984; Mitra, 1985; Brown and Lovie-Kitchin, 1987).

Age-related changes in contrast sensitivity are also demonstrated in low contrast visual acuity (Adams et al, 1988; Lovie-Kitchin, 1989). Again this is reflected in low vision patients, many of whom have decreased tolerance to contrast reduction when reading text (Rubin and Legge, 1989).

1.2.2.3 Central field defects

In all macular disease it is important to detect and monitor the progression of central field defects. The presence or absence of a central scotoma is a stronger indicator of reading speed than is visual acuity (Legge et al, 1985b).

1.2.2.3.1 Retinal scotometry

1.2.2.3.1.1 Conventional methods

Originally tests for visual fields were designed to detect the absolute margins of vision, e.g. Goldman perimeter. More recently, emphasis has been directed towards accurately locating and detecting distribution of central areas of visual loss. The advent of computerised systems, such as the Humphrey field analyser, has allowed accurate determination of central scotoma. In relatively small areas of visual loss precise fixation becomes more important. Patients are required to maintain a precise eye position by fixating a central target. Those with a central scotoma may find this a difficult, if not impossible, task. The fixation target, usually a cross, can be extended in size such that it falls on a viable area of retina. The patient is instructed to direct their eye at the imagined centre of the target. In some instruments the patient's eye can be monitored to ensure that loss of fixation and associated gross eye movements are noted.

1.2.2.3.1.2 Scanning laser ophthalmoscopy

In order to address the problem of eye movements retinal mapping can be performed with a SLO. The operator knows the precise location of the stimulus on the retina and if eye movements are made they can be analysed and corrected.

Early retinal mapping performed with an SLO did not have the advantage of computer controlled graphics. Instead a manually controlled neutral density filter with a 25-50 um pinhole was used to produce the mapping stimulus (Timberlake et al, 1982). In addition, the fixation target was external to the raster. Development of the acoustooptic modulator (AOM, see Appendix I) allowed sophisticated stimuli to be incorporated into the scanning laser beam. Both the fixation cross and the

mapping stimulus were projected in the raster and were under joystick control (Mainster et al, 1982). At that time scotoma mapping was recognised as having two main applications: 1) to provide the ophthalmologist with additional knowledge on the status of the retina prior to laser treatment and 2) to provide information on low vision patients in order to aid rehabilitation.

The basic techniques involved in SLO microperimetry have been reviewed in detail by van de Velde et al (1990).

1.2.2.3.1.3 Amsler grid

Amsler grid tests are generally considered a quick, practical method for detecting defects in the central 20 degrees of the visual field (Amsler, 1953). They are clearly the least expensive and most useful home testing device for patients with potential macular conditions. Many clinics issue such charts to patients who have experienced ARMD in one eye in order to detect an early problem on the second eye.

Although often cited as a sensitive indicator of macular function (Silverstone and Hirsch, 1986) some studies have shown that patients with retinal defects may report normal Amsler grids (Fine et al, 1986; Schuchard, 1993). The sensitivity may be increased by presenting the grid at levels of illuminance that approach threshold values either using crossed polarised lenses to decrease the light entering the eye (Wall and Sadun, 1986), or by projecting the grid in a SLO and controlling its illuminance (Mainster et al, 1982; Schuchard, 1992). The latter method also has the advantage that the operator can view the patient's fundus on the TV monitor and know the precise retinal location of the grid. In addition, the area chosen by the patient to view the central dot of the grid can be determined. In contrast, with the conventional method of Amsler grid testing the patient's fixation cannot be monitored directly.

By presenting Amsler grids at "standard" and threshold values, Schuchard (1992) found that of 89 eyes with central scotoma over 40% were not recognised. Even

when detected, the full extent of the scotoma, compared to hybrid static microperimetry with the SLO, was rarely appreciated. The author suggested that the result obtained with an Amsler grid is often an indication of patients' ability for perceptual completion rather than true retinal function.

1.2.2.4 Fixation

Even when a normal subject attempts to fixate, the eyes are in constant motion as a result of small eye movements (Yarbus, 1967). Such movements can be categorised into three main types (Ditchburn, 1973a): (1) "drifts", periods of fairly slow movement of median amplitude 2-5 minutes of arc (min arc), (2) saccades, occasional sharp movements usually less than 10 min arc, (3) tremor, small irregular oscillatory movements of amplitude of 1 min arc or less. Drifts and saccades determine the accuracy of fixation since they produce larger movements than tremor. In low vision subjects fixation stability is usually less good than in normals (Timberlake et al, 1986; Whittaker et al, 1988a and 1988b) and a detailed assessment of this function is helpful because without a reasonably stable image, reading ability is compromised.

Fixation has been studied previously, but mainly using stationary disc-type (Steinman, 1965; Rattle, 1969; Sansbury et al, 1973) or square (Kosnik et al, 1986) target arrays, cross-hair targets (Adler and Fliegelman, 1934; Nachmias, 1959) or single letters (Whittaker et al, 1988a).

Classical methods for recording eye movements which occur during fixation have been reviewed by Ditchburn (1973b); the more common ones include such devices as search coil eyetracker (Robinson, 1963), Purkinje-image eyetracker (Crane and Steele, 1978), and contact lens techniques (Ratliff and Riggs, 1950; Nachmias, 1959). More recently the SLO has been used to study fixation (Timberlake et al, 1986; Schuchard, 1991). The advantage of the SLO system is that the visual stimuli are viewed continuously on the subject's fundus image, i.e. fixation is assessed directly by comparing stimulus position with retinal features. Further, algorithms have been developed that allow analysis of torsional eye movements (Ott and

Eckmiller, 1989; Ott and Lades, 1990).

Early work on fixation in individuals with central scotomas was undertaken by von Noorden and Mackensen (1962). More recently and with the benefit of new technology in the form of the SLO, Timberlake et al (1986) investigated fixation in three patients with macular disease. Presentation of a square, black target (42x42 min arc) with a bright centre (14x14 min arc) showed that each individual chose to use a single fixation locus, but in none of the three was there any attempt to place the target on the foveola. In one patient an island of vision within an otherwise scotomatous area was discovered. The fixation of these patients was poor compared to the normal observers utilising foveal vision, however, it was as good or better than the fixation of normals attempting to fixate eccentrically. Further, fixation ability did not appear to be related to the eccentricity of the fixation locus.

Schuchard (1991) studied fixation and visual search performance in 3 normal subjects, 4 patients with age-related macular degeneration, 3 with retinitis pigmentosa and 1 with macular oedema. Most patients utilised a single retinal location for fixation, but two patients with central vision loss demonstrated multiple loci. Similarly, Whittaker et al (1988a), using a search-coil eyetracker (i.e. non-SLO) technique, found 39% of subjects with central scotoma adopted two or more distinct PRLs and multiple PRL were more likely if the scotoma exceeded 20 degrees in size. Further, fixation variability increased with scotoma size but rose abruptly when the scotomas exceeded 20 degrees.

In summary, most patients with macular disease use a single locus for viewing while some appear to utilise multiple loci. Currently, there is insufficient data to relate single or multiple loci to specific reasons or individual preference.

1.2.2.5 Specific retinal locations

In patients with central retinal disease few studies have examined the retinal locations used in relation to specific visual tasks. Such information would be valuable in the understanding of the nature and progress of retinal disease and also

in low vision rehabilitation. Patients with central scotomas either attempt to utilise their non-functioning fovea or they view eccentrically.

A preferred retinal location (PRL) is a term for the area chosen by the patient to perform a given visual task. This location may be spontaneous or may result from a conscious decision made by the individual. Patients may have single (Timberlake et al, 1986) or multiple (Whittaker et al, 1988a) PRLs. Alternative retinal locations (ARLs) are substitute areas which are not the patient's first choice.

The location of PRLs in relation to scotomata have been investigated in patients using the SLO (Guez et al, 1993; Fletcher and Schuchard, 1994). In three patients with macular disease studied by Timberlake et al (1986) there appeared to be no simple rule by which the PRLs were selected. They were at different retinal eccentricities in each patient and were not always as close as possible to the foveola. Two patients read text more rapidly with an ARL than with a PRL. This suggests that PRLs may not always provide optimal visual performance for a given task.

Some of the most crucial questions for low vision rehabilitation are: 1) Do patients automatically choose the "best" retinal location for a given task? 2) What constitutes the "best" retinal location? Is a small island of good acuity better than a larger area with relatively poor acuity? 3) Does the PRL change with the visual task or the size of the retinal image?

1.3 Scanning Laser Ophthalmoscope (SLO)

The main feature of the SLO is the ability to view a continuous, real-time TV image of the fundus. The characteristic that makes the instrument invaluable for psychophysical measurements is the facility to observe the location and distribution of visual stimuli on the subject's fundus.

1.3.1 Background

The Flying Spot TV Ophthalmoscope was originally designed as a light-efficient ophthalmoscope (Webb et al, 1980). With development, it has been renamed the

scanning laser ophthalmoscope and has proven to have unexpected virtues in the areas of psychophysics, high contrast imaging, optical sectioning and video angiography. See earlier chapter (section 1.2.1) on imaging.

Development of the SLO system has extended its potential beyond that of an ophthalmoscope and into the domain of an unique instrument for psychophysical measurements. In order to achieve this, two obstacles had to be overcome. First, specific visual stimuli had to be encoded into the raster and second, such encoding could not interfere with the fundus imaging. In the early stages a neutral density filter with a pinhole in it was placed at a point conjugate with the retina and manipulated such that the subject saw a bright spot in the raster (Timberlake et al, 1982). Subsequent incorporation of an acoustooptic modulator (AOM; see Appendix 1) into the system allowed intensity of the illuminating laser beam to be increased or decreased at arbitrary points in the raster such that complex static or dynamic graphics could be produced (Mainster et al, 1982; Timberlake et al, 1986). A computer controls the AOM and any graphics that can be displayed on the computer monitor may be incorporated into the raster. Visual stimuli produced by the SLO are seen in the raster by the subject and in addition can be viewed directly on the retinal image by the operator watching the TV monitor.

A single laser beam is sufficient to produce both the visual stimuli and the fundus imaging, provided the retinal illuminance is relatively high. Typically this laser is Helium-Neon (He-Ne) with a wavelength of 633 nm. This radiation is visible and the brightness of the raster during long testing periods can be uncomfortable for the subject. The introduction of the infra-red diode laser (IR) meant that the fundus could be imaged using a wavelength that was barely visible to the subject, e.g. 800-830nm. Optimum efficiency is achieved if two lasers are used simultaneously; a He-Ne producing the visual stimuli and an IR laser providing the illumination for the fundus imaging.

1.3.2 Patient-SLO interface

The techniques used in the SLO for imaging of the fundus and psychophysical testing are patient-friendly and non-invasive. The patient's head is positioned comfortably on a headrest similar to that used on a slitlamp biomicroscope. Pupillary dilation is not usually required and nothing touches the eye. Further, retinal irradiance is low and therefore the patient experiences no discomfort. Since the laser beam entering the eye is narrow, fundus images can be obtained in patients with media opacities provided a small clear region remains.

1.3.3 Image retention

The images and data collected using the SLO can be stored in a number of ways. The continuous, dynamic TV images are usually recorded directly onto videotape (VHS, superVHS or Umatic). Hardcopy devices, similar to a laser printers, produce an immediate copy of a fundus image from the TV. A computer can be used to digitise and store and enhance single or multiple images. Since images take up a large amount of computer memory, they are more efficiently stored on optical discs.

1.4 Visual Rehabilitation

One definition of rehabilitation is "making fit after disablement". Visual loss causes disruption in all areas of life; work, recreation, relationships and feelings about oneself (Blank, 1957). The ability to function with residual vision varies among individuals and involves many factors, not only visual and disease-related but also psychological and sociological (Wild and Wolffe, 1982). The aim of rehabilitation must be to provide the opportunity for patients to achieve their full potential in life, by assisting their functional and psychological development.

1.4.1 Current methods

Rehabilitation can be considered to consist of two parts; first, the practical assistance and second, the psychological support. Practical help is provided in the

form of low vision devices, both optical and non-optical; for example, magnifying aids, helpful gadgets for the home and advice on lighting and contrast. Psychological support is often supplied indirectly by the help provided by the practical assistance. However, individuals can derive enormous benefit from social support groups (Mehr et al, 1970; Emerson, 1981). Formal rehabilitation courses, available to a few visually handicapped persons, offer tuition in mobility, cooking, and reading skills together with the opportunity to discuss psychological problems.

Rehabilitation techniques and courses vary considerably depending where, i.e. which country or county, and who, i.e. which profession, offers the services. These variations have arisen because of differences in approach to rehabilitation and also financial restrictions. It is widely recognised that low vision services in the United Kingdom (UK) are grossly underfunded (Bruce et al, 1991). This may be one reason why many low vision patients complain about inadequate support.

1.4.1.1 Standard practices in the United Kingdom

In the UK low vision clinics are usually situated in hospitals and staffed by optometrists. A large proportion of patients attending these clinics suffer from macular disease and the most common visual task for which they request help is reading. Vision is carefully assessed and recommendations are made for various optical and non-optical devices. Prescription of aids should be task specific, and magnification should be maintained at the lowest level that allows the task to be performed. Patients return for review at the discretion of the practitioner. For many patients follow-up and reinforcement is important for encouragement of full use of devices and vision.

The efficacy of low vision devices and the benefits which many visually disabled people derive from their use has been well documented (Faes, 1981; Sloan, 1977; Boulton, 1977; Rosenbloom, 1970). Macular degeneration has a relatively good rehabilitation prognosis (Virtanen and Laatikainen, 1991; Banks, 1980; Silver, 1972; Henfi, 1969). In theory, visual performance is enhanced because the magnifying

device enlarges the image such that the detail of an object is placed outside the central scotoma on relatively unaffected retina.

In the UK a different type of low vision service is offered by another group of professionals, namely low vision trainers. It has been stated that the success rate with magnifying devices is considerably improved if patients enter a low vision training programme, however, other than anecdotal evidence there is little to substantiate these claims (Collins, 1987).

1.4.1.2 Low vision training

When a low vision magnifier is prescribed the patient should be "trained" to use the optical device efficiently. Magnifying devices have limitations and disadvantages. It is necessary for the patient to adjust to a reduced working distance, small field of view and small depth of focus. Some practitioners believe that education may be the most important aspect of low vision care (Mehr and Fried, 1975). Whilst it is claimed that practitioners in standard practice ensure that patients have the benefit of full instruction, it may not always be the case.

Low vision trainers consider basic instruction to be inadequate (Backman, 1994). They advocate the use of comprehensive and individually tailored training programmes to ensure the best use of an optical aid and residual vision (Inde, 1978; Nilsson 1986 and 1989; Nilsson and Nilsson, 1994b; Fitzmaurice and Keast, 1984; Fitzmaurice 1985, 1994; Ighe, 1994). Textbooks for optometrists in practice condone this approach but without any obvious critical evaluation (Farrall, 1991; Freeman and Jose, 1991). The programmes are usually based on specialised techniques such as eccentric viewing and steady eye strategy (Collins, 1987). In eccentric viewing the patient is taught the skill of consciously and consistently placing the image of an object onto a non-foveal retinal area which is unaffected by disease. With the steady eye strategy the patient is taught the skill of holding the head and eyes still and moving print passed a fixed line of sight at a set distance.

With a diseased macula the patient is unable to define detail in objects by viewing centrally. By learning to fixate above or below such an object the image will

fall outside the scotoma and thereby improve visual performance. However, in relation to this it may be necessary to magnify the image because acuity of such eccentric regions is less than at the fovea. In theory, the eccentric fixation point should lie just outside the scotoma in order to avoid excessive magnification of the image and to minimise the angle of view; this area should also provide the best visual acuity and sharpest image (Goodrich and Quillman, 1977). In reality, such simple rules may not exist for the determination of the patient's preferred retinal location (Timberlake et al, 1986). Determination of the position, above or below the object, depends on the nature of the scotoma (Inde, 1978). However, Weiter et al (1984) found that when eccentric fixation was present, superior retina was most commonly used. Since English print runs horizontally, the field of fixation (i.e. the amount of text which can be seen while the eye is stationary) should be as wide as possible in the horizontal plane, therefore temporal or nasal eccentric viewing should not be as helpful (Inde, 1978).

Several methods have been employed to teach the patient to locate a target and maintain a steady fixation. Holcomb and Goodrich (1976) described two techniques, one employed a strobe to generate an afterimage on the optimum area of peripheral retina, the other involved verbal direction to encourage the patient to view eccentrically with the appropriate angle. Long training programmes were required (up to fifteen 30-60 minute sessions) and patients' progress was measured by the ability to fixate and recognise tachistoscopically presented letters. The number of patients entered into these programmes was small; however of the two methods, the afterimage technique appeared to be the more effective. Alternative methods include a rotator for teaching visual tracking, fixation and pursuit movements and use of a slide projector for reinforcing fixation, discrimination and recognition of targets (Goodrich and Quillman, 1977). These methods teach "distance" eccentric viewing; however the authors comment that an improvement in reading ability is also a possibility. To date, no objective methods have been used to assess the benefits, if any, of such training programmes. Techniques such as limbal

reflection and/or search coil eyetrackers could clearly provide the required data in this area.

Low vision training programmes which are more clinically orientated started in Sweden in the 1970s (Backman and Inde, 1979). They have become widely available, particularly in Sweden and the USA and more recently have been promoted in the UK. Backman and Inde (1979) developed the basic concepts and techniques and published them in a training manual. Designed for use by the consumer, this book has large print and describes ocular function and different types of eye problems, and it emphasises eccentric viewing training for near vision. Lines above and below individual words aid maintenance of the appropriate fixation angle. The authors state that the techniques are effective, although no results have been published. One investigation in the UK did not support the concept that this programme was beneficial (Culham, 1991).

Training manuals may reduce the costly and time consuming need for one-to-one, patient-to-instructor ratio. However, even with such manuals additional extensive teaching may still be required to produce improved performance.

1.4.1.2.1 Eccentric Viewing (EV) Technique

Most individuals discover eccentric viewing while attempting to perform intermediate or distance tasks such as viewing the television (Collins, 1987). The EV technique develops this concept and makes use of it for near vision tasks. Collins (1987) suggests that an absolute central scotoma is helpful in developing EV techniques, since efforts to acquire them have high reward.

The extent to which the eye is moved from the central point is determined subjectively with the trainer's guidance. Collins (1987) has claimed that an Amsler chart is a useful aid for "refining and identifying the exact angle of best view". Others have advocated a more accurate calculation of the viewing angle, using the formula

$$\tan D = x / WD$$

where D = degrees from the fovea where the image should be placed. WD = working distance, determined by the reciprocal of the dioptres in the aspheric lens. x = the distance from the text to the place above or below, where the eye should fixate to avoid the scotoma (Inde, 1978). However, such calculations are not helpful given the difficulties of fixation within the location and the difficulties of determining the area of retina used for scanning specific objects.

The "clock face" routine allows the patient to appreciate the practical use of EV (Maplesden, 1984). If the trainer's face is imagined as a clock, with the forehead as 12 o'clock and the chin as 6 o'clock, the patient can discover the most suitable viewing angle enabling the facial features to be identified. Successful case studies are reported, but no data or further results are documented. More recently, improved technology has been utilised to provide a computer generated method of training (Fitzmaurice et al, 1993). Once again, positive responses are furnished by case reports alone.

When viewing eccentrically, Maplesden (1984) suggests that eye movements alone are preferable to turning the head which may cause stiff neck muscles and poor posture. However, large numbers of patients utilise postural changes to facilitate EV. Although many practitioners feel that they can predict the angle of gaze from the location of the lesion, Maplesden (1984) has stated that this is not the case.

To encourage EV for near vision, reading exercises with lines or asterisks above and below words are utilised (Collins, 1987). These markers act as a guide to aid maintenance of the viewing angle. Further reading exercises attempt to improve the field of fixation, tracking and localisation ability (Backman and Inde, 1979).

In the early stages of training a typoscope may assist the learning of EV (Collins, 1987). High illumination when reading is usually necessary for low vision patients and the matt black card of the typoscope reduces potential glare, allowing greater comfort. The typoscope also aids tracking across a line of text and location the beginning of adjacent lines.

A marker may be placed on the typoscope to help the patient maintain the best position of view (i.e. EV) while reading. Magnification may also be used in combination with the typoscope. Collins (1987) states that magnification must be kept to a minimum so that the field of view is as wide as possible. However, it is possible that some patients would prefer higher magnification in order to make the task easier.

1.4.1.2.2 Steady Eye Strategy (SES)

The majority of books and papers describing training procedures do not mention the SES, however, Collins (1987) believes it to be essential if the patient is to read with any degree of fluency. He claims that a dramatic improvement in reading speed is possible; 40-60 words per minute could become 100-150 with practise. Watson and Berg (1983) recommend SES when the patient exhibits erratic eye and head movements, or displays an inability to find a line. Individuals who were originally fast readers find it most difficult to adapt to SES since they continue to endeavour to scan text.

It is claimed that after the introduction of EV and SES the power of the magnifier can be dramatically reduced. Reductions from 15X to 8X, from 8X to 2X and from 4X to conventional reading spectacles have been reported (Collins, 1987). The use of weaker magnification would be advantageous since both the field of view and the focal distance would be increased.

Goodrich and Mehr (1986) reviewed published works and current practice in eccentric viewing training. Subjective clinical observation and individual patient reports suggest better functional vision is achieved through training. However, as the authors state, no detailed scientific studies are available to support these anecdotal conclusions. More recently, studies assessing the value of educational training showed that a group of trained subjects had significantly better visual performance than a control group of untrained subjects (Nilsson, 1990b; Nilsson and Nilsson, 1994b).

In order for training to be successful "reprogramming" of the "plastic" visual system is said to be required (Zahn, 1989). Some degree of elasticity and trainability of the human visual system has been demonstrated. Peripheral visual performance is amenable to the learning process (Low, 1943; Saugstad and Lie, 1964) and perceptual ability has been shown to improve with practise (Bruce and Low, 1951). The performance of low vision patients using practise, feedback and instruction techniques has also been examined (Overbury and Bross, 1978). Continued practise was found to be the most important factor for visual improvement, whereas instruction had little benefit over feedback. The results of such studies are relevant to low vision training programmes. First, it indicates that training has the potential to provide improved visual performance. Second, it suggests that practise is more important than expensive, long term instruction.

In summary, low vision rehabilitation aims to optimise visual function but the techniques used are many and varied. None of the current methods appear to be entirely satisfactory. The use of vision aids and illumination have been proven to be beneficial, but in practice patients often do not utilise these to their full effect. Low vision training takes many forms, most of which are poorly described and not validated scientifically. Manpower and financial resources are a severely limiting factor in the provision of low vision services. Since the low vision population is increasing it is essential to determine the benefit/cost elements of rehabilitation techniques.

1.4.2 Areas requiring study

There are several specific areas of study that have not been investigated previously. In low vision rehabilitation of patients with macular disease the image of an object is magnified such that sufficient detail of the object falls outside the central scotoma. However, it is not clear whether patients must also learn to place the magnified image on unaffected, non-foveal retina.

Some patients with macular disease utilise indirect vision, i.e. PRLs, without tuition. It would be helpful to know the proportion of patients that utilise eccentric

vision spontaneously and what factors influence their willingness to reject innate foveal vision. Also it is important to determine whether low vision training improves visual performance over endogenous performance.

All training methods currently available have the inherent disadvantage that the trainer does not know the precise retinal location that the patient chooses to utilise. Further, the trainer cannot be sure that the area chosen by the patient provides the best visual performance. These problems are exacerbated in those patients who do not understand the principle behind eccentric viewing or who cannot communicate effectively. The SLO, with its unique capability of imaging and displaying visual stimuli on the patient's fundus, is ideally suited to studying the effects of low vision training programmes.

1.5 Reading, Pattern Recognition and Image Acquisition

Reading has a number of elements which include image acquisition, pattern recognition and cognitive thought. Speed of reading is probably more related to cortical processing and acquired skills than to straightforward pattern recognition and optical imaging. Image acquisition in normal individuals is good, but in patients with macular disorders it may be sufficiently poor to influence pattern recognition and hence affect reading performance. The present study was designed to isolate cognitive processes and to probe earlier mechanisms, i.e. image acquisition and pattern recognition. Using the SLO, letters can be projected onto the fundus thereby allowing assessment of patients' performance in pattern recognition. By presenting sequences of letters either randomly composed or in the form of simple words some measurement of dynamic pattern recognition can be calculated. When words are used this can be related to reading speed, however, cognitive processes then come into effect. In any given patient, speeds achieved at different retinal locations may be directly compared and will differ on the basis of retinal performance. However, direct comparison of reading speeds between patients would not useful without tests of cognitive skills which have not been undertaken in

this study.

1.5.1 Reading

Reading is a complex skill involving motor (Suppes, 1990), perceptual, memorial and linguistic capabilities (Rayner, 1975a). Providing motor skills are sufficient to locate and stabilise an image, pattern recognition is the next most important task in the reading process.

Krischer et al (1983) state that visual acuity is an essential factor in reading speed. Normal subjects will utilise the fovea when reading, but patients with macular disease and central scotomas may not have sufficient residual vision in this region and eccentric retinal locations may be used.

Age is a primary factor in macular degeneration and there is some evidence that reading speed decreases in normal subjects over the age of 60 (Bouma et al, 1982). Reading rates are especially slow for low vision observers, even when letter size is enlarged to compensate for their visual loss (Bouma et al, 1982). As with all performance skills there is individual variability and some low vision subjects maintain good reading speed even with small print. Reading speed is important in maintaining comprehension and at least 20 words/minute should be achieved for patients to understand text (Bouma et al, 1982).

Sloan and Habel (1973) have reported that reading speed may be related to image size, or the size of the text characters on the retina and that this is independent of whether a large character size is used to generate the image or whether a small character is magnified through visual aids. This suggests that results obtained in the present study, using large retinal images produced by the SLO stimuli, can be related to the situation of reading with a magnifying device.

Skilled normal readers use peripheral vision to gather information on gross text characteristics such as word shape and first and final letters of words (Rayner, 1975b). It has been suggested that in the training process of learning to read, specific retinal areas become more capable of reading efficiently (Mishkin and

Forgays, 1952). Such a concept would imply that individuals from those cultures that read from left to right may have a more highly developed functional role in the right visual field. The concept of specialised non-foveal areas of the retina involved in reading has important implications in low vision rehabilitation. The location and extent of lesions may give rise to more profound visual loss as a result of compromising such areas. Conversely, it may be that with training patients could be induced to utilise these partially pre-programmed locations.

1.5.2 Text characteristics

In any psychophysical analysis of reading skills, attention must be paid to the way in which text is presented. Visual factors which influence reading include the form, size, contrast, legibility and presentation of text. Text may also vary in type style, height-width ratio of characters and colour. Observer variables include viewing angle and distance, viewing time and illumination (Erdmann and Neal, 1968).

1.5.2.1 Form, size, contrast and legibility

Text may be presented in the form of isolated letters, non-sensical words, single words or complete sentences. High contrast between text characters and background is one of the most important characteristics in defining legibility of written material. In many reading situations high contrast text is presented although exceptions do occur frequently, eg. text printed on glossy paper. Low contrast targets are more difficult to determine in both normal and patients groups (Legge et al, 1987). Such targets may determine subtle differences between retinal locations in a given individual. Therefore, in the present study some low contrast targets were utilised. However, for screening purposes the majority of targets presented were of high contrast.

Word legibility increases with improved resolution and enlarged character size (Erdmann and Neal, 1968). Legibility is also affected by word familiarity but not by word length. Familiar words are as easy to recognise as individual letters (Erdmann and Neal, 1968). In the present study, single letters were used to examine pattern

recognition and image acquisition. "Reading speeds" in individuals were assessed on the basis of recognition of a single unique letter in a sequence of similar letters, eg. EEEHEEE, scrolling at speed.

1.5.2.2 Presentation

Text can be presented to patients by means of conventional printed material, TV screens, tachistoscopes, cathode ray tubes and SLOs. Legge et al (1985a) devised a method for presenting text on a TV monitor. A camera acquired an image of a page of text and this was displayed on a monitor. Manipulation of the camera magnification factor resulted in text of different sizes. By means of masks with different size slits or "windows" single lines, letters or words could be presented to the subject. Current computer graphic techniques could be used to generate static or moving text and to obviate the need for the masks. Another method of text presentation, known as Rapid Serial Visual Presentation (RSVP), flashes single words successively in the centre of a monitor while the subject's eye is held still by fixation (Forster, 1970; Turano and Rubin, 1988). Average reading rates of normal subjects using RSVP have been reported to be about 1000 words/minute compared with normal reading rates of around 300 words/minute for conventional printed text (Rubin and Turano, 1992). The authors thought such dramatic increases in reading speeds were related to the removal of programming and execution of saccadic eye movements.

Stationary text has also been presented in a SLO (Mainster et al, 1982; Timberlake et al, 1987b). Timberlake et al (1987b) studied the retinal area used to read stationary nonsensical words in three patients with macular disease. The locus chosen by the patients, i.e. the preferred retinal location (PRL), was the same as that used for fixating and inspecting acuity targets. The nature of eye movements that occurred during reading was investigated. Even in a small group of patients the scanning sequences used to position the letters on the PRL differed between individuals, some were orderly while others were complicated sequences of retinal shifts. Alternative retinal locations were explored and in one patient the reading

rate was faster with a novel location than with the PRL.

1.5.2.3 Effective visual field

The effective visual field is defined as the extent of useful vision around a fixation point and as such plays a crucial role in reading performance. In practice, it is asymmetric around the fixation point (McConkie and Rayner, 1976); it extends from the beginning of the word currently being fixed (but no further than four characters to the left of fixation) and up to 15 characters to the right of fixation (Rayner et al, 1980). Similarly, word recognition in the right visual field exceeds that of the left visual field (Bouma, 1973). If text is masked to limit the effective field then significant errors in reading occur (Poulton, 1962). In any magnifying device the reduced field of view is the primary parameter limiting reading speed (Cohen and Waiss, 1991). Word recognition, both to the left and right of fixation, is dependent on print size. If print size gets too large the letters occupy such a large proportion of the visual field that reading becomes compromised (Bouma et al, 1982). Differences between reading field and word recognition field exist. Lateral interference from adjacent retinal areas is greater in text which extends over a larger area of fundus. Adjacent words and lines have more interference than single words and hence the field of reading is narrowed. However, the reading field can be considered wider with sentences since much of the text is redundant and less information is required compared with single word recognition (Bouma et al, 1982).

This information is important for low vision rehabilitation where either large print or high magnification may be used. It also has profound implications for the present study in that the SLO was used to project characters onto specific areas of retina. In many instances in this study, small windows were used during testing. This would, by design, limit lateral interaction with adjacent retinal areas and reading would be compromised.

Synopsis of the purpose of the thesis:

The aim of the present study was to investigate the concept that low vision training is a legitimate technique for improving the reading ability of patients with visual loss. Macular diseases was the group of conditions warranting examination since they account for the largest cause of irreversible "blindness" in developed countries. No completely satisfactory medical or surgical treatment is available or imminent, therefore, other management possibilities must be explored.

In patients suffering from bilateral macular disease the loss of central vision can be severely disabling. Typically this group has other handicaps such as reduced mobility and mental decline which make them housebound and dependent on entertainment in their own homes. Activities such as watching television, reading and sewing make substantial visual demands. Although studies have demonstrated a favourable prognosis for macular degeneration in low vision aids rehabilitation, it is well known that patients are not receiving sufficient long-term support. Suitable magnifiers are often left unused because of inadequate patient instruction and follow-up. Poor provision of low vision services may entail vast expense in other areas such as social services support or General Practitioner time.

Visual rehabilitation can take several forms which can be provided by different professions. Optometrists supply a low vision service by performing a full assessment of vision and prescribing magnifying devices. Some of the better practices will, in addition, advise on non-optical devices but there is little emphasis on psychological support for the patient. In contrast, low vision trainers are not usually specialists in optics but do provide good psychological support. This profession strongly advocate low vision training, but provide little evidence that patients benefit. The monies required to provide training to the low vision population is overwhelming and the cost/benefit ratio should be addressed.

The present study will attempt to assess any benefits of training under optimum conditions. These include the use of new technology (eg. SLO) which provides information on patients which has not been available previously, a one-to-one

patient-practitioner ratio with adequate time for training and full visual assessment before and after training. Therefore, the first part of this thesis will be concerned with the development of novel techniques for detailed assessment of vision and improved training techniques. The second part will concentrate on identifying the best area of retina for viewing and determining whether this area is always subconsciously determined by the patient or whether low vision training can be influential.

PART 2: MATERIALS AND METHODS

2.1 Preparation of Scanning Laser Ophthalmoscopes

Two SLO systems, both manufactured by Rodenstock [Ottobrunn, Germany] were used in this study. The first, a pre-production prototype SLO, was available from the beginning of the study. The second, a commercial instrument model 103 was acquired subsequently. Both systems required preparation and modification before use.

2.1.1 Modifications

2.1.1.1 Infra-red diode laser

On delivery, the prototype SLO incorporated two lasers, a Helium-Neon (He-Ne) and an Argon. The system was modified in house by the addition of an infrared diode laser (IR) [Sharp Corporation, Osaka, Japan, LT-021MD, 782nm, 20uW]. In the commercial (i.e. 103) version of the SLO, the He-Ne and Argon lasers were standard items but an IR laser was still an optional extra. The addition of an infrared diode was requested at the time of order.

The IR laser was used to produce high contrast images of the patients fundus at a wavelength that was barely visible to the patient. When visible stimuli were required the He-Ne laser was activated simultaneously with the IR laser.

2.1.1.2 Electronics

Since the pre-production prototype SLO had been designed and supplied, electronics had developed rapidly. As a result, Dr George Hughes from the Eye Research Institute in Boston, USA, one of the original designers of the SLO, upgraded the electronics. In particular, the video board was modified to improve image quality and the detector and other aging components were replaced.

Although the commercial 103 SLO system was sold as a working system, severe problems were experienced with several aspects of this instrument including the electronics. Such difficulties were most commonly manifest in terms of unwanted and uncontrolled movements of the optical head, inappropriate closing of the safety

shutter and poor control of laser parameters. Rodenstock had no real solution to these problems and addressed them by frequently adjusting and replacing the relevant circuit boards.

2.1.1.3 Optics

The field of view on the prototype instrument extended approximately 18 degrees in the horizontal by 13 degrees in the vertical. In practice, this small field of view limited the number of fundal landmarks and in many cases it was difficult to locate and maintain position on specific retinal areas.

In an attempt to increase the field of view an external optical system was designed. This system expanded the laser beam and formed a larger raster on the subject's fundus. See Results (section 3.1.2.2).

2.1.1.4 Computer hardware and software

As supplied, both of the SLOs had the potential of performing basic psychophysical tests. For the present study, additional software was required and developed for more informative tests of residual visual function. Additional programmes also facilitated subsequent analysis. Computer programming was undertaken by Dr Fred Fitzke from the Institute of Ophthalmology, London.

The computer of choice in this study was an Acorn RISC machine (ARM) with ARM3 RISC processor [Cambridge, UK] since it provided much greater capacity (16M memory) and processing speeds than conventional computers. A Hawk V10 framegrabber [Wild Vision, Tyne and Wear] was used for image processing and an optical disc drive was employed to store the large number of images generated. The complexity of this ancillary equipment was made necessary by the number of difficult tasks required. For example, the computer facilitated the projection of graphics in the SLO raster and was also used for digital acquisition and analysis of fundal images.

2.1.2 Calibration

Accurate calibration of both the radiant emission from the various laser sources

in the SLO and their resultant retinal irradiance was a fundamental requirement prior to undertaking human exposure. Knowledge of the former together with beam shaping optics enabled calculation of the latter and ensured compliance with the codes of practice for laser safety.

2.1.2.1 Safety levels

Many publications attest to the concept that light levels used in the SLO are extremely low in comparison with other methods of ocular examination (Mainster et al, 1982; Webb, 1983). However, safe working practices were constantly applied throughout this study and involved radiometric and photometric measurements of the radiation emitted by the system at regular intervals of approximately 2 months. Measurements were undertaken using an UDT radiometer.

Codes of practice for laser safety show a wavelength, power, spot size and time dependency (BS EN 60825, 1992). In national and international codes of practice of laser safety simplified tables are presented which indicate maximum permissible exposure (MPE) times for any given boundary conditions. In this study, MPE was derived from published work specifically addressing the safety aspects of the SLO (Klingbeil, 1986; see Appendix II).

Several calculations could be undertaken to determine the effective retinal irradiance given that the retinal exposure from the SLO is complicated by the scanning nature of the beam. For example, calculations could be undertaken measuring the irradiance within the scanning spot, configuring a time component for the duration of the spot at a given location and a second time component for the number of exposures any given spot would experience in a given time period. A more simple treatment was the one used in the present study whereby the irradiance was measured over the total area of the raster. This measurement as a safety concept is only tenable because the commercial SLO had safety shutters incorporated which extinguished the irradiant beam in the event of any scan failure. The response time of the shutter was 200ms.

Retinal irradiance (W/cm^2) was determined by measuring the output of the laser with a UDT radiometer and calculating the extent of the raster on the retina (cm^2) (see below, section 2.1.2.2).

Special consideration would have to be made with the Argon laser as in this case photochemical damage considerations have to be incorporated in order to avoid the blue light hazard problems and thus avoid the potential of inducing loss of blue-green colour discrimination. In the current work, no investigations were undertaken with the Argon laser.

Rodenstock are a responsible manufacturer and have obviously designed the system to ensure compliance with all national and international safety requirements. The German test houses are probably the most stringent in Europe and as a result of such scrutiny the system has many back-up sensors to ensure the safety of both patients and clinicians.

2.1.2.2 Raster size

The optics of the SLO are designed to produce minimum beam cross section in the plane of pupil and the raster is formed by the divergent beam on the retina. The angular extent of the raster was determined by placing a piece of card perpendicular to the axis of the laser beam at a distance of approximately one meter from the beam focus.

The raster may be considered to consist of picture elements or "pixels". In the image processing of our system there were 256 pixels in the horizontal and 256 pixels in the vertical. By determining the overall size of the raster, the angular extent of each pixel was calculated. See Results (section 3.1.2).

2.1.2.3 Raster graphics

An acoustooptic modulator (AOM) allows the intensity of the laser beam to be varied in a controlled fashion throughout the scan. The AOM varies the intensity of each pixel in response to electronic signals from the Acorn Archimedes computer and Wild Vision frame grabber. Any video graphics which can be displayed on a

video monitor can be projected onto a patient's fundus. In our system we chose to modulate the He-Ne beam. If suitable lasers were available it would have been possible to produce colour stimuli.

The intensity of the raster for each digital value from the computer can be measured directly (in uW) by placing a radiometer at the beam focus. Using these values the contrast of the stimuli in the raster were calculated.

Two formulations have commonly been used to calculate contrast in test stimuli. The Michelson equation is used for periodic stimuli, such as sinusoidal gratings:

$$\text{Contrast} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

where L_{max} and L_{min} are the maximum and minimum luminance values respectively (Michelson, 1927).

A different equation, the Weber fraction, is used to measure local contrast of a single target of uniform luminance seen against a uniform background:

$$\text{Contrast} = \frac{\Delta L}{L}$$

where ΔL is the increment or decrement in the target luminance from the uniform background L (see Peli, 1990).

These two calculations are not comparable nor do they provide a common range of values. The Michelson equation determines contrast values in the range 0 to +1.0 (or 0 to 100%) whereas the Weber fraction gives a range of -1.0 to infinity. Contrast of the test stimuli in the present study have been calculated using both methods (see Results, section 3.1.3).

2.2 Source of Subjects

Both normal observers and low vision patients were recruited into the following studies. Normal volunteers were enlisted from friends and colleagues. The low vision patients had attended Moorfields Eye Hospital or Department of Ophthalmology, St Thomas' Hospital. The main sources of patients were

1) general out-patient clinics
2) retinal diagnostic departments and
3) low vision clinics.

Patients had undergone full ophthalmological examination and had been prescribed magnifying devices from a low vision clinic.

2.3 System Assessment

Before starting the clinical study, a series of pilot studies were undertaken to provide baseline data. These preliminary studies were undertaken during a period of development of both SLO hardware and software.

2.3.1 Scotoma mapping

In the present study it was essential that the extents of retinal lesions in each low vision subject were accurately defined. The SLO allowed imaging of the fundus such that the morphological aspects could be determined. In addition, it was necessary to correlate the fundus appearance with visual function. The basic method of investigating visual performance was scotoma mapping.

A) In-house software

Before Rodenstock's commercial software was available (see next section), we developed in-house programmes for microperimetry. In contrast to the Rodenstock software which iterated out eye movement, this programme was specifically designed to determine the magnitude of eye movements and their importance during testing. A pilot study using automatic kinetic microperimetry in the

prototype SLO is described below.

The computer programme could move the stimuli either

1. from a non-seeing area to a seeing area, or
2. from a seeing area to a non-seeing area.

1. Scotoma mapping from non-seeing to seeing in normal subjects

A fixation target, external to the SLO raster, was positioned for each individual such that the subject's optic nerve head was imaged in the centre of the TV monitor. The mapping stimulus was initially positioned at the centre of the raster and therefore at the centre of the physiological blind spot. A stimulus spot, 24x24 min arc, with a contrast of -90% was programmed to move centrifugally on a series of 24 radial tracks at 15 degree intervals. In a typical test procedure, movement of the test spot was initiated and the subject was instructed to respond immediately to its appearance by pressing a button. The test spot automatically returned to the centre of the blind spot and began to traverse the next radial track.

2. Scotoma mapping from seeing to non-seeing in normal subjects

The optic nerve head was imaged in the centre of the TV monitor as described above. The previously described stimulus spot, in this experiment, first appeared at the edge of the raster and in this case moved centripetally on 24 radial tracks. The patient was instructed to respond immediately to the disappearance of the stimulus. Each response on the button caused the stimulus to move to the next meridian.

Depression of the response button also activated the framegrabber to acquire, digitise and store the coincident fundus image on the monitor and also to store the x, y coordinates of the mapping stimulus.

Each mapping procedure was performed twice in quick succession on each subject in order to provide a "pair" of maps. Each of the pair of scotoma maps had 24 digitised fundus images and 24 pairs of x, y coordinates of stimuli position. Three calculations were made using this information (see below); i) the amount of eye movements that had occurred during the test, ii) the differences in each of the

coincident stimulus positions between the paired maps, and iii) the differences between each of the stimulus positions in the paired maps after compensation for eye movements.

i) Calculation of eye movements

The stability of fixation was assessed by measuring eye movements in the digitised fundus images. This was achieved using an alignment procedure, designed in-house, known as the "flicker method" in which the first image in the digitised sequence was taken to be the master and the other images are manually aligned to it using the computer mouse to superimpose prominent retinal features. The master image and the image to be aligned were presented alternately on the monitor at a frequency of 11 frames/sec. In the manner of a flick cartoon, misaligned images were seen as movement, whereas correct alignment resulted in a stationary picture.

Alignment of the digitised images resulted in a measurement of displacement in pixels in the x and y axes; these values were stored by computer. Repeatability of the manual alignment was assessed.

The displacement of each frame in the sequence was denoted by v_1, z_1 and v_2, z_2 for the first and second map in the pair respectively. The differences in the eye movement values were calculated for each frame using

$$\text{Eye movement distance} = \sqrt{(v_1-v_2)^2+ (z_1-z_2)^2} \qquad \text{Equation (1)}$$

and the standard deviation of these values was calculated.

ii) Differences in stimulus positions

The stimulus coordinates in the first map and the second map of the pair were denoted by x_1, y_1 and x_2, y_2 respectively. The distance between the position of each stimulus was calculated using

$$\text{Uncorrected Distance} = \sqrt{(x_1-x_2)^2+ (y_1-y_2)^2} \qquad \text{Equation (2)}$$

The standard deviation of all these distance values represented the variability due to both subjective responses and fixation inaccuracies.

iii) Differences in stimulus position after correction for eye movements

Each stimulus position (x, y) was compensated for fixational inaccuracy by subtracting the relevant eye movement value (v, z).

The new differences between paired maps was calculated using the new stimulus positions in equation (2) to give "corrected distance". The standard deviation for the corrected values was also calculated.

Subjects:

Five normal subjects, aged 25-40, with visual acuity of 6/6 were recruited to this study.

Procedure:

The non-test eye was covered and the subject was positioned in a headrest specifically designed to minimise head movement. Subjects were given clear instructions to maintain precise fixation on a small section of the target throughout testing.

The parameters of the mapping stimulus were chosen to be comparable size to target III in the Goldman perimeter (i.e. 24 x 24 min arc); the contrast was -92% and the velocity in the raster was 2 degrees/sec.

In order to generate a "pair" of scotoma maps the microperimetry programme was repeated twice in quick succession without the subject moving his head or changing the fixational position.

To demonstrate the validity of this method one observer (CJ) was asked to fixate alternately two locations separated by 2.5 degrees. In essence, this subject made deliberate eye movements of 2.5 degree and in between each movement he responded to the stimulus. The data were analysed empirically.

The reaction time for two individuals (FF and LC) to respond to the mapping stimulus was measured. The stimulus was presented on three occasions to retinal areas nasal and temporal to the optic nerve head. The computer calculated the time difference between presentation of the stimulus and the depression of the button on the response button.

b) Rodenstock commercial software

At the beginning of the study we were using a prototype instrument and commercial software for scotoma mapping was not available. However, Rodenstock was in the process of preparing software to be used with the 103 SLO. We acquired a 103 SLO and the relevant software subsequently. This commercial scotoma mapping programme was a manual hybrid microperimetry, based on original programmes from ERI, Boston (Timberlake et al, 1982). In this method the operator viewed the patient's fundus on the TV monitor, moved the cursor to the required retinal location and presented the mapping stimulus. The patient had a hand-held response button and was instructed to depress the button if the stimulus was seen. Presentation of the stimulus caused the frame grabber to acquire an image of the fundus with the stimulus located on it. The first image of the sequence was the "master" image. All subsequent images were aligned with key features used as reference points in the master image (e.g. blood vessel crossings). The stimulus was repeatedly repositioned on the fundus, presented and each image was aligned until a sufficiently detailed scotoma map was obtained.

2.3.2 Assessment of fixation

In this pilot study the ability of normal and low vision subjects to fixate targets at different retinal locations was assessed. A variety of stimuli was presented, some target arrays were stationary and others were moving text. In the case of the latter, the stimuli were presented within a small portion of the raster, termed the "window". The method of using a window to control the extent of text presented was similar to the technique devised by Legge et al (1985a), where a TV monitor was

masked to provide windows of different sizes. In this study, the window was 4.3 degrees horizontally and the vertical dimension varied with the size of text. The size of the window limited the area of retina used and was important in discriminating function at specific locations.

To quantify fixation stability, images of the subjects' fundus were acquired throughout a period of fixation of 7.5 seconds. In all subjects there was sufficient contrast in these images that retinal features such as blood vessels could be used as landmarks for comparison between images. Images were stored on video tape (sVHS) and sample images were acquired by means of the Wild Vision frame grabber and digitised by the Archimedes computer. The number of frames and the speed of acquisition of images was limited by the capacity of the computer. Forty four images were digitised in sequence at a rate of 6 per second. Of these the first 32 frames of good quality, e.g. unaffected by blinks, were used. Thus 5.5 seconds of fixation were sampled. One image of the sequence, usually the first, was taken as a "master", to which the other images were manually aligned by the operator using the computer mouse to superimpose prominent features. This alignment procedure was the same as the "flicker method" described in the previous pilot study (section 2.3.1). Alignment of the digitised images resulted in measurements of displacement on both the x and y axes which were recorded in pixels.

The x, y values provided a measurement of eye movements and these were used to calculate the Bivariate Contour Ellipse Area (BCEA) (Steinman, 1965; Tatsuoka, 1971; Ditchburn, 1973a; Timberlake et al, 1986), which allowed comparison of our data with existing literature. The BCEA is a two dimensional ellipse which describes the retinal area within which the centre of the target was imaged 68% of the time, and it is expressed in min arc^2. The standard deviations of the eye positions in the horizontal and vertical meridians were also calculated.

The shape and orientation of the bivariate contour ellipse, as shown on the graphs in the results section, depended upon the type of eye movements that occurred while the subject was maintaining fixation. If the horizontal and vertical eye

movements were identical in size and frequency then the ellipse would appear circular. However, if the observer made large horizontal scanning movements when reading the scrolling text then the ellipse would be extended horizontally. Similarly, if vertical eye movements were predominant, e.g. during letter recognition of a large target, then the ellipse would be vertically orientated.

A computer programme was designed to handle raw data, to undertake the calculations and to draw the ellipses. Dummy data, generated by the computer, were used to provide evidence that the programme was functioning correctly.

The BCEAs were analysed using the Student's t test and analysis of variance (ANOVA) with multifactorial structure. As the data set was unbalanced the ANOVA required adjustment (Montgomery, 1984).

Subjects:

Twelve observers with no known ocular problems and seven patients with macular disease were recruited to the study.

Procedure:

The subject was positioned in a headrest specifically designed to minimise head movements. Dental bites would have been preferable method for minimising head movements, but some patients would have found this unacceptable.

With low contrast fixation targets it was often difficult for the operator to discriminate the stimuli against the background image of the fundus and as a result we developed a method of locating the stimuli by means of a calibrated grid on the computer monitor.

EXPERIMENT 1: The effect of fixation target form and size.

The fixation stability of four normal and seven low vision subjects were studied using the following visual stimuli:

(i) "basic" Snellen E. For normal observers the letter size was 20 min arc, for low vision patients the basic size (i.e. minimum resolvable) varied up to 80 min arc.

(ii) enlarged Snellen E. This was larger than the basic E target by a factor of 2, 4

or 8 and was used to study the effect of a larger stimulus on the fixation stability.

(iii) fixation cross embedded in letters, e.g. TH+LH. This target was used to investigate the effect of contrast and texture around the fixation point.

For each individual subject the size and contrast (both positive and negative) of the basic Snellen E and the embedded cross were selected such that the targets were easily recognised.

The preferred retinal location (PRL) was determined by asking each subject to fixate the stimulus. The operator then observed the location of the stimulus on the fundus image displayed on the TV monitor.

This experiment was completed on two separate occasions on subject CJ.

A further eight normal observers were studied using targets of negative contrast only:

(i)-(iii) as above

(iv) a single cross, i.e. +, sized 20 min arc.

(v) a grid pattern of the letter H extending 100x100 min arc with a fixation cross in the centre.

All subjects were directed to "watch the target carefully and steadily". In addition, one observer (AM) was instructed to "hold the eye still on one specific point on the target".

EXPERIMENT 2: Alternative retinal locations (ARLs) for fixation in low vision subjects.

In four patients (JW, AA, DB and KA) a series of further observations were made, using targets (i) or (iii) above, in that they were encouraged to fixate with ARLs (i.e. not their primary PRL), either of their own choice or determined by the investigator.

EXPERIMENT 3: The effect of scrolled text on fixation stability.

In this part of the experiment the stimuli were moved horizontally through a

window and four retinal locations were examined. Subjects were directed to hold fixation on a stationary fixation target (extending 10 min arc) within the SLO raster while sequences of random letters were scrolled at the fovea, and 2, 4 and 6 degrees superiorly. In practice, those patients with gross central scotomas were unable to locate the fixation target. This group were instructed to fix their gaze on an alternative fixation target which was the smallest they could see.

In the first set of measurements both positive and negative contrast text was used and the velocities were 0.6, 1.1 and 1.7 degrees/sec (these are referred to as speed 1, 2 and 3 respectively). After analysis of these data, a further group of observers were examined with negative stimuli with velocities of 0.6 (speed 1), 1.7 (speed 3) and 4.4 (speed 4) degrees/sec.

The subjects were asked to identify the letters as they were scrolled across the fixation point or at the eccentric retinal locations. In order to preserve undisturbed fixation, subjects were not required to read the letters aloud. In a single presentation some 30 letters might be viewed and it was unreasonable to expect the subject to recite such sequences. In this study our prime aim was to assess fixation stability but in section 2.3.3 below the accuracy of letter recognition was addressed in detail.

2.3.3 Letter recognition using scrolling text

In order to determine subjects' abilities to recognise text at different retinal locations, a computer programme was developed that allowed control of moving letters in the SLO raster. These visual stimuli could be controlled in size, contrast and velocity.

Although the letters presented in the SLO could range in size from 10 to 900 min arc, in these experiments the letters used were 30, 60 or 90 min arc. These sizes were approximately symmetrical in both the vertical and horizontal axes. Both relatively bright (i.e. positive) and dark (i.e. negative) letters on a constant background were used.

Only the letters E, H, I, L, T, F, were used so that aliasing effects due to

producing curved or diagonal lines in the raster were avoided. The sequence of letters was generated randomly by the computer. In an attempt to minimise the effects of the "crowding phenomenon" (Rubinstein and Underwood, 1985) and also to allow the subject the opportunity of reading the letters aloud, adjacent letters in the sequence were separated by one character space.

Text was presented in a window measuring 4.3 degrees horizontally, the vertical dimension of which varied with the letter size. This window could be located anywhere within the raster under the direct control of the operator. Within the window, letters first appeared on the right and were scrolled through to the left. The angular velocity, or scrolling speed at the retina was varied from 0.74 to 3.8 degrees/sec. This represents a range of 44 to 228 letter presentations per minute for text sized 30 min arc, and 22 to 114 letters per minute for text of 60 min arc.

Subjects:

In this study the subjects were (a) two normal female observers (25 and 32 years old) both with Snellen acuity of 6/6 and (b) two patients: one male patient (75 years) with ARMD (longstanding disciform degeneration) with visual acuity of 3/60; and one female patient (35 years) with juvenile macular disease (fundus flavimaculatus) with visual acuity of 6/18.

Procedure:

The non-test eye was patched. Once placed comfortably in the headrest, the subject was directed to fixate a stationary target within the SLO raster. The minimum resolvable size of the text in each experiment was determined for each subject by initial pilot measurements. A sequence of six letters was presented to each of the predetermined retinal locations which varied between individuals. Subjects were instructed to hold fixation while the letters were scrolled and to read the letters aloud. They were directed to pay attention to the accuracy rather than the speed of their response. If they were unsure they were encouraged to make a "best guess". The operator typed the responses into the computer, the data were

printed at the end of the experiment and the percentage read correctly was calculated. At each location up to ten separate presentations were made to allow calculation of standard error of the mean.

The investigation on the normal observers took four to five hours in total and was spread over three sessions. Each of the two patients underwent one session of testing lasting approximately two and a half hours. Regular breaks during the testing period helped to minimise fatigue.

EXPERIMENT 1: Letter recognition at different retinal locations in normal observers.

Text was scrolled at five retinal locations displaced sequentially in 2 degree steps superior to the fovea. The letters were 30 min arc in size; the contrast was +55% which was the maximum positive value available on the chosen background. Two scrolling speeds were used: 1.5 and 3.8 degrees/sec.

EXPERIMENT 2: Effect of letter contrast at different retinal locations in normal observers.

Text contrast was varied from -90 to +55% and letters were scrolled at 2 and 6 degrees eccentricity in the superior retina. Letter size was 30 min arc and speed was 1.5 degrees/sec.

EXPERIMENT 3: Letter recognition at different retinal locations in the patient with age-related macular degeneration.

This patient stated that he commonly used one of three different retinal areas depending on the nature of the visual tasks. The position of each retinal location was initially determined by asking the patient to view a letter in the SLO raster. The area used was observed on the TV monitor and recorded. The visual performance of each of the loci was investigated using letters of 90 min arc and contrasts of -85 to +55%.

In order to compare the patient's performance at a specific locus, the experiment

was repeated with a normal observer utilising a retinal area at 6 degrees eccentricity. The only difference was that the window was displaced only vertically and not laterally.

EXPERIMENT 4: Letter recognition at different retinal locations in the patient with juvenile macular disease.

With this patient the investigation was divided into two phases. In order to correlate function with morphology of the lesions, windows were placed in varying locations centrally, inferiorly and superiorly. In the second phase, a more extensive investigation of foveal function was undertaken using different letter contrast. Again, in order to compare the patient's performance the experiment was repeated with a normal subject. Letter size was 60 min arc and speed was 1.5 degrees/sec.

2.4 Clinical Study

The aims of this study were:

1) to investigate the nature of residual vision in patients with macular disease and
2) to examine the concept that low vision training influences reading ability.

The study was divided into two phases: in the first, low vision subjects underwent extensive clinical and functional assessment. The second phase consisted of low vision training using the SLO.

2.4.1 Patients

Subjects were recruited according to the following criteria:

a) bilateral age-related macular degeneration (ARMD) of greater than one year duration and stable for the last six months (i.e. subjective assessment plus no medical advice required)

b) scotoma that could be identified using the SLO

c) aged over 55 years

d) visual acuity of 6/18 or less

e) no other significant ocular disease

f) no significant mental or physical deficiency and

g) ability to attend multiple appointments.

ARMD was chosen as the most suitable ocular condition for the present study since a large and growing number of people are affected. Current treatment regimes offer little benefit and severe disability can arise. Also, this group of patients are often highly motivated since they are frequently house-bound and reading and watching television become increasingly important. In addition, patients with ARMD have been reported to respond well to low vision training techniques (Nilsson, 1990b).

2.4.2 Clinical assessment of vision

Two aspects of visual performance were examined: visual acuity and reading speed. Corrected distance vision was measured in each eye at the beginning and the end of the study using a Bailey-Lovie low vision acuity chart. With the magnifying aid that individual patients habitually utilised for reading, near vision acuity was evaluated at each assessment throughout the study using near Bailey-Lovie charts.

For measurement of reading speed, paragraphs of prepared text ranging from N5 to N36 were available. Six different stories were adapted from a school textbook suitable for a reading age of 12 years (Newson, 1970). Each story was of similar length, punctuation and word complexity (see Appendix III). At each assessment the patient was presented with a different piece of text. Selection of the appropriate size of text for each individual using their magnifier was determined at the first assessment. The same size of text was used throughout the study. Patients were required to read aloud as quickly and accurately as possible. The number of words read correctly per minute (wpm) was recorded.

2.4.3 Functional assessment of vision using the scanning laser ophthalmoscope

In order to identify the nature of visual loss and to evaluate residual visual performance, patients were examined using the following techniques. The aim of these investigations was to identify the retinal areas to be used in low vision training. In those patients with a visual defect significantly greater in one eye, the

better eye was used for low vision training. In eyes with comparable visual performance, dominance and the subject's preference were considered but if necessary full functional assessment with the SLO was undertaken on both eyes before selection was made. The non-test eye was covered during the investigations if necessary.

2.4.3.1 Scotoma mapping

Defects in the central visual field were mapped in each patient using the SLO and the Rodenstock commercial software. The procedure is described in detail in section 2.3.1. The mapping stimulus was chosen to be equivalent in size to a Goldman III target, e.g. 24 by 24 min arc and with a contrast of -90%.

2.4.3.2 Identification of preferred and alternative retinal locations

The preferred retinal location (PRL) was determined by asking each subject to view a defined stimulus in the SLO raster. The operator observed the location of the stimulus on the fundus image displayed on the TV monitor. A variety of sizes of Snellen E were available ranging from 44 to 218 min arc; the stimulus just above resolvable size was selected. The contrast was -90%. The PRL was the area that the patient repeatedly utilised for both fixation of a stationary target and pursuit of a moving target. The region of retina within which the PRL was located was classified as central, superior, inferior, temporal or nasal after Guez et al (1993), (Figure 2).

Patients were encouraged to fixate the same target with alternative retinal locations (ARLs). The ARLs could either be of the patient's choice or they could be determined by the investigator. Suitable ARLs were loci that were

1) relatively unaffected by disease
2) close to the fovea with good visual acuity and/or
3) positioned such that the patient would not be attempting to read into a scotomatous area.

In each patient two specific ARLs were identified for further investigation.

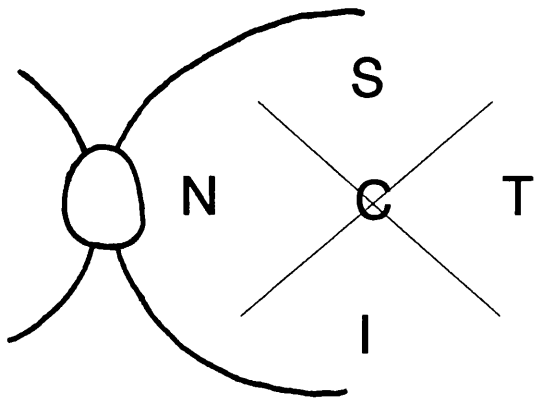


FIGURE 2: CLASSIFICATION OF RETINAL ZONES
C=central; S=superior; I=inferior
N=nasal; T=temporal

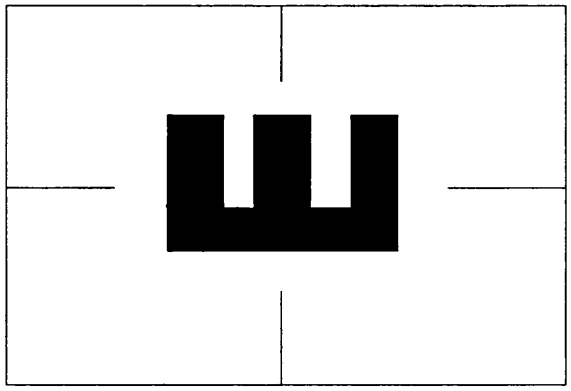


FIGURE 3: ACUITY TARGET IN SLO RASTER

2.4.3.3 Acuity mapping

With the use of a computer programme supplied by Rodenstock but originally developed at the Eye Research Institute, Boston, measurements of visual acuity were made with the SLO. Crosshairs extending from each edge of the SLO raster provided guidance for the patient's fixation. At the imaginary centre of the crosshairs a Snellen E of varying orientations was presented for 250ms (see Figure 3, p73). The patient reported the direction of the E (up, down, left, right) and the operator relayed this to the computer. Two correct responses resulted in the next target in the sequence being smaller, whereas the target size was increased after a single incorrect response. Threshold was established by a three step reversal staircase method. The smallest gap size detected by the patient was calculated and converted into minutes of arc. Measurements of acuity were undertaken at the PRL and both the ARLs in each patient.

2.4.3.4 Fixation stability

The ability of the patient to stabilise the image on a given retinal area was defined as "quality" of fixation. This was examined using the same target as described in section 2.4.3.2, i.e. just above resolvable size with a contrast of -90%.

Each patient was instructed to "watch the target carefully and steadily", first with the PRL and then with each of the two predetermined ARLs in turn. Images were stored on videotape and processed as described in section 2.3.2.

2.4.3.5 Search and identification

Each patient was required to locate and identify a target within the SLO raster using his PRL and ARLs. The stimulus, a single letter larger than the limit of VA with a contrast of -90%, was placed at a random location in the raster but always at approximately the same distance from the centre. The time taken to locate and identify this target was recorded. In cases where patients were repeatedly unsuccessful in the employment of these retinal locations the operator assisted them with verbal guidance.

2.4.3.6 Letter recognition

Although referred to as "reading" tests the following experiments were designed to investigate letter recognition skills rather than intellectual and cognitive skills. Patients' ability to recognise letters at different retinal locations was determined by scrolling text at the PRL and the two ARLs.

Only the letters E, H, L, I, T, F were used. Contrast was -90% and letters in sequence were separated by one character space (see section 2.3.3). The text dimensions were chosen to be just above resolvable size for each patient.

Random sequences of letters were presented at each retinal location in turn at a set velocity of 1.9 degrees/sec. Patients were instructed to read the letters aloud, paying attention to the accuracy rather than the speed of response. The operator viewed the text on the patient's fundus via the TV monitor and calculated the accuracy of the response. Before measurements were made, the task was demonstrated and the patient had the opportunity to practise. The number of letters presented to each retinal location depended on several factors including the patients' ability to maintain steady eye position. In those individuals who were unable to fixate steadily, only limited presentations were possible. Hence, the results were converted into percentage values.

2.4.3.7 Speed of recognition

In the assessment of "reading speed", all characters in the sequence were chosen to be identical except for a single letter. The patients' task was to identify the unique letter. Text size was the same as above, but in contrast to the previous assessment there was no character spacing between letters, e.g. EEHEE or HHLHH.

Five scrolling speeds were possible; speed 1, 2, 3, 4 and 5. These related to angular velocities of 1, 1.9, 3, 3.8 and 4.9 degrees/sec respectively. The speed was increased until the patient was unable to recognise the unique letter. Failure to identify the letter correctly on three occasions determined the upper speed of reading. Those individuals who were unable to identify the letter at speed 1 were

given a score of < 1 degree/sec.

2.4.3.8 Repeated clinical assessment

In order to determine whether the initial investigations undertaken with the SLO had influenced the patients' visual performance the clinical reading tests described in section 2.4.2 were repeated.

2.4.4 Low vision training with the scanning laser ophthalmoscope

Each patient attended six appointments at weekly intervals. Throughout the training programme the following aspects were emphasised:

1) patient's understanding of different eye positions and the efficient use of vision
2) measurement of visual performance at the PRL and ARLs
3) determination of the retinal location providing optimum performance
4) investigation of the influence of the training programme on "normal" visual tasks such as reading.

In order to facilitate these objectives each appointment was divided into three parts: the interview/discussion, practise of eccentric viewing and measurements using the SLO and, finally, the clinical assessment.

In the first part, patients were able to discuss their progress with the training techniques and comment on achievements and/or difficulties experienced during the interval since their last appointment. More objective evidence of their ability to locate and maintain different eye positions was obtained using the SLO. The patient's assertions were verified and the discussion on eccentric viewing continued with the benefit of guidance from the operator based on SLO information.

During the second part of the appointment, emphasis was placed on practise and improvement of eccentric viewing techniques. This was achieved using the SLO tests described below which were also used for measurement of patients' progress.

In the third part of the appointment, detailed clinical assessment of reading performance was undertaken.

Typical appointments lasted one to one and a half hours. After each test, patients

were given time to rest in an attempt to minimise fatique.

2.4.4.1 Fixation stability

In an attempt to improve fixation stability using the three predetermined retinal locations, patients were required to practise fixating a target in the SLO raster. Using the same method as described in section 2.4.3.4. (p74) the BCEA was calculated for each of the three retinal areas in every patient. This allowed direct comparison of fixation stability between locations and between appointments.

2.4.4.2 Search and identification

With the use of a single letter at varying locations in the SLO raster the search and identification time (see section 2.4.3.5, p74) was measured at each appointment in order to determine any changes in performance and to identify the retinal location allowing optimum performance.

2.4.4.3 Letter recognition

Letters were scrolled at different retinal locations (see section 2.4.3.6, p75) and the percentages read correctly were analysed at each appointment in order to determine any changes in performance and to identify the retinal location allowing optimum performance.

2.4.4.4 Speed of recognition

The experiment presenting scrolling letters at increasing speeds (see section 2.4.3.7, p75) was repeated at each appointment in order to determine any changes in performance and to identify the retinal location allowing optimum performance.

2.4.4.5 Repeated clinical assessment

In order to determine any change between pre- and post- training performances the clinical tests described in section 2.4.2 (p71) were repeated at the end of each training session.

2.4.4.6 Statistical analysis

The statistical tests utilised for analysis of this data included the Student's t test and analysis of variance (ANOVA).

2.4.4.7 Attendance

Hospital notes with clinical information were stored in the Medical Records Department but separate confidential files of study data and attendance dates were held in the SLO room. All data were gathered and stored in a manner that complied with the Data Protection Act. Contact by telephone and/or letter was made when patients failed to attend and further appointments were offered.

2.4.4.8 Questionnaire

In an attempt to acquire some constructive criticism and feedback from the patients involved in the study a simple questionnaire was designed. The aim was to address some of the psychological aspects of training. The questionnaire was presented to the patient at the completion of their programme. They were encouraged to take the form home, consider their responses and then return it, anonymously, by post.

PART 3: RESULTS

3.1 Calibration

3.1.1 Safety levels

Helium-neon (He-Ne) lasers utilised in SLOs are categorised as Class IIIb laser products. Infra-red diodes (IR) are also Class IIIb. Before exposures of subjects to the SLO, detailed measurements of radiant emission were undertaken (see Tables 1A and 1B, 2A and 2B).

The retinal irradiance was calculated for each raster size (see below). British Standard EN 60825 (1992) provides universal guidelines for all laser products, but Klingbeil (1986) has investigated the safety aspects specific to SLOs. Klingbeil recommends a maximum laser power in the region of 10mW whereas typical values for SLOs are less than 100uW (Appendix II). As such, SLOs are considerably less hazardous than conventional ophthalmoscopes. In the present study, even when the retinal irradiance from both lasers were summated the exposure levels were within the maximum permissible limits.

3.1.2 Fundus image acquisition and field of view

3.1.2.1 Prototype scanning laser ophthalmoscope with standard field

Figure 4A shows an image of a normal fundus taken using a combination of He-Ne and IR laser light.

In order to specify the field of view, measurements of the laser beam raster were made at a distance of 127cm (see Figure 5).

$$\text{Horizontal} = 2 \times \tan^{-1}\left(\frac{0.5 \times 39.5}{127}\right) = 17.68 \text{ degrees}$$

$$\text{Vertical} = 2 \times \tan^{-1}\left(\frac{0.5 \times 28}{127}\right) = 12.58 \text{ degrees}$$

TABLE 1A: CALIBRATION OF HELIUM NEON LASER IN PROTOTYPE SCANNING LASER OPHTHALMOSCOPE (POSITIVE STIMULI)

DIGITAL VALUE	RADIANT EMISSION (uW)	MICHELSON CONTRAST (%)	WEBER FRACTION
254	34.9	86.1	12.4
248	32.5	85.2	11.5
240	30.8	84.4	10.8
232	29.0	83.5	10.1
224	27.5	82.7	9.6
216	25.6	81.6	8.8
208	24.1	80.5	8.3
200	22.4	79.2	7.6
192	20.8	77.8	7.0
184	19.3	76.3	6.4
176	17.8	74.5	5.8
168	16.2	72.3	5.2
160	14.9	70.3	4.7
152	13.6	67.9	4.2
144	12.3	65.1	3.7
136	11.1	62.0	3.3
128	9.8	58.1	2.8
120	8.6	53.6	2.3
112	7.6	49.0	1.9
104	6.5	42.9	1.5
96	5.6	36.6	1.2
88	4.7	28.8	0.8
80	4.0	21.2	0.5
72	3.2	10.3	0.2

Background greylevel = 64
Background intensity = 2.6uW

TABLE 1B: CALIBRATION OF HELIUM NEON LASER IN PROTOTYPE SCANNING LASER OPHTHALMOSCOPE (NEGATIVE STIMULI)

DIGITAL VALUE	RADIANT EMISSION (uW)	MICHELSON CONTRAST (%)	WEBER FRACTION
56	2.1	-10.6	-0.2
48	1.6	-23.8	-0.4
40	1.1	-40.5	-0.6
32	0.8	-52.9	-0.7
24	0.5	-67.7	-0.8
16	0.3	-79.3	-0.9
8	0.2	-85.7	-0.9
0	0.1	-92.6	-1.0

Background greylevel = 64
Background intensity = 2.6uW

TABLE 2A: CALIBRATION OF HELIUM NEON LASER IN COMMERCIAL SCANNING LASER OPHTHALMOSCOPE (POSITIVE STIMULI)

DIGITAL VALUE	RADIANT EMISSION (uW)	MICHELSON CONTRAST (%)
254	12.1	90.3
248	11.5	89.8
240	10.8	89.1
232	10.1	88.4
224	9.4	87.6
216	8.8	86.8
208	8.1	85.8
200	7.5	84.7
192	6.9	83.5
184	6.3	82.1
176	5.8	80.7
168	5.3	79.1
160	4.8	77.1
152	4.5	75.8
144	4.1	73.7
136	3.7	71.3
128	3.1	66.7

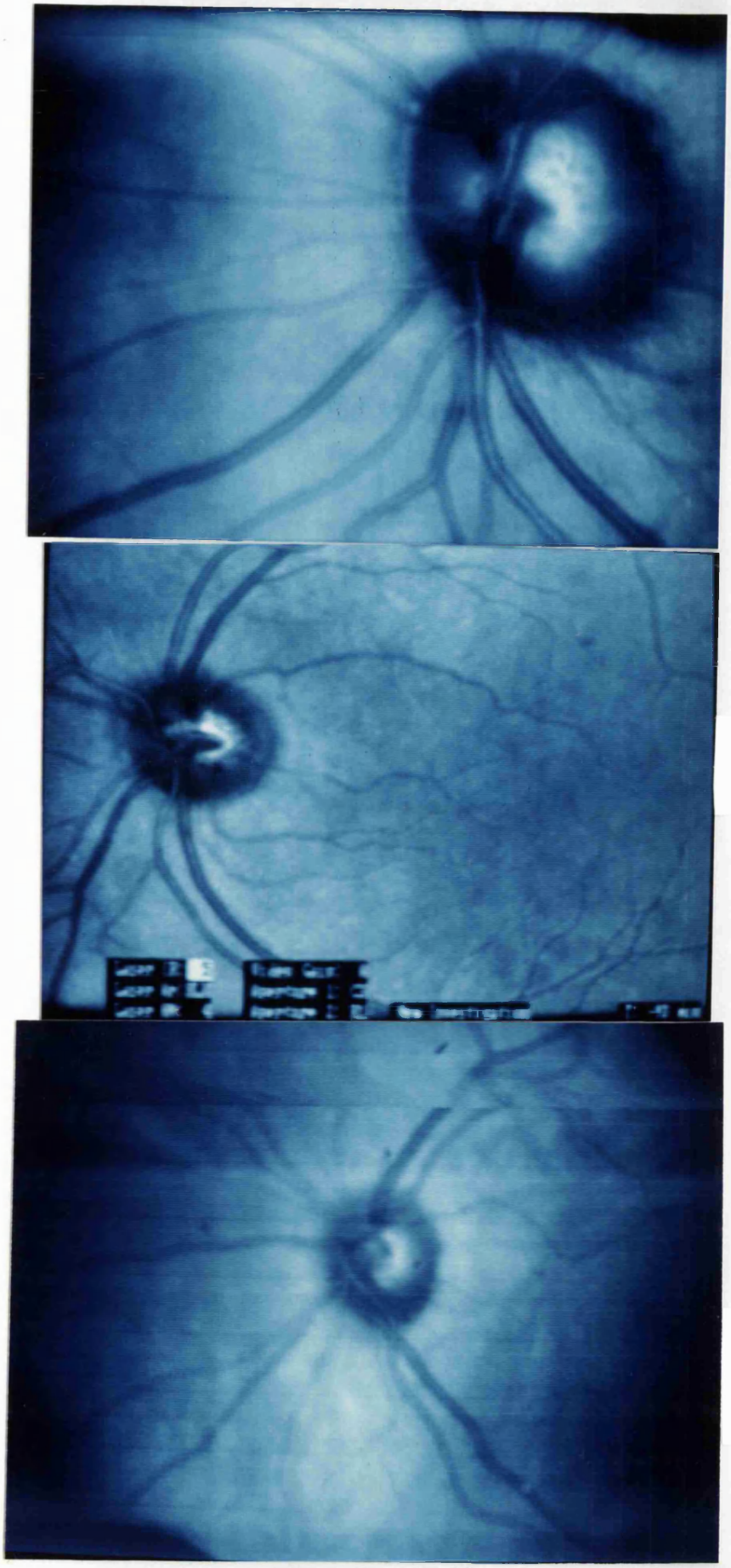
Background greylevel = 0
Background intensity = 0.62 uW

TABLE 2B: CALIBRATION OF HELIUM NEON LASER IN COMMERICAL SCANNING LASER OPHTHALMOSCOPE (NEGATIVE STIMULI)

DIGITAL VALUE	RADIANT EMISSION (uW)	MICHELSON CONTRAST (%)
120	2.9	-61.3
112	2.7	-63.5
104	2.6	-64.6
96	2.3	-68.1
88	1.9	-72.9
80	1.4	-79.3
72	1.2	-82.0
64	1.1	-83.3
56	0.9	-86.2
48	0.8	-87.6
40	0.8	-88.2
32	0.7	-89.1
24	0.7	-89.1
16	0.7	-89.1
8	0.6	-90.1
0	0.6	-90.1

Background greylevel = 255
Background intensity = 12.1 uW

FIGURE 4: FUNDUS IMAGES FROM:



A: PROTOTYPE SLO, STANDARD FIELD

C: COMMERCIAL SLO

B: PROTOTYPE SLO, WIDE FIELD

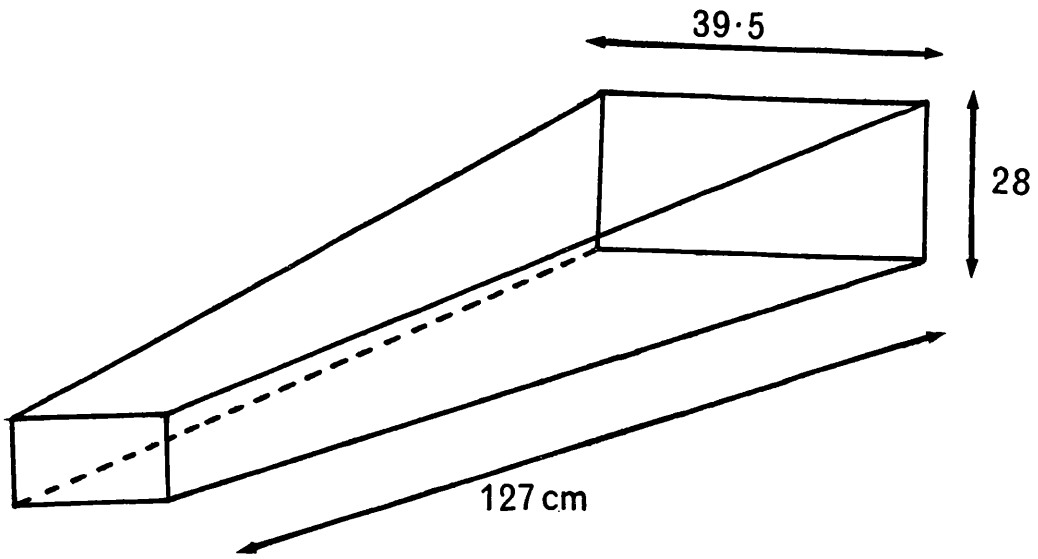


FIGURE 5: MEASUREMENT OF LASER RASTER

Calculation of angle subtended by each pixel in the raster:

The raster was uniform and was composed of 256 pixels both in the horizontal and in the vertical. Since the horizontal aspect of the raster was larger than the vertical it followed that a single pixel had its maximum length in the horizontal.

$$1 \text{ pixel (horizontal)} = \frac{17.68 \text{ deg}}{256} = 4.14 \text{ min arc}$$

$$1 \text{ pixel (vertical)} = \frac{12.58 \text{ deg}}{256} = 2.95 \text{ min arc}$$

From the literature it is known that the retinal magnification factor at the posterior pole of the schematic eye is 276 micrometres/degree (Holden and Fitzke, 1988). Hence 1 min arc equals 4.6 microns and one pixel in the digitised image represented 19.06 by 13.56 microns on the retina.

For convenience these results are displayed in Table 3.

Retinal irradiance was calculated using the factor:

$$\frac{276\text{um}}{\text{degree}} = \frac{0.0276\text{cm}}{\text{degree}}$$

Horizontal (cm) = 17.68 deg x 0.0276 cm/deg = 0.488 cm

Vertical (cm) = 12.58 deg x 0.0276 cm/deg = 0.347 cm

Area of retina = 0.169 cm^2

The radiant emission chosen for the raster background was 2.6 uW and 29 uW for the He-Ne and IR lasers respectively. Hence the retinal irradiance was 15.38 uW/cm^2 and 171.59 uW/cm^2.

TABLE 3: COMPARISON BETWEEN RASTER PARAMETERS OF THE SCANNING LASER OPHTHALMOSCOPES

SLO	FIELD OF VIEW H x V (degrees)	SIZE OF PIXELS H x V (minarc)	SIZE OF PIXEL ON RETINA H x V (microns)
PROTOTYPE	17.68 x 12.58	4.14 x 2.95	19.06 x 13.56
PROTOTYPE WITH EXTERNAL OPTICS	35.10 x 26.65	8.23 x 6.25	37.86 x 28.75
COMMERCIAL	30.94 x 24.39	7.25 x 5.72	33.35 x 26.31

3.1.2.2 Prototype scanning laser ophthalmoscope with wide field

In an attempt to overcome the restricted field of view provided by the prototype SLO an external optical system was designed (Figure 6). After experimentation the final system consisted of achromatic imaging lenses PAC019 and PAC025 [Newport, England] with focal lengths of 19mm and 38.1mm respectively and effective diameters of 12.2mm.

An example of a fundus image produced by this system is shown in Figure 4B, p85.

In order to specify the field of view, measurements of raster were made at a distance of 57cm. Using the calculations described above the angular subtence of the raster was found to be 35.1 degrees in the horizontal by 26.65 in the vertical. One pixel in the raster subtended 8.23 min arc by 6.25 min arc and one pixel in the digitised image represented 37.86 by 28.75 microns on the retina (see Table 3).

The radiant emission chosen for the raster background was 2.6 uW and 29 uW for the He-Ne and IR lasers respectively. Hence the retinal irradiance was 3.65 uW/cm^2 and 40.69 uW/cm^2.

3.1.2.3 Commercial scanning laser ophthalmoscope

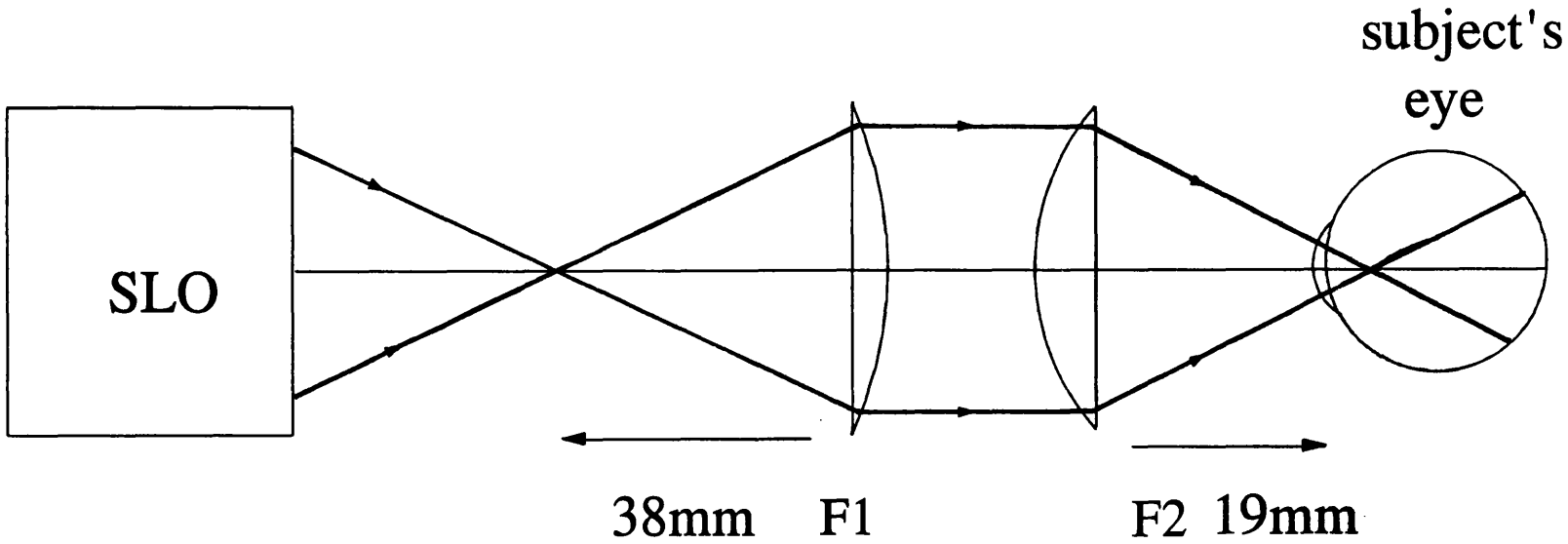
Figure 4C shows an image produced by this system.

In order to specify the field of view, measurements of raster were made at a distance of 112cm. Using the calculations described above the angular subtence of the raster was found to be 30.94 degrees in the horizontal by 24.39 in the vertical. One pixel in the raster subtended 7.25 min arc by 5.72 min arc and one pixel in the digitised image represented 33.35 by 26.31 microns on the retina (see Table 3).

The radiant emission chosen for the raster background was 12.1 uW and 14.1 uW for the He-Ne and IR lasers respectively. Hence, the retinal irradiance was 21.04 uW/cm^2 and 24.52 uW/cm^2.

* Footnote: The different distances utilised in the calculation of the angular subtence of the raster related to practical aspects of measurement.

FIGURE 6: PRINCIPLE OF EXTERNAL LENS SYSTEM



F1 = 26.3 D, effective diameter 12.2 mm
F2 = 52.6 D, effective diameter 12.2 mm

3.1.3 Contrast of stimuli

3.1.3.1 Prototype scanning laser ophthalmoscope

The relationship between the computer control (i.e. digital value) and radiant emission of the He-Ne laser in the prototype SLO is listed in Table 1A and 1B and illustrated in Figure 7. These values varied by small amounts over a period of six months. The maximum and minimum values measured are shown by the error bars.

The radiant emission from the commercial SLO was measured and found to be a factor of 3 less than that of the prototype. However, the contrast of the stimuli within the raster were comparable in the two systems.

Radiant emission values of 2.6uW for the prototype and 12.1 or 0.62uW for the commercial SLO were chosen for the background brightness. This value provided an adequate range of positive and negative foreground values for the visual stimuli. Results of calculating the contrast from the Michelson equation and Weber fraction are shown in Tables 1A and 1B and Figure 8.

3.1.3.2 Commercial scanning laser ophthalmoscope

Tables 2A and 2B show the laser radiant emission for a range of computer digital values and the calculated contrast of the visual stimuli using the Michelson equation.

3.2 System Assessment

3.2.1 Scotoma mapping

A) In-house software

Analysis:

The flicker method of analysis for measuring eye movements was found to be useful and with experience it was possible to align each fundus images to the master image to within one pixel. In order to determine the repeatability of these measurements one sequence of images was aligned three times on one day and once again four weeks later. The range of mean pixel values of X and Y varied by 0.13 and 0.43 which was equivalent to 0.54 and 1.27 min arc respectively.

FIGURE 7: PROTOTYPE SLO HELIUM-NEON LASER EMISSION UNDER COMPUTER CONTROL

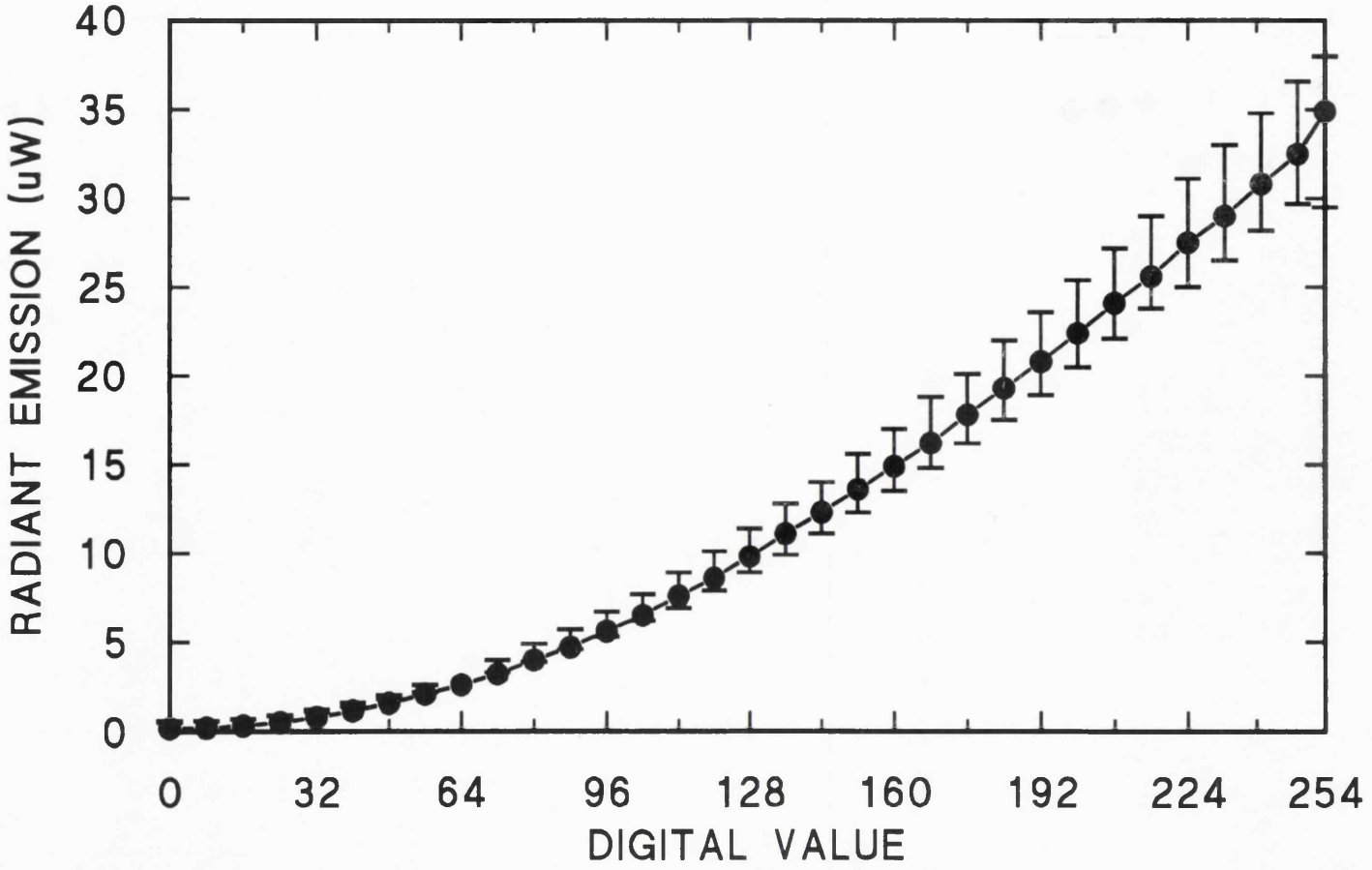
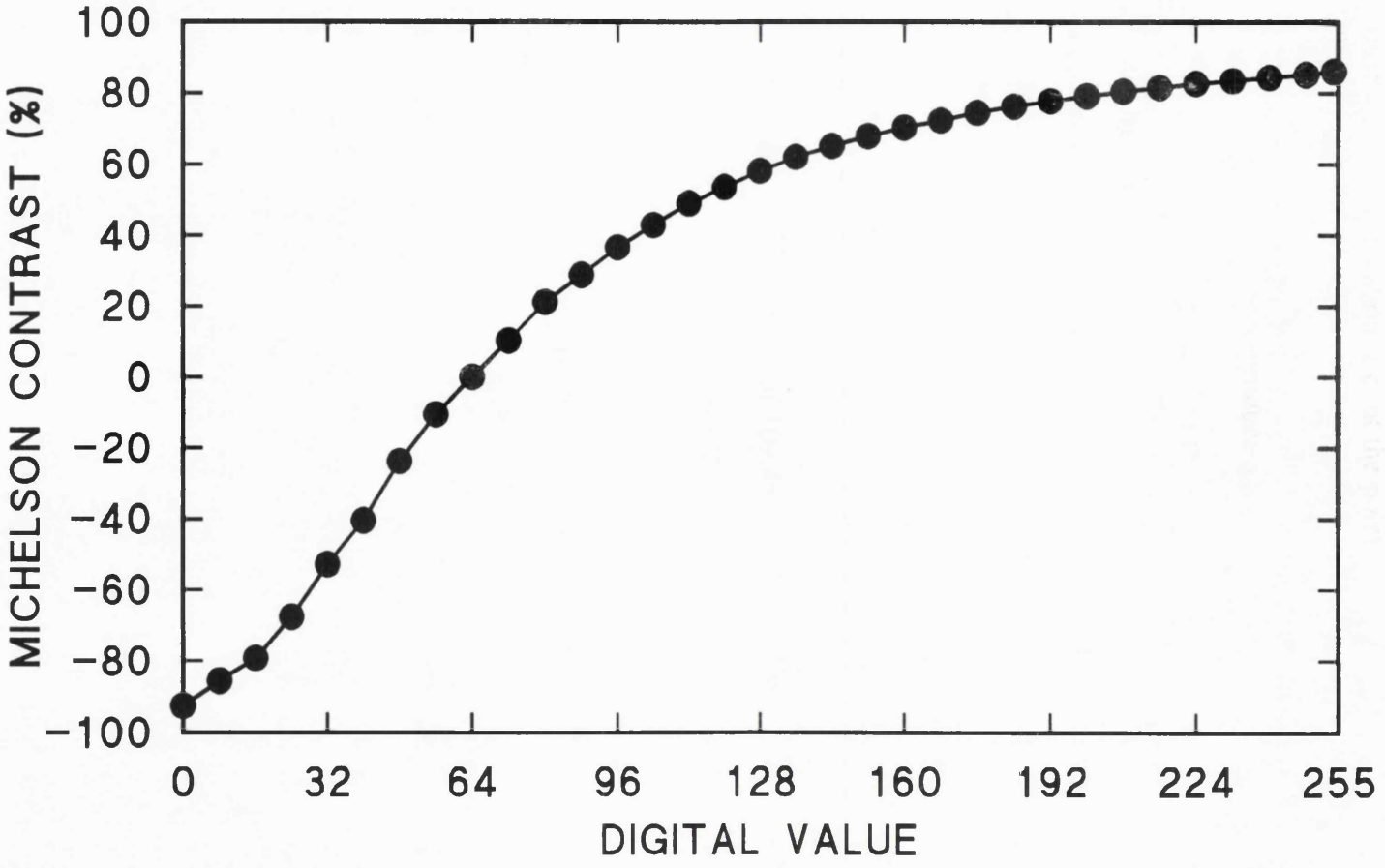


FIGURE 8: CONTRAST OF VISUAL STIMULI
DUE TO CHANGES IN HELIUM-NEON RADIANT EMISSION



Stimuli moving from non-seeing to seeing:

Figure 9 shows the results of normal observer CJ making deliberate eye movements, by fixating two locations separated by 2.5 degrees, throughout the testing period. In the uncorrected images in Figure 9A the mapping stimuli are scattered whereas in Figure 9B, after compensation for eye movements, the stimuli are positioned at their true retinal location, i.e. at the point where the subject responded to them.

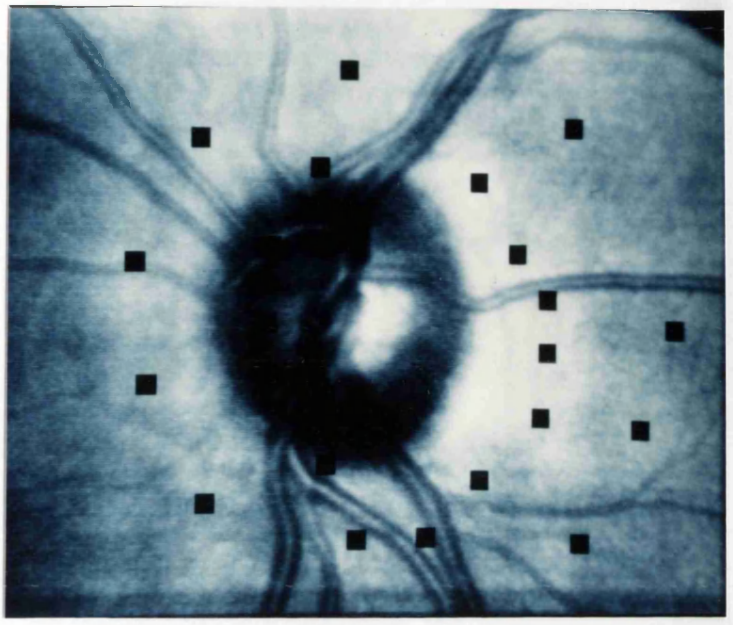
The measurement was repeated twice to produce a pair of maps. When comparing the positions of the mapping stimuli in the paired maps it was possible to measure the distance between each consecutive pair of stimuli. For a complete scotoma map the following were calculated both before and after correction for eye movements

i) the mean distance, representing changes in both fixation and subject's response

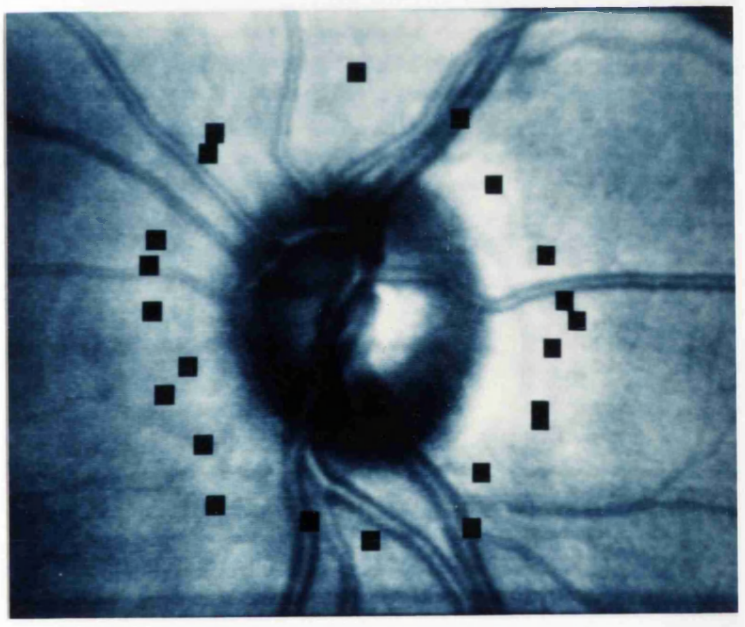
ii) the S.D., showing the variability.

For the demonstration case CJ the mean uncorrected distance of 169.99 min arc was greater than the mean corrected distance of 109.45 min arc (Table 4). Similarly, the S.D. for the uncorrected distances (92.54 minarc) was greater than the S.D. of the corrected distances (53.2 minarc). Hence correcting for eye movements had the effect of making the paired maps more alike and as such allowed the repeated maps to define the edge of the scotoma more precisely. The residual differences in distances were due to variability in the subject's responses.

In the test case described above the subject made deliberate eye movements; however, in the experiment proper five normal observers attempted to maintain steady fixation throughout the test. Figure 10 shows the results of scotoma mapping from non-seeing to seeing areas for subject KN. The uncorrected stimuli positions for paired maps 1 and 2 are illustrated in Figure 10A whereas Figure 10B shows the relative corrected stimuli positions. The mean distance and the S.D. were 50.89 and 31.68 min arc respectively before correction of eye movements and 41.97 and 25.17 min arc after correction (see Table 4).



A:



B:

FIGURE 9: SLO IMAGES OF SCOTOMA MAPPING OF PHYSIOLOGICAL BLIND SPOT IN NORMAL OBSERVER
A: BEFORE COMPENSATION OF EYE MOVEMENTS
B: AFTER COMPENSATION OF EYE MOVEMENTS

TABLE 4: RESULTS OF SCOTOMA MAPPING FROM NON-SEEING TO SEEING BEFORE AND AFTER CORRECTION FOR EYE MOVEMENTS

SUBJECT		UNCORRECTED DISTANCE (minarc)	CORRECTED DISTANCE (minarc)
CJ (DEMO	MEAN	169.99	109.45
ONLY)	SD	92.54	53.20
JS	MEAN	145.64	88.83
	SD	29.12	38.01
KN	MEAN	50.89	41.97
	SD	31.68	25.17
CW	MEAN	28.67	27.93
	SD	16.31	12.15
KS	MEAN	30.21	30.35
	SD	15.68	19.08
LC	MEAN	42.88	47.43
	SD	24.29	26.95
AVERAGE	MEAN	59.66	47.30
(OF 5)	SD	23.42	24.27
T-TEST	MEAN		p>0.05
	SD		p>0.05

FIGURE 10A: SCOTOMA MAP OF PHYSIOLOGICAL BLIND SPOT:
NON-SEEING TO SEEING
BEFORE CORRECTION OF EYE MOVEMENTS

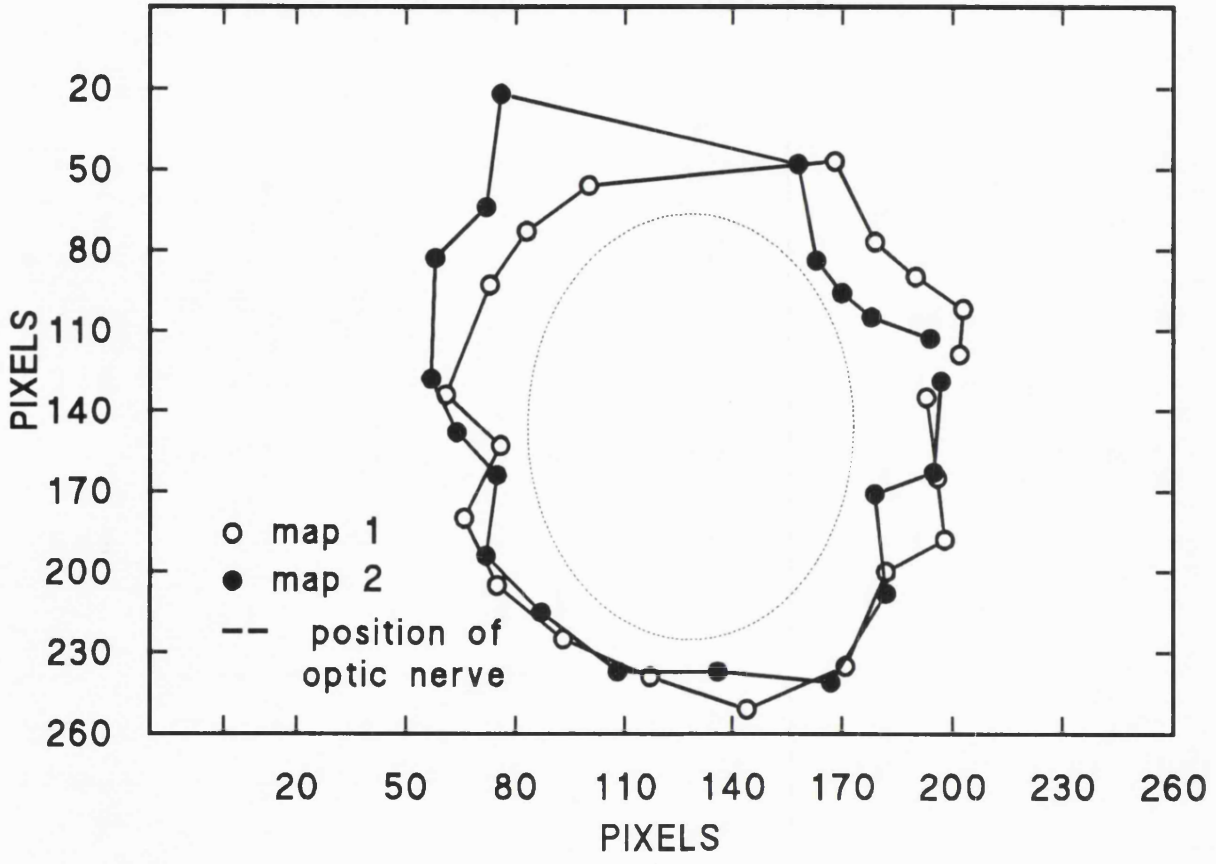
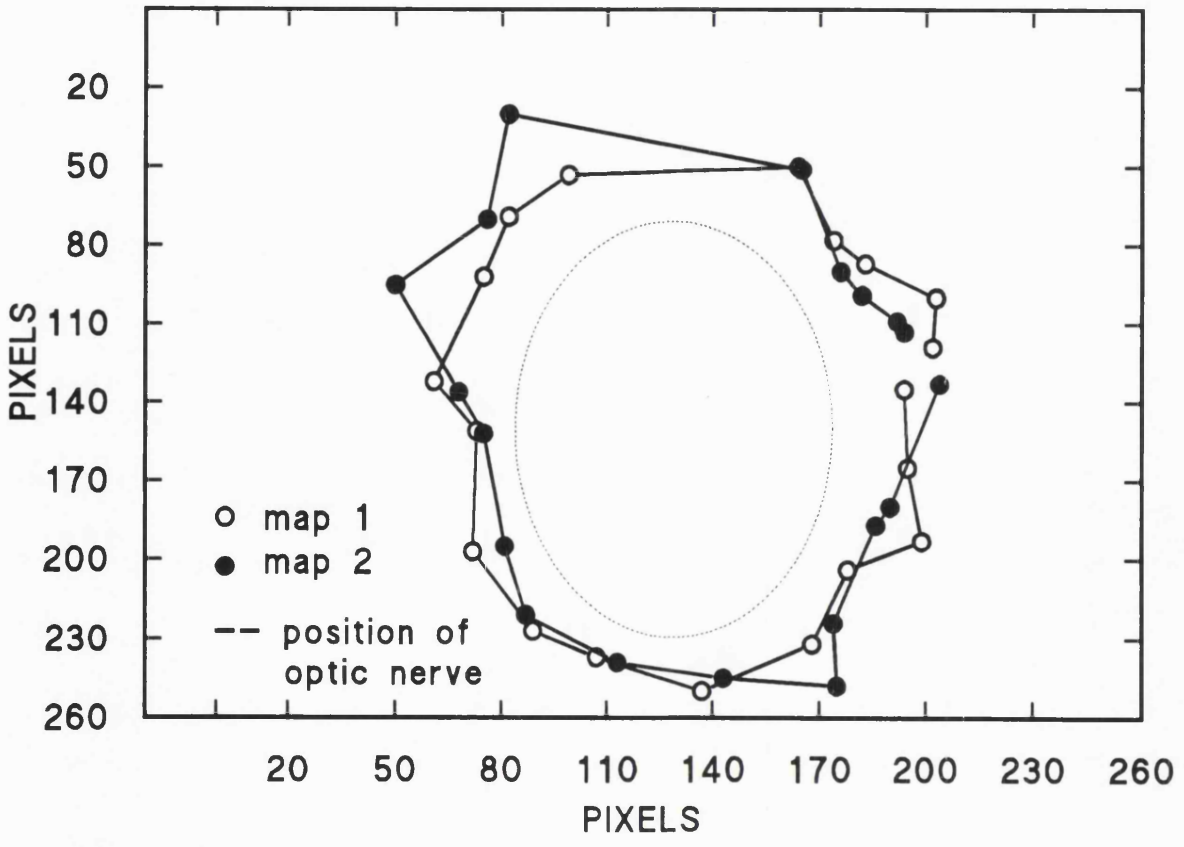


FIGURE 10B: SCOTOMA MAP OF PHYSIOLOGICAL BLIND SPOT:
NON-SEEING TO SEEING
AFTER CORRECTION FOR EYE MOVEMENTS



Stimuli moving from seeing to non-seeing:

Figure 11A shows the uncorrected stimuli positions for subject KS. The corrected stimuli positions are illustrated in Figure 11B. The mean and S.D. distances were 46.48 and 44.7 min arc respectively before correction of eye movements and 43.05 and 31.33 min arc after correction (see Table 5).

In the above two examples the mean distances and the related S.D. have decreased after correction for eye movements. However, it can be seen from the table that for some subjects these distances increased after correction. A paired t-test was used to compare the means and S.D. of the uncorrected distances and the corrected distances. There was no significant difference at the 0.05 level for scotoma mapping from either seeing to non-seeing areas or non-seeing to seeing areas. In summary, correcting for eye movements had little effect on the reproducibility of scotoma mapping in normal observers with good fixation.

For all subjects, the size of the scotoma relating to the optic nerve head appeared to be larger when the mapping stimulus moved from a non-seeing area to a seeing area compared with the stimulus moving from a seeing to a non-seeing area (see Figures 10 and 11). This difference could be accounted for by reaction time which was measured and found to be approximately 400 ms (see Table 6). Since the mapping stimulus was moving at a velocity of 2 degrees/sec, the measured reaction time would allow the stimulus to travel almost 1 degree further than the edge of the scotoma. The dotted line on Figures 10 and 11 show the approximate position of true margin of the physiological blind spot.

This method of scotoma mapping was used on several patients with ARMD without success. The two main problems were patients'

a) lack of sufficiently good fixation and

b) slowness in responding to the moving stimulus.

Hence, no useful results were obtained.

FIGURE 11A: SCOTOMA MAP OF PHYSIOLOGICAL BLIND SPOT:
SEEING TO NON-SEEING
BEFORE CORRECTION OF EYE MOVEMENTS

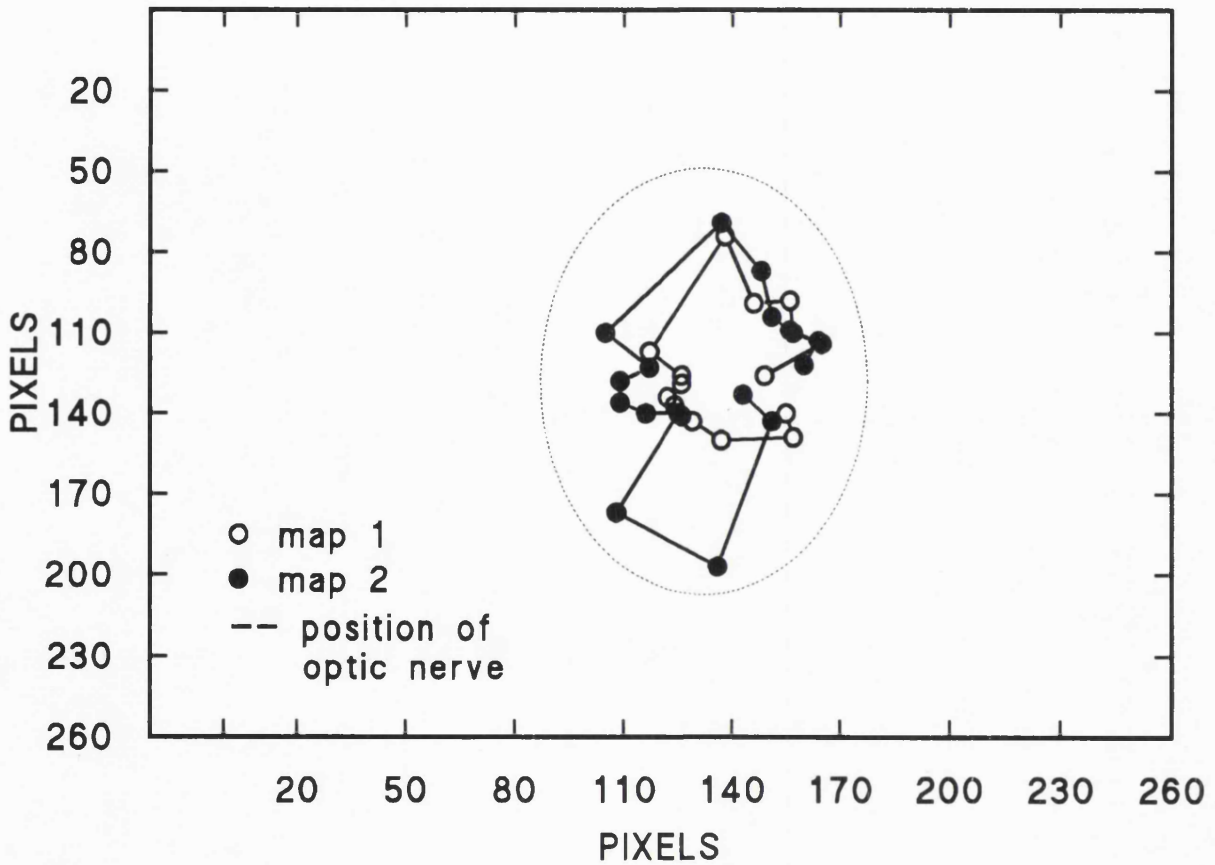


FIGURE 11B: SCOTOMA MAP OF THE PHYSIOLOGICAL BLIND SPOT:
SEEING TO NON-SEEING
AFTER CORRECTION FOR EYE MOVEMENTS

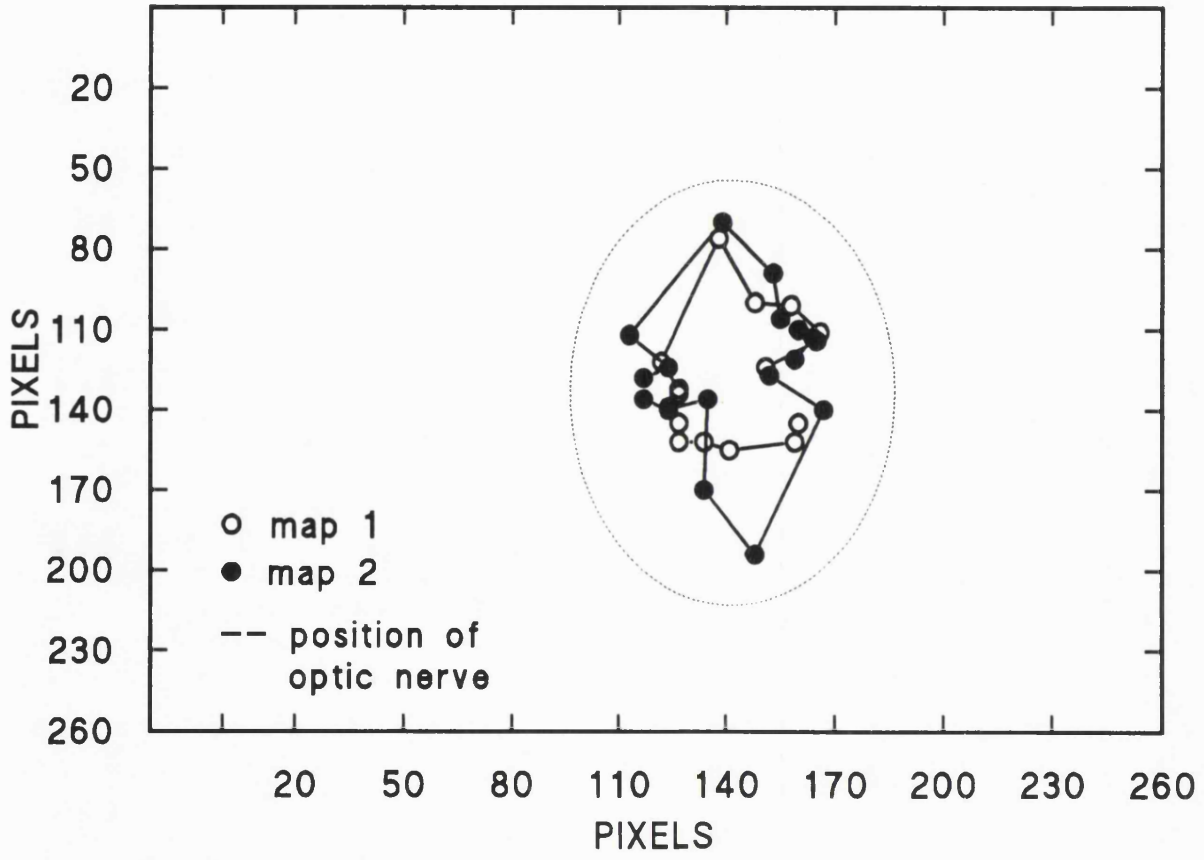


TABLE 5: RESULTS OF SCOTOMA MAPPING FROM SEEING TO NON-SEEING BEFORE AND AFTER CORRECTION FOR EYE MOVEMENTS

SUBJECT		UNCORRECTED DISTANCE (minarc)	CORRECTED DISTANCE (minarc)
JS	MEAN	77.95	105.42
	SD	26.11	47.74
KN	MEAN	41.23	78.93
	SD	24.4	25.48
CW	MEAN	39.24	45.75
	SD	20.93	26.43
KS	MEAN	46.48	43.05
	SD	44.70	31.33
LC	MEAN	17.01	19.15
	SD	9.52	11.45
AVERAGE	MEAN	44.38	58.46
	SD	25.13	28.49
T-TEST	MEAN		$p>0.05$
	SD		$p>0.05$

TABLE 6: REACTION TIME OF TWO NORMAL SUBJECTS TO THE PRESENTATION OF A MAPPING STIMULUS

SUBJECT	RETINAL AREA ADJACENT TO OPTIC NERVE	RANGE (ms)	MEAN (ms)
FF	temporal	330 - 490	421
	nasal	410 - 500	430
LC	temporal	330 - 660	435
	nasal	250 - 410	370

B) Rodenstock commercial software

Figure 23 (p134) shows the fundus image of a patient with ARMD. The mapping stimuli presented to the patient were of equivalent size to a Goldman III target and of -90% contrast. The areas of residual vision and dysfunction are displayed on the fundus image.

3.2.2 Assessment of fixation

Details of subjects recruited to this study are displayed in Table 7. Results depicted in this section are based on raw data (see Appendix IV). For ease of presentation, selected and averaged data only are tabulated in this chapter.

EXPERIMENT I: The effect of fixation target form and size.

Averaged results from all the normal subjects are shown in Table 8; individual patient results are shown in Tables 9 and 10. In the table, S.D. is the standard deviation of the horizontal (H) and vertical (V) eye movements. For the patients, the retinal location of PRLs is described in distance in terms of degrees from the fovea and in angular displacement in terms of a clockface position. The orientation of the ellipse is described in degrees deflection from the horizontal.

There was a large inter-subject variability of BCEA, both within the normal group (range 21 to 1405; Appendix IV, Table 1) and between patients (range 36 to 15,903; Appendix IV, Table 2). In the normal group the fixation stability did not appear to correlate with age.

In a given subject measurements were fairly reproducible, for example, the measurements on CJ were repeated on two separate occasions (range 99 - 356 and 47 - 214; Appendix IV, Table 1) but the small improvement in fixation stability demonstrated in the second sitting was not statistically significant (t test;$p > 0.05$).

The instructions given to subjects may have been responsible for variations in the results. For example, for AM the standard instruction "watch the target carefully and steadily" gave BCEAs of 129 and 369 min arc^2, whereas the novel instruction "hold your eye still on one specific point on the target" gave results of 87

TABLE 7: SUMMARY OF SUBJECTS' DETAILS

SUB-JECT	AGE	SEX	EYE	VA	DIAGNOSIS	SIZE (DEG)
CJ	36	M	R	6/6		
CL	28	M	R	6/6		
PK	51	F	R	6/6		
EM	27	F	R	6/6		
DS	32	M	R	6/6		
IM	32	M	R	6/6		
AP	27	F	R	6/6		
JS	71	M	R	6/6		
PJ	33	M	R	6/6		
AM	58	M	R	6/6		
DD	59	M	R	6/6		
AJ	25	F	R	6/6		
EF	35	F	L	6/18	FUNDUS FLAVIMACULATUS	20
JW	72	F	R	6/60	GEOGRAPHIC ATROPHY	4
AA	61	M	L	6/60	ATYPICAL STARGARDTS	12
DB	75	M	R	3/60	DISCIFORM DEGENERATION	12
NH	35	M	R	6/60	BULL' EYE MACULOPATHY	12
HW	61	M	R	6/9	NEOVASCULAR MEMBRANE	4
KA	68	M	L	6/12	MACULAR HOLE	7

M=male, F=female, R=right, L=left.
SIZE (DEG)= approximate diameter of lesion.

TABLE 8: EXPERIMENT I AVERAGED FIXATION DATA FOR TWELVE NORMAL SUBJECTS VIEWING DIFFERENT STATIONARY TARGET ARRAYS

TARGET	LETTER SIZE (min arc)	CONTRAST (%)	SD(H)	SD(V)	BCEA
E	20	-25	6	4	183
E	20	+25	4	4	116
E	160	-25	8	6	350
E	160	+25	7	7	343
TH+LH	20	-25	4	3	102
TH+LH	20	+25	5	5	152
+	20	-25	4	3	81
GRID	100	-25	5	3	116

TABLE 9: EXPERIMENT I FIXATION STABILITY DATA OF LOW VISION PATIENTS VIEWING STATIONARY TARGETS

SUBJ -ECT	TARGET	PRL (deg)	PRL clock posit -ion	TARGET SIZE (min arc)	CONTR -AST (%) +	CONTR -AST (%) -	SD (H)	SD (V)	ELLIP -SE (deg) + contr -ast	ELLIP -SE (deg) - contr -ast	AVERAGE BCEA
EF	E	fovea		80	80	80	7	6	27	12	346
	TH+LH	fovea		80	80	80	5	4	180	140	101
JW	E	2	5	80		50	16	6		167	495
	TH+LH	2	5	80		50	11	8		154	603
AA	TH+	6	12	80		95	41	46		87	13367
DB	E	6	3	80	50	50	13	4	161	171	261
	E	6	3	160	50	50	8	3	169	161	146
	TH+	6	3	80	50	50	9	7	121	171	322

EF fundus flavimaculatus
JW geographic atrophy
AA atypical Stargardts
DB disciform degeneration

TABLE 10: EXPERIMENT I FIXATION STABILITY DATA OF LOW VISION PATIENTS VIEWING STATIONARY TARGETS

SUBJ -ECT	TARGET	PRL (deg)	PRL clock posit -ion	TARGET SIZE (min arc)	CONTR -AST (%) +	CONTR -AST (%) -	SD (H)	SD (V)	ELLIP -SE (deg) + contr -ast	ELLIP -SE (deg) - contr -ast	AVERAGE BCEA
NH	E	6	11	40	50	50	11	12	26	92	900
	E	6	11	80	50	50	11	21	74	79	1744
	TH+LH	6	11	80	50	50	7	17	76	95	693
KA	E	fovea		40	50	50	7	3	160	3	134
	TH+LH	fovea		60	50	50	8	4	9	168	206
HW	E	fovea		40	25	25	8	4	155	3	168
	E	fovea		80	25	25	6	5	97	10	185
	TH+LH	fovea		40	25	25	3	4	45	107	68

NH Bull's eye maculopathy
KA macular hole
HW neovascular membrane

and 112 min arc^2 (Appendix IV, Table 1).

In normal subjects the enlarged Snellen E (up to 160 min arc) induced significantly less stable fixation compared with the basic sized E of 20 min arc (F test, $p=0.012$). The results for the single fixation cross, fixation cross embedded in letters and the grid pattern were not significantly different compared with the basic E (t test;$p>0.05$) (see Table 8).

In normal subjects the standard deviation of horizontal eye position during fixation was significantly greater than the standard deviation of vertical eye position (t test, $p<0.01$). The orientation of the ellipse in both the normal and patient groups tended to have a strong horizontal component although the absolute value appeared to vary.

The polarity of contrast of the targets had no significant effect on the fixation stability of either normal subjects or patients (t test;$p>0.05$).

By observation of the fovea on the TV monitor relative to the target it was noted that all normal subjects used the fovea to fixate the targets. Patients EF, KA and HW used the residual elements of their foveae for viewing, whereas patients JW, AA, DB, and NH utilised an eccentric PRL.

EXPERIMENT 2: Alternative retinal locations (ARLs) for fixation in low vision subjects.

Fixation stability using the ARLs (Table 11) was equivalent or notably worse when compared with the PRL. Values ranged from 128 to 15,903 minarc^2.

EXPERIMENT 3: The effect of scrolled text on fixation stability.

The question of whether moving text would influence fixation was investigated by presenting scrolled text at specific locations while the subject attempted to fixate a stationary target. Averaged BCEAs for normal subjects viewing scrolled text are shown in Table 14 and averaged results for individual patients are shown in Tables 12 and 13.

TABLE 11: EXPERIMENT II FIXATION STABILITY DATA OF PATIENTS USING ALTERNATIVE RETINAL LOCATIONS FOR VIEWING STATIONARY TARGETS

SUBJ -ECT	TARGET	PRL (deg)	PRL clock posit -ion	TARGET SIZE (min arc)	CONTR -AST (%) +	CONTR -AST (%) -	SD (H)	SD (V)	ELLIP -SE (deg) + contr -ast	ELLIP -SE (deg) - contr -ast	AVERAGE BCEA
JW	E	2	12	80		50	28	15		179	2888
AA	TH+	6	2	80		95	70	33		172	15903
DB	E	6	10	80	50	50	5	7	105	52	192
	E	6	2	80	50	50	10	4	157	166	177
	E	6	10	160	50	50	6	8	130	89	251
	E	6	2	160	50	50	17	3	175	178	330
	TH+	6	10	80	50	50	5	4	123	176	128
	TH+	6	2	80	50	50	13	3	173	8	238
KA	E	3.5	12	40	50	50	22	12	164	150	1114

JW geographic atrophy
AA atypical Stargardts
DB disciform degeneration
KA macular hole

TABLE 12: EXPERIMENT III FIXATION STABILITY OF INDIVIDUAL PATIENTS VIEWING SCROLLED STIMULI OF VARIOUS SPEEDS AT DIFFERENT RETINAL LOCATIONS

SUBJECT	RETINAL LOCATION (deg)	BCEA SPEED 1	BCEA SPEED 2	BCEA SPEED 3
EF	fovea	1195	3048	3724
	2	1818	690	380
	4	810	1189	1093
	6	2401	413	606
NH	fovea	2651	5626	806
	2	3749	6094	1576
	4	15699	10249	4817
	6	2587	2791	3706

EF fundus flavimaculatus: letter size 80 min arc, contrast -85/+75%
NH Bull's eye maculopathy: letter size 60 min arc, contrast -/+50%

TABLE 13: EXPERIMENT III FIXATION STABILITY OF INDIVIDUAL PATIENTS VIEWING SCROLLED STIMULI OF VARIOUS SPEEDS AT DIFFERENT RETINAL LOCATIONS

SUBJECT	RETINAL LOCATION (deg)	BCEA SPEED 1	BCEA SPEED 2	BCEA SPEED 3
KA	fovea	251	423	256
	2	182	259	262
	4	203	253	505
	6	358	723	265
HW	fovea	111	214	174
	2	208	101	166
	4	275	89	133
	6	355	447	227

KA macular hole: letter size 80 min arc, contrast -/+90%
HW subretinal membrane: letter size 40 min arc, contrast -/+25%

TABLE 14: EXPERIMENT III AVERAGED FIXATION STABILITY DATA FOR NORMAL SUBJECTS VIEWING SCROLLED STIMULI OF VARIOUS SPEEDS AT DIFFERENT RETINAL LOCATIONS

RETINAL LOCATION (deg)	BCEA SPEED 1	BCEA SPEED 2	BCEA SPEED 3	BCEA SPEED 4
fovea	277	239	328	408
2	515	942	456	718
4	669	249	592	1432
6	368	194	475	1651

A typical example of BCEAs for a normal subject is shown in Figure 12. Examples of patients with relatively good and poor fixation stability are shown in Figures 13 and 14; the graphs are plotted on equivalent axes for comparison. In each figure four bivariate contour ellipses are shown; one of these ellipses (A) is for a stationary Snellen E target. This ellipse is included to demonstrate changes in relative size and orientation of the other three ellipses, e.g. 1, 2, 3, which represent the progressively increasing scrolling speeds of 0.6, 1.1 and 1.7 degrees/sec.

In Figures 15A and B (p118), the fundus photographs illustrate the influence of macular disease on fixation. The normal observer utilised the fovea and the retinal area used to view the target fell within the black dot. In contrast, an individual with juvenile macular disease viewed eccentrically and the area used was 15,000 min arc^2 which is represented by the ellipse.

In both the normal and patient groups the best fixation was achieved with the stationary targets ($p < 0.001$). Using ANOVA, the speed of the text did not significantly affect the fixation stability ($p > 0.05$); neither did the retinal position of the presented stimuli ($p > 0.05$). There was no significant difference between the horizontal and vertical standard deviations for any of the four speeds ($p > 0.05$).

Performance was related to both the magnitude and location of retinal damage and similar parameters of relatively unaffected retina. Two extreme examples are shown in Figures 13 and 14. For patient EF (Table 12) fixation stability was worse when the text was scrolled across the fovea, i.e. the region of maximum vision. At the retinal locations of 2, 4 and 6 degrees, where vision was more compromised, fixation was more stable. That is, the distracting stimulus had less influence in regions where vision was poor. In contrast, patient NH with Bull's Eye maculopathy demonstrated worst stability in a region of poor vision (4 degrees), where he could only just recognise the letters and made searching eye movements in order to read them. When the letters were scrolled across the fovea, where he was unaware of them, fixation was good. It became less stable when the text was scrolled at 6 degree location which was his PRL.

FIGURE 12: BCEAs IN NORMAL OBSERVER VIEWING STATIONARY AND SCROLLED STIMULI

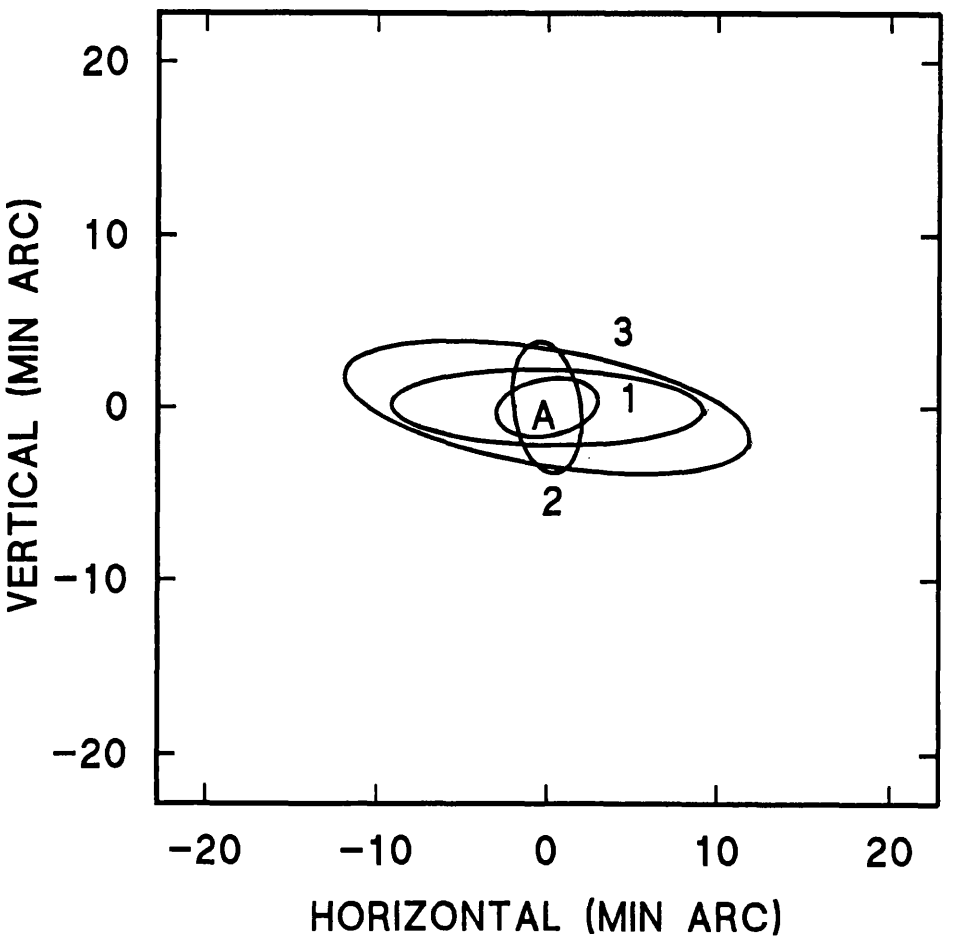


FIGURE 13: BCEAs IN PATIENT VIEWING STATIONARY AND SCROLLED STIMULI

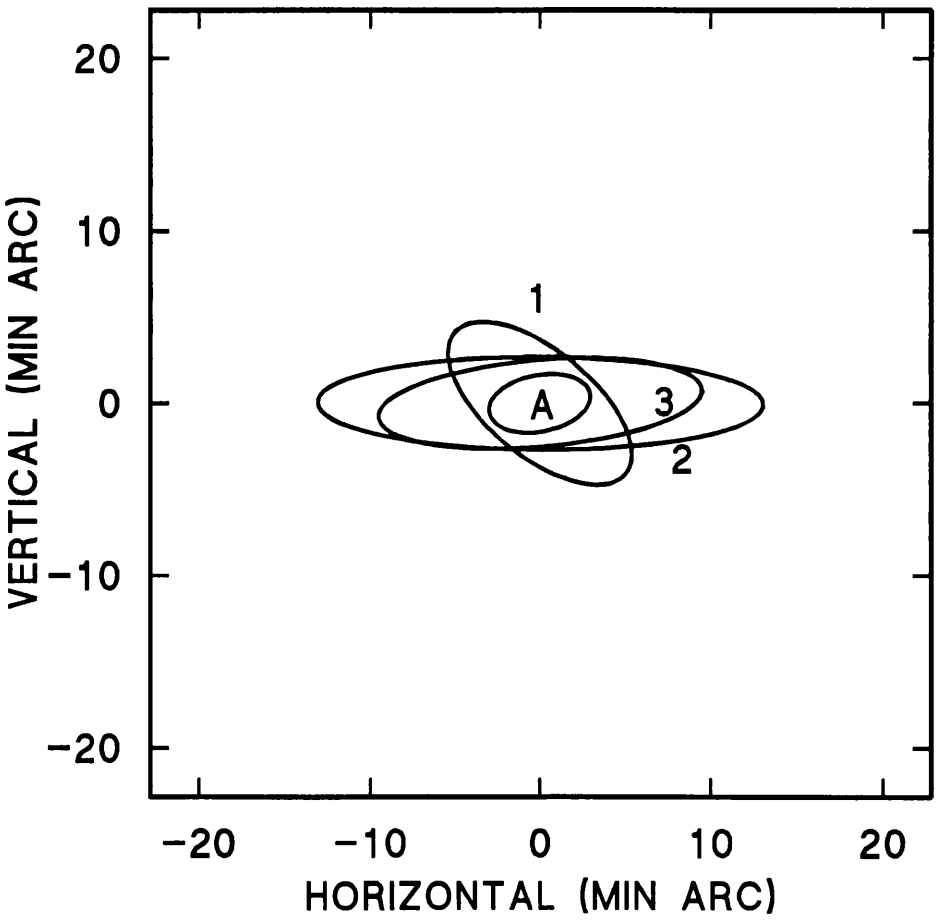
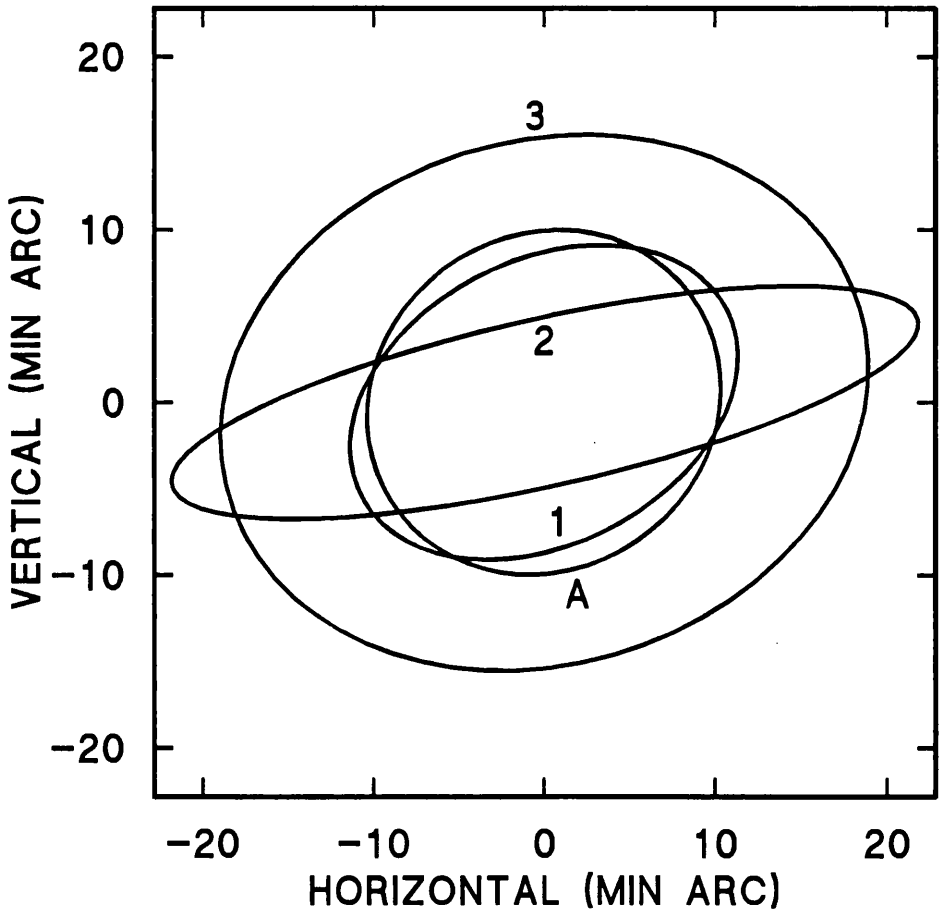
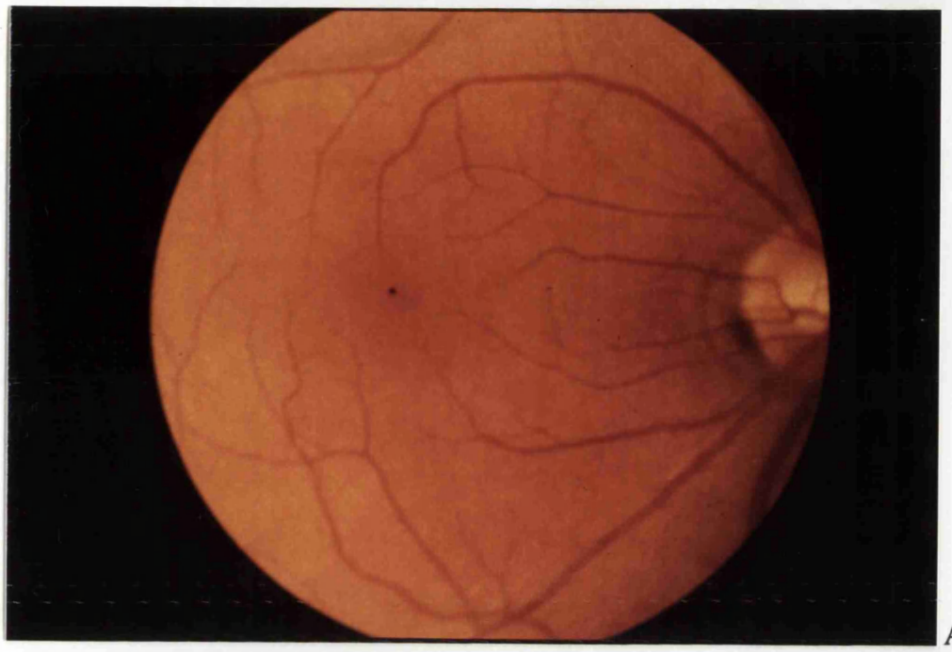
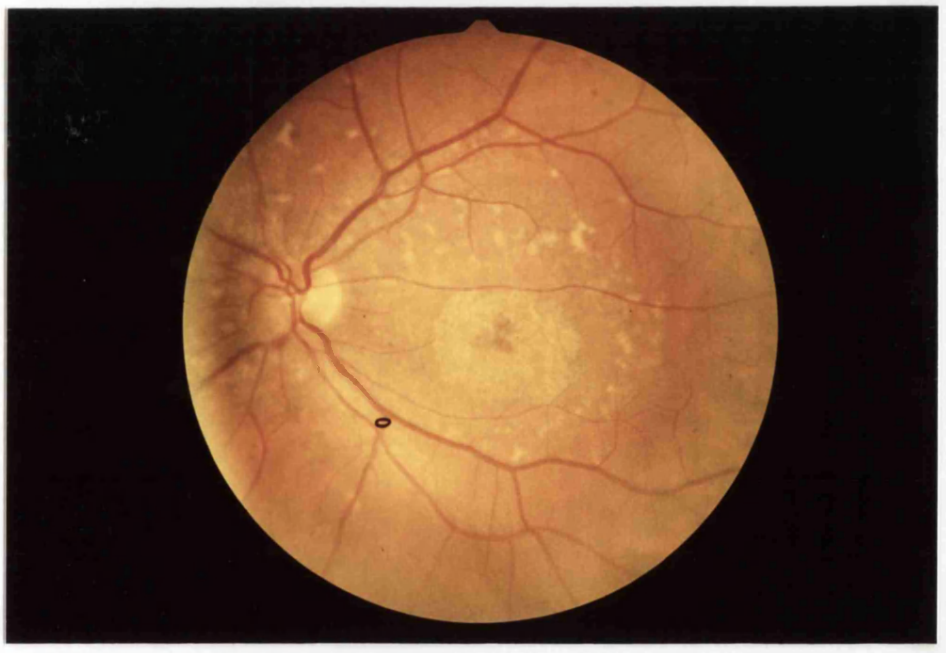


FIGURE 14: BCEAs IN PATIENT VIEWING STATIONARY AND SCROLLED STIMULI





A:



B:

FIGURE 15: FUNDUS PHOTOGRAPHS INDICATING POSITION OF FIXATION AND SIZE OF BCEA IN
A: NORMAL OBSERVER
B: SUJECT WITH JUVENILE MACULAR DISEASE

3.2.3 Letter recognition using scrolling text

EXPERIMENT 1: Letter recognition at different retinal locations in normal observers.

Figure 16 shows the percentage of letters read correctly at five retinal locations 2, 4, 6 and 8 degrees superior to the fovea. The letters were 30 min arc in size with a contrast of +55%. Two scrolling speeds were used; 1.5 and 3.8 degrees/sec.

The two normal individuals showed similar performance. At the fovea (i.e. 0 degrees retinal eccentricity) 100% of letters were read correctly, but visual performance declined rapidly with increasing eccentricity, falling to 50% at 5 degrees. This pattern was more marked with the faster scrolling speed of 3.8 deg/sec. For example, 4 degrees from the fovea, less than 60% of letters were read correctly at the faster speed, but accuracy was over 80% with the slower speed. The slower speed was used for all subsequent experiments described in this section.

EXPERIMENT 2: Effect of letter contrast at different retinal locations in normal observers.

The effects of letter contrast at 2 and 6 degree eccentricity in the superior retina are shown in Figure 17. The results from the two individuals were similar. At 55% contrast, either positive or negative, both observers attained 100% accuracy for letters presented at 2 degrees, but only 45-60% accuracy at 6 degrees. The location closer to the fovea allowed 90% accuracy to be maintained for contrasts above + and - 25%. Below this contrast there was a rapid drop in visual performance. Within the range of contrasts used, performance across the positive/negative contrasts appeared to be symmetrical.

EXPERIMENT 3: Letter recognition at different retinal locations in a patient with age-related macular degeneration.

Patient DB stated that he had a preferred retinal location but two alternative areas were used in addition for various visual tasks. The position of each location was determined by asking the patient to read a letter in the SLO, the retinal area

FIGURE 16: NUMBER OF LETTERS READ AT DIFFERENT RETINAL LOCATIONS BY NORMAL OBSERVERS

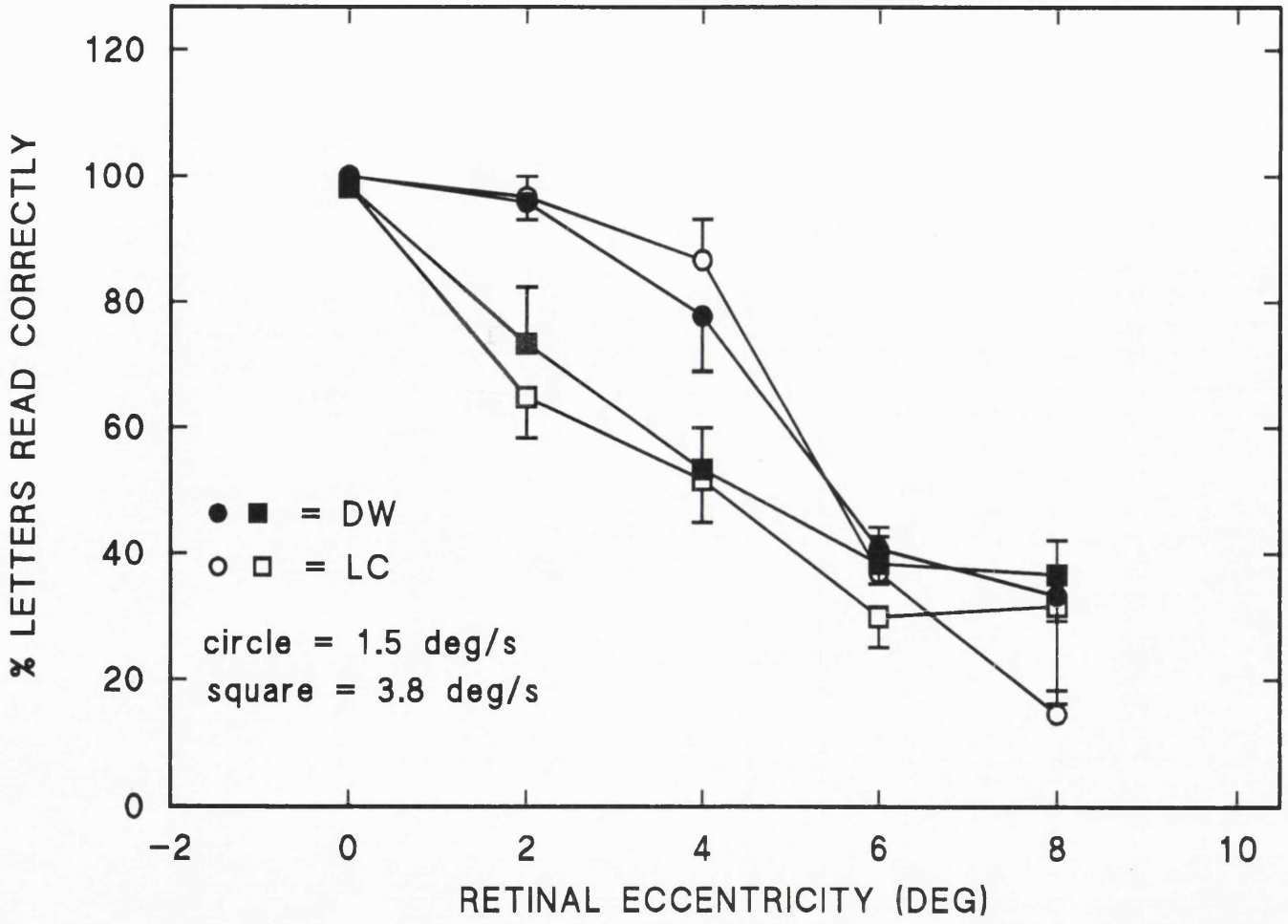
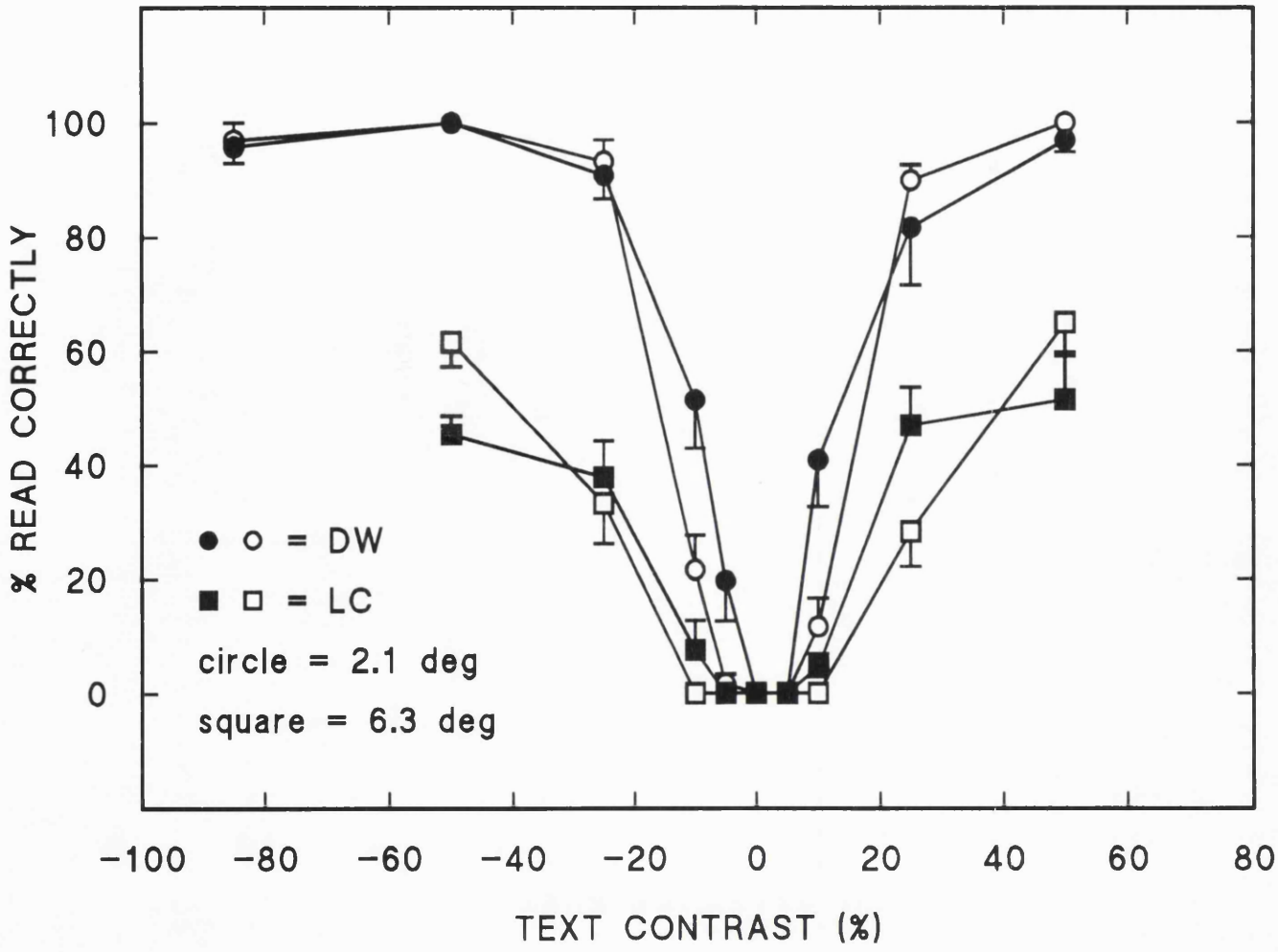


FIGURE 17: PERCENTAGE OF LETTERS OF VARIABLE CONTRAST READ BY NORMAL OBSERVERS



used could be seen on the monitor (see Figure 18A). Visual performance of these locations were investigated using 90 min arc letters of variable contrast (Figure 19).

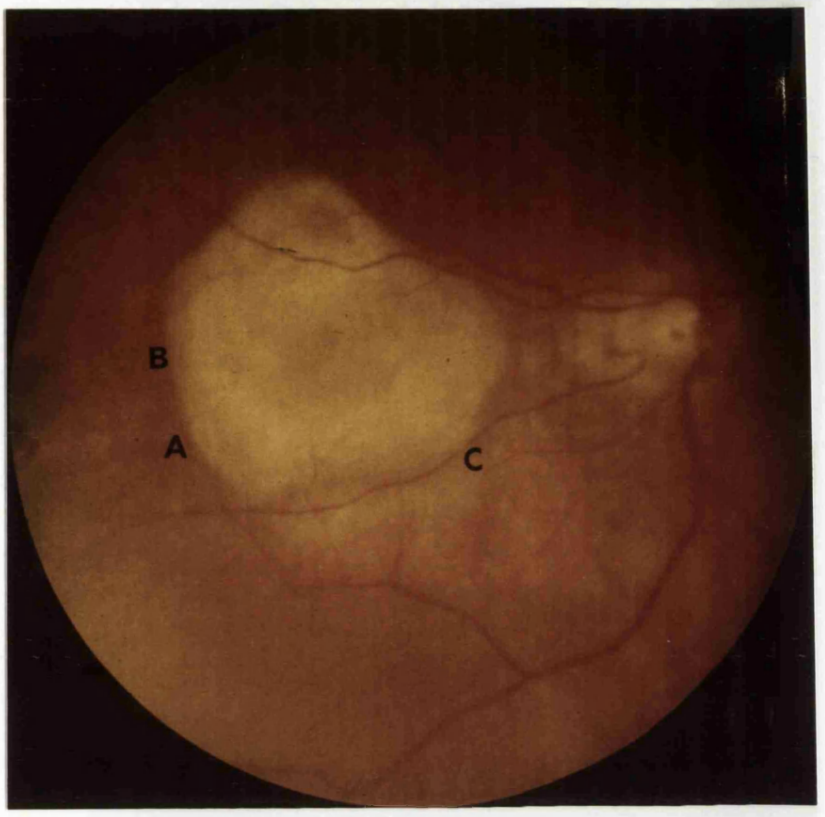
There was a small difference in performance between locations, with area A allowing the best performance at +25% contrast. Conversely, at -25% contrast all three locations provided poor performance. The identification of retinal area A (Figure 19) as the most appropriate area of the three tested for the specific visual task used in this experiment coincided with the patient's subjective preference for reading normal print with his optical magnifier.

In order to compare this patient's visual performance to that of a normal observer the experiment was repeated with a normal subject (Figure 19). The same stimulus parameters were used, but the window was positioned differently. In the normal the window was positioned vertically above the fovea, whilst in the patient it was displaced vertically and laterally. The normal observer's performance appears to be more symmetrical than that of the patient, but it must be borne in mind that a different retinal location was tested.

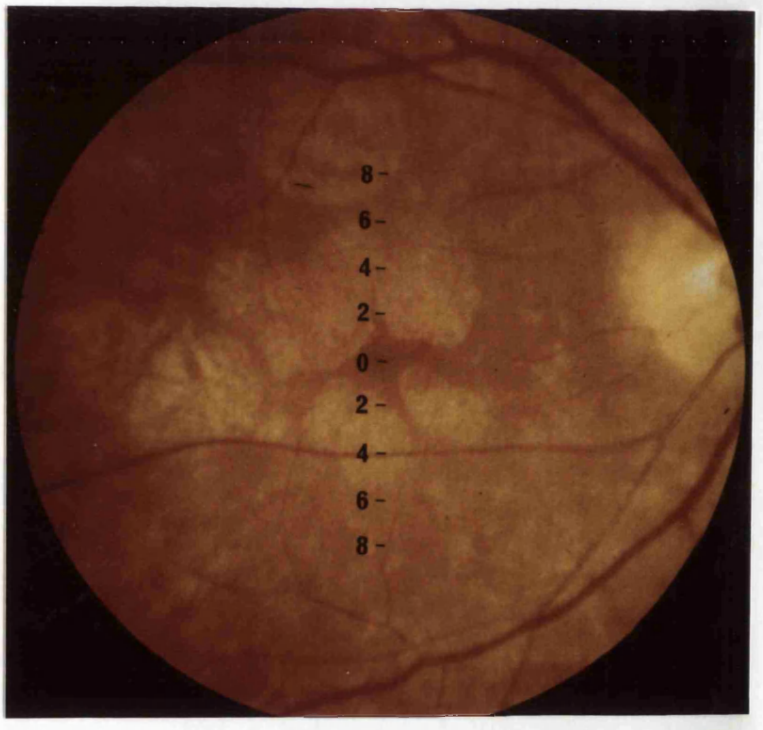
EXPERIMENT 4: Letter recognition at different retinal locations in a patient with juvenile macular disease.

The fundus appearance of patient EF's right eye is shown in Figure 18B. The superior retina appeared to be more affected than the inferior, but in both typical yellowish flecks were apparent. The fovea and foveola appeared relatively normal.

With this patient the investigation was divided into two phases. In the first, windows were placed in varying locations centrally, inferiorly and superiorly (see Figure 18B), in order to correlate function with morphology of the lesions. In the second, a more extensive investigation of foveal function using different letter contrast was undertaken. The results of phase one for a 60 min arc target are illustrated in Figure 20. A near-normal response was demonstrated at the fovea while the retina below the fovea allowed considerably better performance than that above. For example, with the stimulus 2 degrees inferiorly 55% of letters were read correctly, but at 2 degrees superiorly the accuracy was almost 0. The results of the



A:



B:

FIGURE 18: FUNDUS PHOTOGRAPHS OF PATIENTS WITH:
A: AGE-RELATED MACULAR DISEASE
B: JUVENILE MACULAR DISEASE

FIGURE 19: NUMBER OF LETTERS READ CORRECTLY AT DIFFERENT RETINAL LOCATIONS BY NORMAL OBSERVER AND PATIENT WITH ARMD

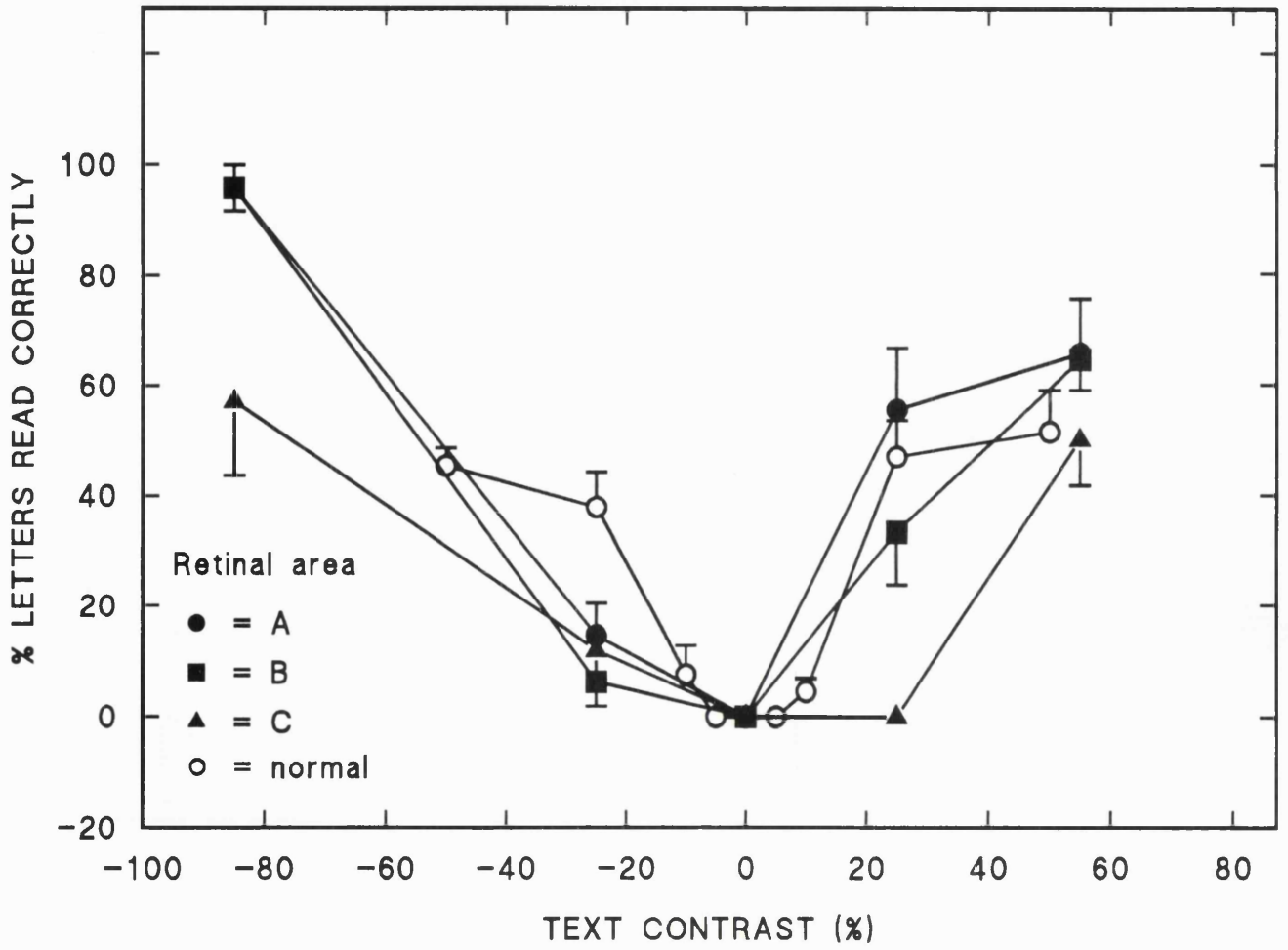
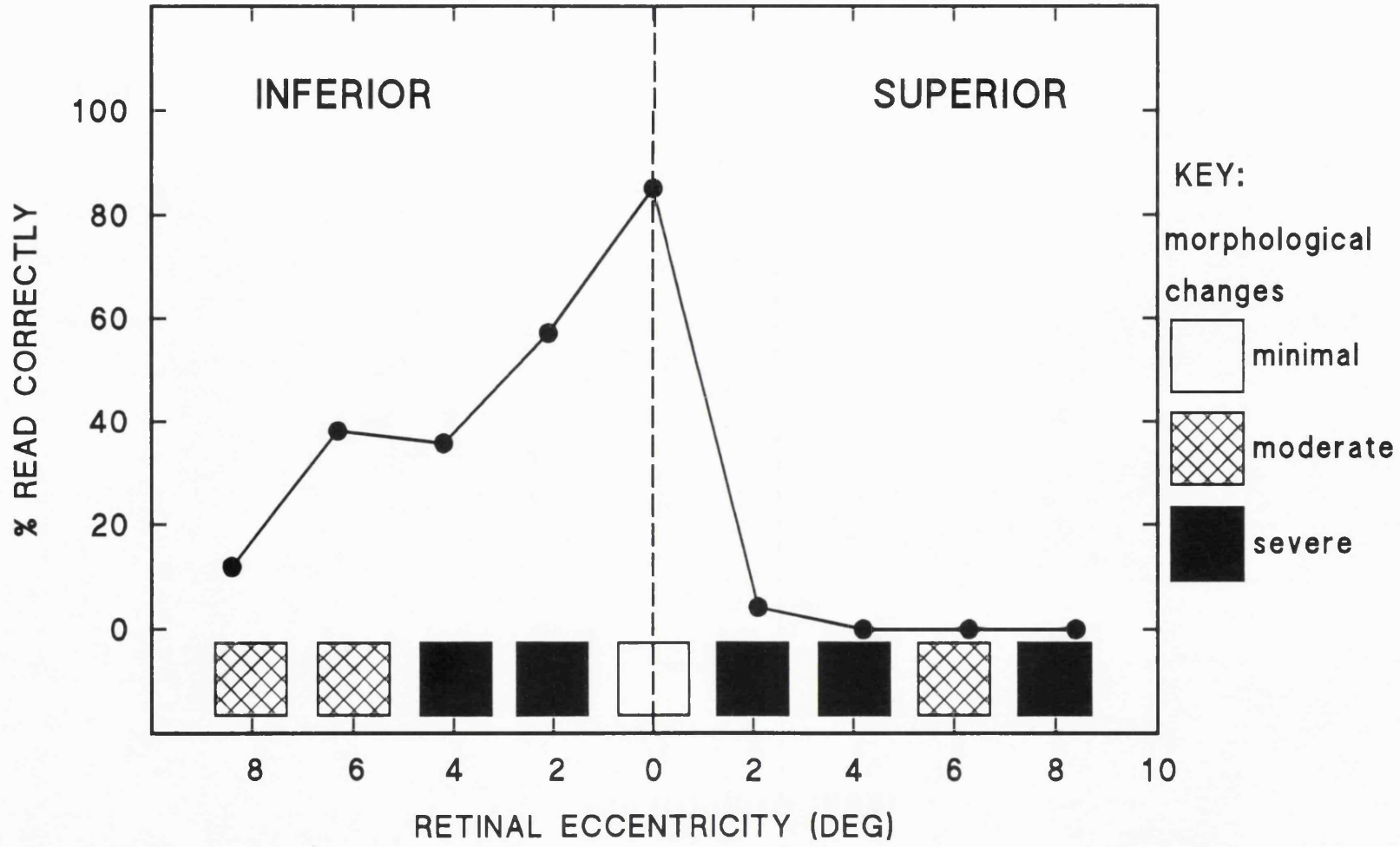


FIGURE 20: NUMBER OF LETTERS READ AT DIFFERENT RETINAL LOCATIONS BY PATIENT WITH JUVENILE MACULAR DISEASE



second phase, for foveal function are illustrated in Figure 21. At this location, responses to positive and negative contrast appeared to be approximately symmetrical, however, when compared to those of a normal observer, the patient's responses were abnormal in the lower contrast range (i.e. plus and minus 5 to 20%).

3.3 Clinical Study

3.3.1 Patients and attendance

Of the thirteen patients assessed initially, eleven fulfilled the criteria and were recruited to the study (see page 70 and Table 15). Each subject was scheduled to attend six appointments. However, the number of appointments was flexible and some patients only attended five since they worked faster and information was acquired more rapidly. The total cumulative contact time with the research worker was at least six hours per patient.

In a few cases the schedule of appointments extended over a period of up to ten weeks; this was due to patients' ill heath, holidays, difficulties arranging escorts, etc. All patients completed the full programme of the study.

In recruiting patients with ARMD, a variety of visual abilities were inevitable. In each of the tests discussed below a wide variety of results were obtained and significant differences between patients were demonstrated ($p < 0.0001$).

3.3.2 Clinical assessment of vision

Distance visual acuity was measured initially and again at the end of the study. Snellen acuities and the equivalent Bailey-Lovie logMAR results are shown in Table 16.

In three patients performance remained unchanged, in seven there was an improvement, while in one vision became worse. The Student's t test showed a significant difference, at the 5% level, between acuity before and after training ($t=2.765$). However, it must be noted that the test was quite weak because few data values were available.

FIGURE 21: PERCENTAGE OF LETTERS OF VARIABLE CONTRAST READ BY PATIENT AND NORMAL USING THE FOVEA

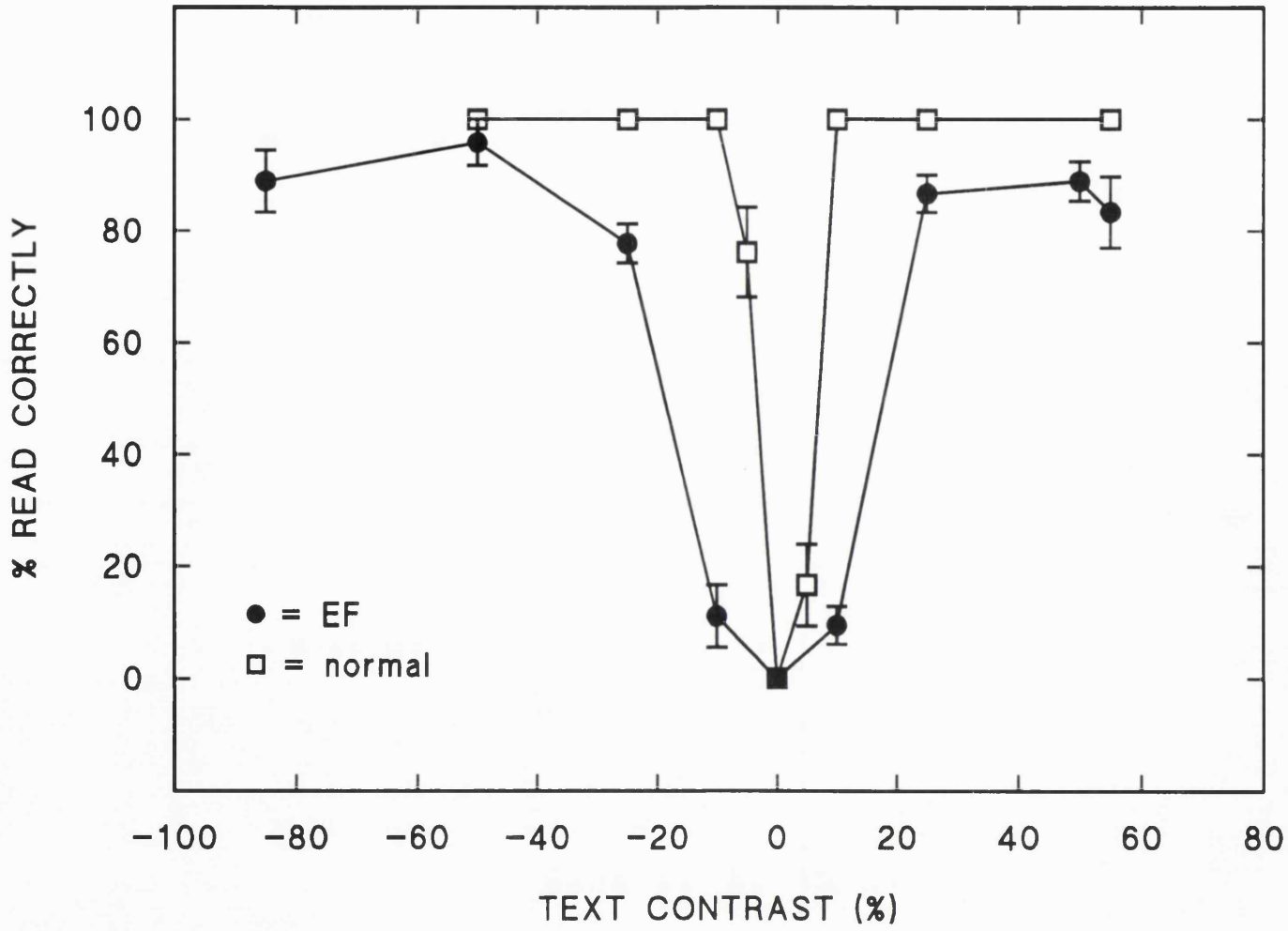


TABLE 15: SUMMARY OF PATIENTS' DETAILS

PATIENT	AGE	GENDER	EYE	REFRACTION	VA	SIZE (DEG)
AA	64	M	L	-1.50/-1.00X80	2/60	12
GJ	84	M	R	+1.50/-1.00X90	6/19	8
CP	82	M	L	+2.00/-0.50X80	2/60	8
DS	71	F	L	+1.00	1/48	28
NG	73	F	R	+2.50/-2.00X85	1/60	20
EP	72	F	R	+3.00/-0.50X10	1/38	12
DR	75	F	L	+3.00/-1.00X90	3/38	30
IS	80	F	L	+1.50/-1.50X90	6/38	4
JD	73	F	L	+1.00/-0.50X30	6/60	12
JP	71	F	L	0.00/-1.00X100	6/38	10
RB	68	M	L	+2.00/-0.50X75	6/60	10

M=male, F=female, R=right, L=left.
SIZE (DEG)=approximate maximum extent of lesion

TABLE 16: DISTANCE VISUAL ACUITY MEASURED USING A BAILEY-LOVIE CHART

PATIENT	EYE	VA BEFORE TRAINING SNELLEN (logMAR)	VA AFTER TRAINING SNELLEN (logMAR)
AA	L	2/60 (1.5)	2/60 (1.5)
GJ	R	6/19 (0.5)	6/19 (0.5)
CP	L	2/60 (1.5)	3/19 (0.8)
DS	L	1/48 (1.7)	$3/60^{+1}$ (1.3^{+1})
NG	R	1/60 (1.8)	$2/38^{-1}$ (1.3^{-1})
EP	R	1/38 (1.6)	$2/38^{-2}$ (1.3^{-2})
DR	L	3/38 (1.1)	3/38 (1.1)
IS	L	6/38 (0.8)	6/30 (0.7)
JD	L	6/60 (1.0)	$3/24^{-1}$ (0.9^{-1})
JP	L	6/38 (0.8)	$6/19^{+1}$ (0.5^{+1})
RB	L	$6/60^{-1}$ (1.0^{-1})	$3/38^{-2}$ (1.1^{-2})

The smallest N point print that patients were able to read with the use of their magnifier at each assessment is shown in Table 17. There was strong evidence that near VA improved during the course of the study ($p < 0.0016$).

Reading speeds of text of a size specified for each patient are displayed in Table 18. There was some evidence that the number of words per minute varied during the course of the study, but the trend was not constant and more data would be required for a definitive statement.

3.3.3 Functional assessment of vision using the scanning laser ophthalmoscope

3.3.3.1 Scotoma mapping

A detailed scotoma map was produced for each patient. Valuable information was thereby obtained regarding the nature of the macular lesion, e.g. the scotoma's shape, location and extent. This served to identify retinal areas of non-function and residual vision.

In nine of the eleven patients a dense central scotoma was identified which extinguished foveal function (see Figure 22). In the other two cases, although significant scotomas were observed foveal function remained intact (see Figure 23).

3.3.3.2 Identification of preferred and alternative retinal locations

The range of sizes of stimuli available in the SLO raster are shown in Table 19. For each patient, a stimulus just above resolvable size was selected.

The preferred retinal location (PRL) was the patient's choice and its position was identified by observing the stimulus on the patient's fundus. Of the eleven patients, ten had a strong predilection for single specific areas which they selected consistently. The one patient who did not have a clearly defined PRL shifted his fixation unsystematically between a single eccentric area of retina and the foveal region.

The positions of the PRLs on the retina were noted for each of the eleven patients. In two individuals, scotoma mapping showed preservation of the central

TABLE 17: NEAR VISUAL ACUITY MEASURED USING BAILEY-LOVIE CHARTS

PATIENT	1ST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT	5TH MEASUREMENT
AA	N10	$N10^{-1}$	N10	N6	$N8^{+2}$
GJ	N5	N5	N5	N5	N5
CP	N5	N5	N5	N5	N5
DS	N32	$N32^{+1}$	N32	N20	$N24^{+1}$
NG	N10	N8	$N10^{+2}$	$N10^{+2}$	N6
EP	N16	$N16^{+1}$	N12	$N12^{+2}$	$N12^{+1}$
DR	$N10^{-2}$	$N10^{+2}$	$N8^{-1}$	$N10^{+1}$	N8
IS	N5	$N5^{-2}$	$N5^{-1}$	N5	N5
JD	N6	$N5^{-1}$	$N5^{-1}$	$N5^{-1}$	$N6^{+1}$
JP	N8	N8	N8	N5	N5
RB	$N5^{-1}$	N5	$N6^{-2}$	N5	$N5^{-1}$

TABLE 18: NUMBER OF WORDS READ PER MINUTE USING TEXT OF SPECIFIC SIZE

PATIENT	SIZE OF TEXT	1ST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT	5TH MEASUREMENT
AA	N10	40	36	47	60	55
GJ	N5	101	101	101	100	89
CP	N5	15	19	19	29	24
DS	N36	9	9	11	18	12
NG	N10	10	10	13	10	16
EP	N14	9	11	21	22	13
DR	N10	31	54	48	66	58
IS	N6	102	120	90	136	84
JD	N6	31	38	25	34	33
JP	N8	47	62	61	61	55
RB	N5	33	28	25	38	36

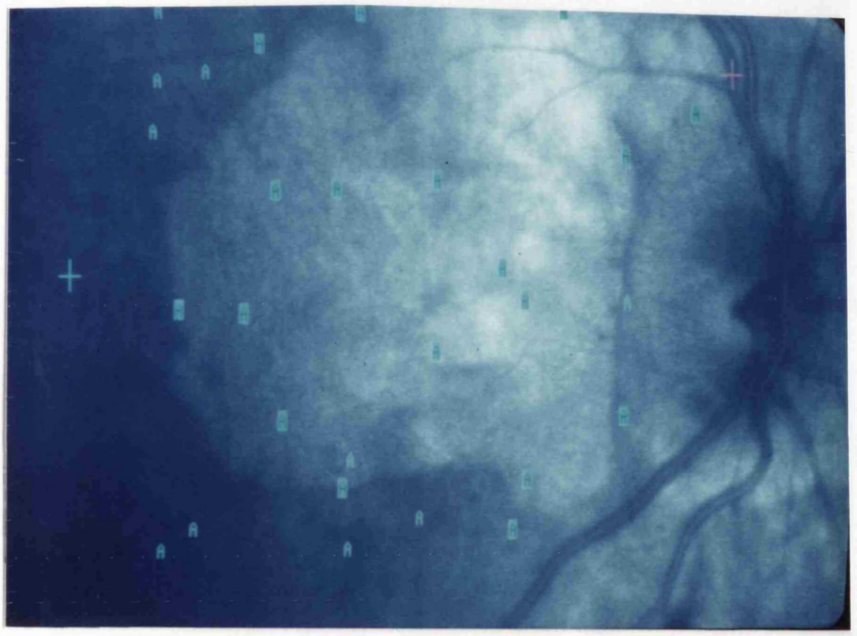


FIGURE 22: SCOTOMA MAP OF PATIENT WITH AGE-RELATED MACULAR DISEASE AND NO FOVEAL FUNCTION

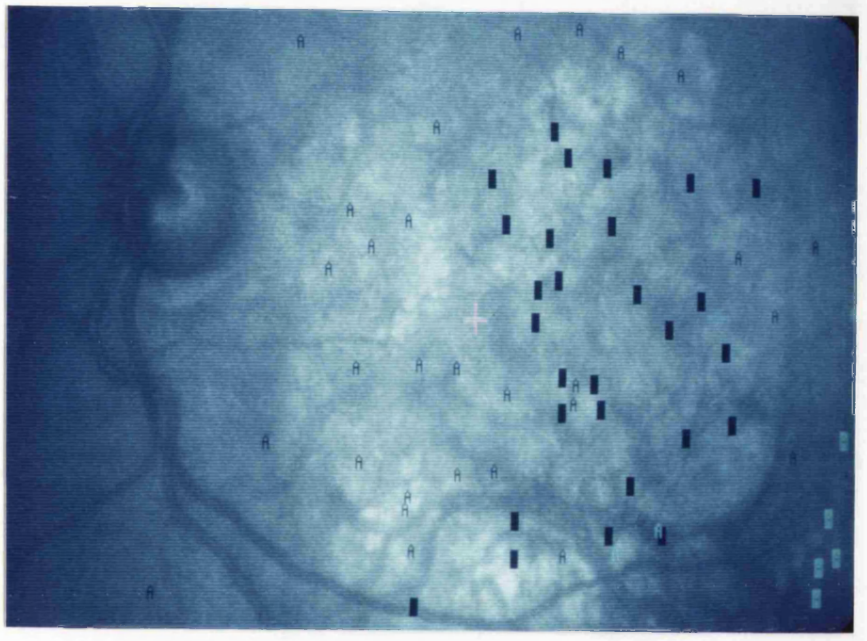


FIGURE 23: SCOTOMA MAP OF PATIENT WITH AGE-RELATED MACULAR DISEASE AND FOVEAL FUNCTION

Key:
red cross - fixation target
black boxes - non-seen stimuli
open A - seen stimuli
blue stimuli (bottom right of image) - artifact

TABLE 19: RANGE OF SIZES OF STIMULI AVAILABLE IN THE SCANNING LASER OPHTHALMOSCOPE RASTER

INSTRUMENT SETTING	ACTUAL SIZE HORIZONTAL X VERTICAL (MIN ARC)
0.5	40 X 44
1	80 X 87
1.5	114 X 131
2	160 X 174
2.5	200 X 218

visual field and their respective PRLs were found to be at the foveae. Another patient, as mentioned above, varied fixation between the fovea and a locus in the superior retina. The other eight patients chose eccentric loci and made no attempt to view with the fovea. In all but one case the PRLs were immediately adjacent to the macular lesion.

The locations of the eccentric PRLs were broadly categorised into the following localities relative to the fovea: 2 superior, 5 nasal and 2 temporal. Only three of these nine patients appreciated that they were not using the fovea, the others felt that they were viewing "straight ahead" when using their eccentric PRL.

Visual performance at the PRL and two ARLs of each patient are described in detail below.

3.3.3.3 Acuity mapping

The smallest gap sizes that could be detected at the PRL and ARLs in each patient are shown in Table 20.

Individual differences between patients were marked and the range was large with patients GJ and IS demonstrating relatively good acuity while DS and DR had poor acuity.

When analysed as a group, it was found that visual acuity at the various locations did not differ significantly, i.e. the ARLs allowed similar performance to the PRLs.

3.3.3.4 Fixation stability

The extent of retina area utilised to view a target (i.e. BCEA) for each patient is shown in Tables 21 and 22.

Fixation variability between patients was noted. The two patients (JD and GJ) who retained their foveae had significantly better fixation stability than the rest of the group ($p < 0.001$).

With the exception of foveal fixation, there was no evidence that BCEAs varied with the retinal location; i.e. fixation stability was similar at the PRLs and ARLs.

The average BCEA tended to decrease with time from 8342 minarc^2 at the first

TABLE 20: VISUAL ACUITY AT DIFFERENT RETINAL LOCATIONS MEASURED USING THE SLO (MIN ARC)

PATIENT	PRL	ARL1	ARL2
AA	27	16	31
GJ	6	19	9
CP	24	18	53
DS	46	31	50
NG	31	14	16
EP	21	50	29
DR	43	41	43
IS	10	9	15
JD	26	18	15
JP	11	12	25
RB	16	16	34

TABLE 21: BCEA (MIN ARC^2) MEASURED USING A STATIONARY TARGET AT DIFFERENT RETINAL LOCATIONS

PATIENT	RETINAL LOCATION	IST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT
AA	PRL	7804	24358	14575	8890
	ARL1	19364	19498	14810	25253
	ARL2	5077	34582	5421	5342
GJ	PRL	93	148	164	191
	ARL1	320	438	388	836
	ARL2	328	254	260	393
CP	PRL	1135	6683	9426	7598
	ARL1	4588	8932	6777	5949
	ARL2	11959	4547	6643	16966
DS	PRL	4393	7057	11732	9414
	ARL1	19030	1094	3794	1204
	ARL2	13373	3662	5114	2099
NG	PRL	13613	16597	9590	11605
	ARL1	13815	36921	8563	315
	ARL2	20980	716	6097	2612
EP	PRL	4437	5223	2493	1978
	ARL1	6428	661	267	969
	ARL2	3472	10067	3874	9045

TABLE 22: BCEA (MIN ARC^2) MEASURED USING A STATIONARY TARGET AT DIFFERENT RETINAL LOCATIONS

PATIENT	RETINAL LOCATION	IST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT
IS	PRL	581	482	368	719
	ARL1	2846	383	204	456
	ARL2	1650	861	1404	3395
DR	PRL	23883	8400	1493	3296
	ARL1	2300	1601	2431	2008
	ARL2	1559	5254	25126	14854
JD	PRL	1674	939	3170	863
	ARL1	1598	832	788	1637
	ARL2	2667	1486	2411	598
JP	PRL	7084	8817	3567	3386
	ARL1	4116	1154	950	1418
	ARL2	1052	2421	2876	1736
RB	PRL	15532	1406	1375	1691
	ARL1	14829	14095	31544	3498
	ARL2	43692	2094	20825	6283

measurement to 4742 minarc^2 by the fourth measurement. The BCEA was found to decrease continuously during the course of the study ($p<0.0316$); i.e. fixation stability improved with time. Figure 24 shows the performance of patient NG throughout the study.

3.3.3.5 Search and identification

The times taken by patients to locate and identify targets using their PRLs and ARLs are displayed in Tables 23 and 24.

Even before training there was a real difference between performances of PRLs and ARLs with PRLs allowing faster identification. Such significant differences were maintained throughout the study ($p<0.0016$). In contrast, the performances of ARL1 and ARL2 were found to be similar.

Search times were found to decrease during the course of the study ($p<0.0001$).

3.3.3.6 Letter recognition

The percentages of letters read correctly at different retinal locations are shown in Tables 25 and 26.

Important differences were found between the PRLs and ARLs, with the PRLs allowing significantly better performance ($p<0.0001$). No significant difference was observed between ARL1 and ARL2.

There was strong evidence that the percentage of letters read correctly overall increased steadily throughout the training programme ($p<0.0009$).

3.3.3.7 Speed of recognition

The maximum speed that text could be scrolled with patients able to identify the unique letter in the sequence is shown in Tables 27 and 28. Only five scrolling rates were available; speeds 1 to 5 represented angular velocities of 1, 1.9, 3, 3.8, 4.9 degrees/sec respectively. If the task was not acheived at the slowest speed then a score of <1 was given.

Overall, the speed of scroll increased during the course of the study with a significant positive trend ($p<0.0131$).

FIGURE 24: FIXATION STABILITY OF PATIENT WITH AGE-RELATED MACULAR DISEASE

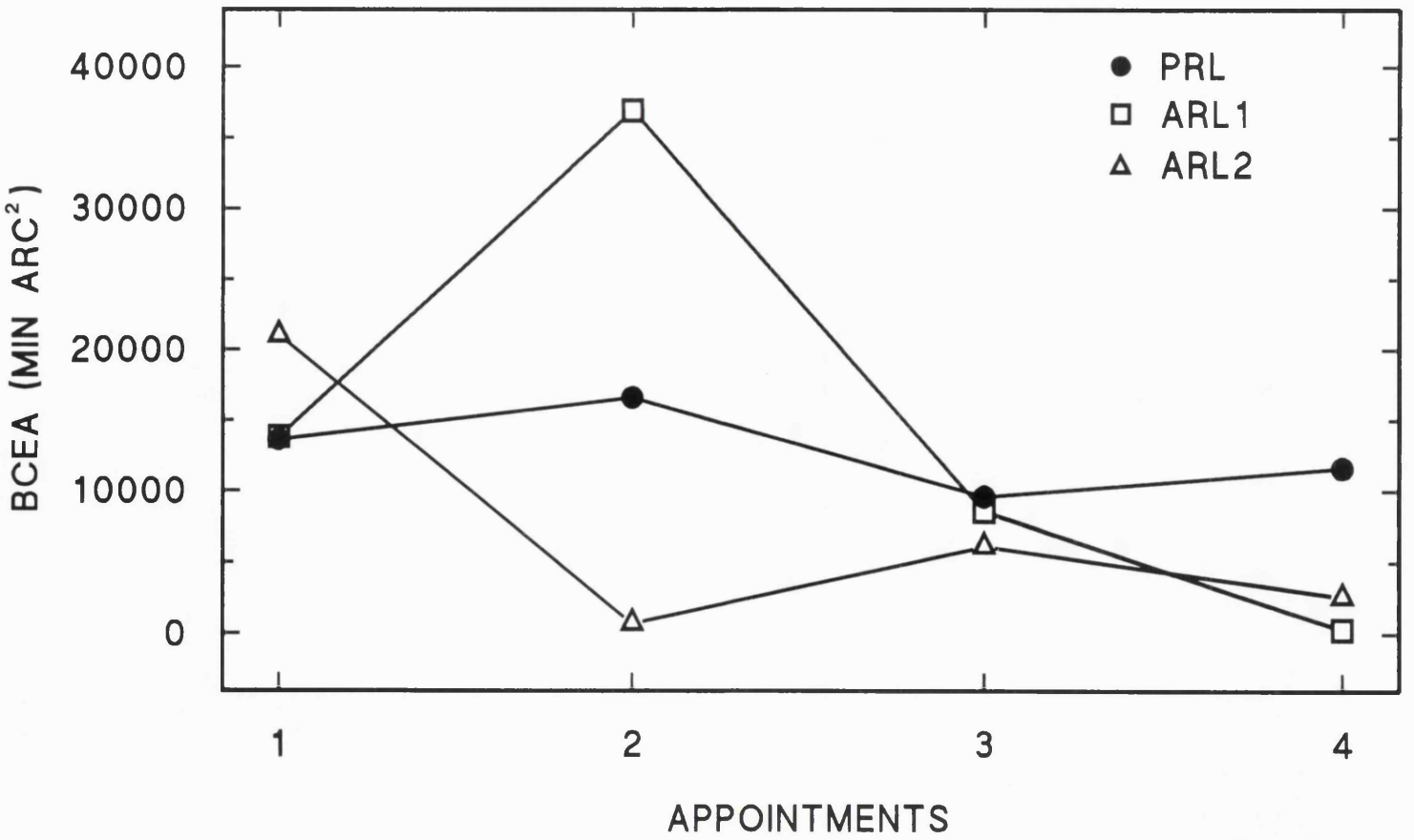


TABLE 23: TIME IN SECONDS REQUIRED TO LOCATE AND IDENTIFY A TARGET IN THE SLO RASTER

PATIENT	RETINAL LOCATION	IST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT
AA	PRL	3	21	2	1
	ARL1	92	99	2	1
	ARL2	42	50	2	5
GJ	PRL	2.5	1.5	1	1
	ARL1	4.5	2.5	1	2
	ARL2	77	35	2	22
CP	PRL	3.5	3	1	2
	ARL1	80	7	3	2
	ARL2	35	5	1	1
DS	PRL	2	2	2	2
	ARL1	10	2	2	1
	ARL2	2	3	2	2
NG	PRL	4	2	3	2
	ARL1	3	2	2	1
	ARL2	52	3	1	2
EP	PRL	2	1	1	2
	ARL1	1.5	4	1	1
	ARL2	12	2	3	3

TABLE 24: TIME IN SECONDS REQUIRED TO LOCATE AND IDENTIFY A TARGET IN THE SLO RASTER

PATIENT	RETINAL LOCATION	IST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT
DR	PRL	1	1	1	1
	ARL1	1	1	2	1.5
	ARL2	8	1	1	1.5
IS	PRL	2	1	1	1
	ARL1	3	2	2	2
	ARL2	2.5	4	2	2
JD	PRL	1.5	1	1	1
	ARL1	1.5	1	2	1
	ARL2	3	1	2	1
JP	PRL	2	1.5	1	3
	ARL1	3	1.5	1.5	2
	ARL2	2	1.5	5	2
RB	PRL	3	1	2	1
	ARL1	2.5	7	8	2
	ARL2	2.5	4	4	2

TABLE 25: PERCENTAGE OF LETTERS READ CORRECTLY AT DIFFERENT RETINAL LOCATIONS

PATIENT	RETINAL LOCATION	1ST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT
AA	PRL	85	80	86	85
	ARL1	50	30	73	80
	ARL2	20	50	75	42
GJ	PRL	50	100	100	100
	ARL1	40	0	38	30
	ARL2	10	0	0	15
CP	PRL	93	100	100	100
	ARL1	75	80	86	100
	ARL2	100	100	80	100
DS	PRL	92	80	100	100
	ARL1	100	37	100	90
	ARL2	20	56	90	90
NG	PRL	70	100	100	90
	ARL1	89	71	91	70
	ARL2	10	80	90	60
EP	PRL	100	100	100	100
	ARL1	70	60	83	92
	ARL2	61	80	100	100

TABLE 26: PERCENTAGE OF LETTERS READ CORRECTLY AT DIFFERENT RETINAL LOCATIONS

PATIENT	RETINAL LOCATION	1ST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT
DR	PRL	80	100	100	73
	ARL1	80	100	80	73
	ARL2	90	32	100	45
IS	PRL	88	90	73	90
	ARL1	17	56	53	60
	ARL2	25	40	47	40
JD	PRL	92	100	100	92
	ARL1	77	62	100	100
	ARL2	90	100	100	90
JP	PRL	100	93	87	100
	ARL1	47	90	100	100
	ARL2	85	87	91	100
RB	PRL	80	75	90	100
	ARL1	67	58	59	60
	ARL2	55	62	40	54

TABLE 27: MAXIMUM SPEED OF SCROLL FOR RECOGNITION AT DIFFERENT RETINAL LOCATIONS (DEGRESS/SEC)

PATIENT	RETINAL LOCATION	IST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT
AA	PRL	3	1.9	1.9	1.9
	ARL1	3.8	3	1.9	3
	ARL2	<1	<1	3.8	3
GJ	PRL	4.9	4.9	4.9	4.9
	ARL1	<1	1.9	1	1
	ARL2	1	<1	<1	1.9
CP	PRL	4.9	4.9	4.9	4.9
	ARL1	4.9	3.8	3.8	4.9
	ARL2	<1	3	3	1.9
DS	PRL	3.8	4.9	4.9	4.9
	ARL1	3.8	4.9	4.9	4.9
	ARL2	1	1	1.9	1
NG	PRL	3.8	<1	<1	<1
	ARL1	3	<1	<1	1
	ARL2	1	<1	<1	1.9
EP	PRL	1.9	4.9	4.9	4.9
	ARL1	1	4.9	4.9	4.9
	ARL2	3.8	1.9	4.9	4.9

TABLE 28: MAXIMUM SPEED OF SCROLL FOR RECOGNITION AT DIFFERENT RETINAL LOCATIONS (DEGRESS/SEC)

PATIENT	RETINAL LOCATION	IST MEASUREMENT	2ND MEASUREMENT	3RD MEASUREMENT	4TH MEASUREMENT
DR	PRL	4.9	4.9	4.9	4.9
	ARL1	1	1	4.9	4.9
	ARL2	4.9	1	4.9	<1
IS	PRL	4.9	4.9	4.9	4.9
	ARL1	1	3	3.8	4.9
	ARL2	1	1	1	1
JD	PRL	4.9	4.9	4.9	4.9
	ARL1	4.9	3.8	3	1.9
	ARL2	3	4.9	4.9	3.8
JP	PRL	4.9	4.9	4.9	4.9
	ARL1	3	4.9	4.9	3.8
	ARL2	<1	3	4.9	4.9
RB	PRL	4.9	4.9	4.9	4.9
	ARL1	<1	1.9	4.9	4.9
	ARL2	<1	4.9	4.9	<1

The maximum speed of scroll was significantly higher for PRLs than ARLs ($p < 0.0001$). In contrast to all other measurements, in this test a significant difference existed between the ARLs, with ARL1 allowing better performance than ARL2 ($p < 0.0008$).

3.3.3.8 Questionnaire

All the patients responded to the questionnaire. Copies of the completed forms are presented in Appendix V.

PART 4: DISCUSSION

4.1 Calibration

4.1.1 Fundus Image Acquisition and field of view

In the prototype SLO the relatively small field of view of less than 18 by 13 degrees caused certain restrictions. First, during imaging of the macular region few landmarks were visible and it was often difficult to identify the exact location of the area being viewed. This was particularly true in patients whose macula had a grossly abnormal appearance. Second, during psychophysical testing significant eye movements caused the fundus image to vanish from the TV monitor. The preliminary study on fixation (see section 4.2.2 below) could be undertaken with this field of view since eye movements made during testing were relatively small. However, scotoma mapping (section 4.2.1 below) was difficult to undertake on all but the subjects with the steadiest fixation.

In an attempt to overcome these restrictions the prototype SLO was modified by the addition of the external optical system (section 3.1.2.2, p89). The field of view was effectively doubled to 35 by 26 degrees. However, the result was not completely satisfactory; image quality decreased (see Figure 4B) and the smallest amount of misalignment of the subject's eye meant that the image on the TV monitor was lost. Hence this optical system was not practical for use with patients.

The commercial SLO, which became available later in the study, had several advantages. The field of view was 31 by 24 degrees, the quality of the images was of such a standard that fundal details were easily identifiable and during testing the patient could make some eye movements without the images on the TV disappearing. Hence, for the clinical study (section 4.3) this SLO was the preferred system.

4.1.2 Contrast of stimuli

For calculation of contrast of the stimuli, the Michelson equation was considered to be more appropriate than the Weber fraction since letters presented in the raster had some periodic characteristics. Existing literature on presentation of text to

normal and low vision subjects has used the Michelson definition, therefore the present results may be directly compared with other major works. In addition, the Michelson calculation allows the contrast values for positive (bright) and negative (black) stimuli to be symmetrical and therefore easily understood when presented in graphical form, for example see Figure 21 (p127).

4.2 System Assessment

4.2.1 Scotoma mapping

A) In-house software

This method of scotoma mapping using the prototype SLO was both difficult for the subjects and very time-consuming for the operator. As discussed above, the limited field of view on the prototype SLO meant that the fundus image disappeared from the TV monitor if a large eye movement occurred. This was particularly true in elderly patients with small pupils. Further, due to the small laser beam raster, a mapping stimulus moving at 2 degrees/sec was visible for only 3-4 seconds before disappearing either into the scotoma or off the edge of the raster. Hence measurements could not be made in elderly individuals unable to maintain a steady eye position and/or respond rapidly. Even in our group of young normal observers, measurements often had to be repeated in order to acquire a full set of data. In an attempt to overcome this problem the experiment was repeated with the addition of the external optical system which provided a wider field of view. However, fundus images were of too poor quality for subsequent analysis to be undertaken.

Method of analysis:

When adequate measurements were achieved in normal observers, the flicker method of manual image alignment was shown to be repeatable and accurate. However, together with the calculation of stimuli positions and compensation for eye movements this was immensely time-consuming. An automatic alignment programme was developed but it required images with high contrast landmarks and

the prototype SLO images were of insufficient quality for the computer programme to work reliably.

In early work with the SLO Timberlake et al (1982) demonstrated the viability of scotoma mapping. Retinal maps of the physiological blind spot were produced using a stimulus not formed by an AOM as in the present study, but by a pinhole of 50 um in a neutral density filter. The results were similar to the present study with the perimeter of the blind spot being smaller with inward movement of stimuli compared with the outward movement (see Figures 11 and 10, p97-101). In both studies this effect was due to the dynamic form of measurement and could be explained by the reaction time.

In a later study, Timberlake et al (1989) used an automated computer technique similar to the one used in the present study for presenting mapping stimuli on radial tracks. In our method, the aim was to study the reproducibility of scotoma mapping using stimuli moving along fixed tracks. Difficulties arose when the subject did not fixate accurately and the stimulus crossed the scotoma boundary at an unusual angle. On repetition of the map, it was unlikely that the stimulus was presented in the same manner.

It was interesting that eye movements did not significantly influence the results of scotoma mapping in normal observers. Although it was not possible to measure in our elderly individuals we would expect the result to be different for patients with central scotoma and poor fixation. This method needs to be re-evaluated in elderly patients since relative to younger subjects, older individuals' response times may be decreased (Bartley, 1960), particularly if they have ARMD (Lovie-Kitchin and Brown, 1986).

B) Rodenstock commercial software

This method of scotoma mapping, in contrast to the in-house programme, was designed to iterate out eye movements during testing. This technique was ideal for the clinical study (section 4.3.3.1) where the size of the scotoma needed to be

determined accurately but we did not wish to study eye movements during testing. Further, it was an easy technique to use with patients. First, the commercial instrument had a larger field of view which provided the advantages discussed previously. Second, the operator had control over the placement of the stable stimuli thus removing dynamic response time and the mapping procedure could be done at a leisurely rate which was more appropriate for elderly patients.

4.2.2 Assessment of fixation

Several methods of measuring eye movements in digitised images are available. Timberlake et al (1986) utilised a registration procedure whereby each frame was marked at several points using computer graphics. One mark was placed on the stationary target and at least two other marks were located on different retinal features. Eye movements were calculated by measuring relative changes in position of the marked retinal features. Both this method of analysis and the flicker alignment technique utilised in the present study are time consuming, but the latter is slightly faster, although it cannot resolve fully torsional eye movements. As with the scotoma mapping analysis, in an attempt to minimise data processing time an automatic flicker alignment programme was developed. This was unsuccessful because the SLO images were of insufficient quality. In the future, as images improve this programme will become useful.

Classical methods for recording eye movements have been reviewed by Ditchburn (1973b); the more common ones include such devices as search coil eyetracker (Robinson, 1963), Purkinje-image eyetracker (Crane and Steele, 1978), and contact lens techniques (Ratliff and Riggs, 1950; Nachmias, 1959). The resolution of the SLO at 4 min arc was lower than these other techniques which can provide accuracy of up to 10 sec arc; however, measurements with the SLO are adequate to determine fixation ability in normal and low vision observers. The successful application of SLO technology for detailed measurement of eye movements has been demonstrated previously (Ott and Eckmiller, 1989; Ott and Lades, 1990; Schuchard, 1991). The main advantage of the SLO system is that the

visual stimuli are viewed continuously on the subject's fundus image, i.e. fixation is assessed directly by comparing stimulus position with retinal features.

Stationary targets:

In the present study the size and contrast of the stimuli used in the SLO were determined for each subject by pilot measurements. In agreement with other more conventional tests of visual acuity (Kitchin and Bailey, 1981) and contrast sensitivity (Brown and Lovie-Kitchin, 1987), we found that in our visually compromised observers both parameters had to be increased, compared with normals, in order to provide recognisable targets.

The stimuli in this study were specifically chosen to investigate the effects of reading related targets on fixation. For comparative purposes the Snellen E, 20 min arc in size, was used as a standard target. In the normal group fixation stability was influenced by target size. When the Snellen E increased in size, from 20 min arc up to a maximum of 160 min arc, the fixation stability decreased. This is in general agreement with previous observations. In a study by Steinman (1965), normal subjects fixated the centre of discs of different sizes, i.e. 1.9 to 87.2 min arc, and known luminance. One subject increased eye movements with increased size; the other subject, who exhibited less stable fixation for all targets, was not so influenced by the size. In another study, subjects fixated the centre of a disc ranging in size from 19 to 240 min arc (Rattle, 1969). While fixation remained stable for targets 19 to 78 min arc, eye movements increased for stimuli 140 to 240 min arc. Fixation began to get notably worse with targets of approximately the same diameter as the fovea, e.g. 110 min arc. In respect of contrast, shape and form the stimuli in the present study differ markedly from those of Steinman and Rattle. However, all three sets of stimuli were of similar size and therefore it is of interest that the results are comparable.

In order to examine the possibility of effects on fixation by the target surround we used arrays with multiple stimuli. By doing so, it was possible to assess any

effects of contrast, texture and crowding (Rubinstein and Underwood, 1985). No significant effects were observed in either our normal or patient groups.

For stationary targets in this study the overall standard deviation of horizontal eye movements was greater than the standard deviation of vertical eye movements and this is in agreement with previous results (Kosnik et al, 1986). Unlike most previous studies which used bright targets of a single luminance and of simple geometric construction, i.e. a square or a circle, in the present study all fixation targets had a more complex structure. In both the normal and patient groups the polarity of contrast, i.e. black on white or white on black, did not have any measurable influence on fixation performance. This lack of influence of contrast polarity was perhaps not surprising since reverse contrast has not been reported to have an effect on reading related tasks in either normals (Legge et al, 1985a and 1987) or patients with central loss but with clear media (Legge et al, 1985b). This observation should not be confused with the fact that, in practice, reverse contrast (white on black) is often more comfortable for low vision patients to read, perhaps because of the absence of glare (Genensky et al, 1972; Mehr et al, 1973).

Although studies have reported a change in macular function (Elliott and Whitaker, 1991) and a progressive loss of photoreceptors (Marshall, 1987; Gartner and Henkind, 1981) and retinal pigment epithelium (Dorey et al, 1989) with age, we did not find accuracy of fixation to be age dependent, confirming previous psychophysical observations (Kosnik et al, 1986). Age-related deficits in acuity have been demonstrated (Greene and Madden, 1987) and this may suggest that there is not a strong correlation between acuity and fixation.

Any individual undertaking a psychophysical task progresses through a period of learning (Overington, 1976). The initial phase of this is often determined by both the pretest explanation and the performance instructions. The subjects in this study were directed to "watch the target carefully and steadily". The alternative instruction to the subject of "hold the eye still on one specific point on the target" may account for different results. This concept has been demonstrated by Steinman

et al (1967), and our subject AM, who was instructed to "hold" fixation on the basic and the enlarged E. Learning and experience after the initial phase appeared to have little effect on the results, as indicated by consecutive experiments with subject CJ.

Given the diversity of macular lesions in our small patient group the wide range in responses was not unexpected (Tables 9 and 10, p107-8). Of the three patients who fixated with their fovea, two had patchy remnants of foveal function, and one had a small central scotoma which did not involve the parafovea. All these patients showed relatively normal fixation. Of the four patients that did not use the fovea for fixation, all had pathologies which resulted in an absolute central scotoma. In this group by using their preferred retinal location, two patients showed performance within the normal range and two did not. The former were age-related macular lesions and the latter were juvenile macular conditions. Psychophysical tests would suggest that with increased size of central scotomas, fixation ability would decrease (Whittaker et al, 1988a), however, the problem is complex and shape and position of lesions together with the mosaic of functioning photoreceptors should also be considered. Such variation may be displayed by individual patient's responses. For example, patient DB viewed eccentrically in order to avoid the large, long standing disciform scar, and the PRL was positioned at 6 degrees eccentrically (Area A; Figure 18A, page 123). His fixation stability under these conditions was remarkably good, e.g. 261 min arc^2 (Table 9). In contrast, patient AA, who had longstanding juvenile macular disease and a PRL at approximately equidistant eccentricity, had considerably worse fixation stability, e.g. 13,367 min arc^2. It would be of interest to undertake longitudinal studies of fixation performance in subjects with age-related and juvenile macular disease as the condition progresses. This would provide useful information on the destruction of foveal function and development of PRLs in the long term. In the future, it may be possible to correlate fixation stability and nature of disease, size and position of scotoma and rod/cone survival.

Scrolled text:

Scrolled text provides a means of investigating visual performance at specific retinal locations and may be of help in the rehabilitation of patients with compromised vision. The measurement of the BCEA indicated the area of retina used to view the centre of the text. Although we had expected that scrolling text through a fixation point may act as a distraction and therefore increase the BCEA, data from our normal subjects showed that this was not the case. Also, no increase was noted in the normal group at different eccentric retinal locations. Further, in our limited patient group no systematic variation was found.

Given the predominance of horizontal eye movements in the fixation of stationary stimuli it was surprising to observe that these eye movements did not increase with horizontally scrolled text and that they were also unaffected by text speed. However, in the majority of subjects the temptation to track the target was suppressed and therefore only small saccadic movements were observed and these did not influence the size of the BCEA. In the normal group all individuals stated that reading became more difficult as the scrolling speed increased. At the fastest speed difficulty was expressed by some observers even when stimuli were located at the fovea. While we could have increased the speed still further, in an attempt to deliberately provoke horizontal tracking movements, this was beyond the scope of the present study. Given the degree of compromised vision in the patient group we elected to use only the three slower speeds in the subsequent studies.

Patients KA (macular hole) and HW (neovascular membrane) had good fixation for both stationary and scrolled text (Tables 10 and 13; p108 and 112). Visual acuity was better than 6/18 and the damage to the macula was of limited extent. These two individuals seemed able to fixate as effectively as normals and in doing so they appeared to overcome their visual deficiency for this task. The BCEA of these patients would strongly suggest that fixation was not directly related to acuity. This is particularly so in the case of KA who was unable to see the centre of the target due to foveal loss but could perceive its upper and lower edges. Therefore, this task

was comparable to viewing between two points or fixating pericentral targets (Schuchard and Raasch, 1992).

The fixation stability of NH (Bull's eye maculopathy) and AA (Stargardts') was considerably worse for all targets. In addition NH was relatively more distracted by the scrolling stimuli than were the other patients and normal observers. The relatively poor performance of NH may be related to two underlying factors. First, he had a large central scotoma. Secondly, the disease may have compromised receptor cell function in a diffuse manner extending outside the central lesion. Before testing commenced NH described his vision as "decreased detail in the central region" but he was unaware of the large dense central scotoma. He was surprised when targets placed on the fovea disappeared. This suggested that he did not usually attempt to utilise direct vision, but instead routinely utilised a "pseudo-fovea", which was situated at approximately 6 degree eccentricity in the superior retina. At this retinal location normal visual acuity in the region of 6/15 would be expected (see Table 29); this patient had notably worse acuity of 6/60.

In summary, there are five main findings in this study. First, the ability to maintain steady fixation varied significantly in normal subjects. Second, in a limited patient population large variations in fixation were observed. Third, in normal subjects fixation was affected by the size of stationary targets but not by the form or polarity. Fourth, in both normal and patient groups stationary targets allowed more accurate fixation compared with fixating a stationary stimulus in the presence of scrolled text. Fifth, the speed of scrolling text and the retinal location did not influence fixation stability.

4.2.3 Letter recognition using scrolling text

Visual performance depends upon the physical parameters of the stimulus and upon the location of the resultant image together with cognitive factors. Where cognitive factors are important they will be discussed.

TABLE 29: NORMAL VISUAL ACUITY RELATED TO RETINAL ECCENTRICITY

ECCENTRICITY (DEG)	LUDVIGH	WERTHEIM
0	6/3	6/6
1	6/4.5	-
2	6/7.5	-
3	6/10	-
4	6/12	-
5	6/14	6/18
6	6/15	-
7	6/17	-
8	6/18	-
9	6/20	-
10	6/21	6/30
15	-	6/43
20	-	6/55
30	-	6/100
40	-	6/150
50	-	6/200

Data taken from graphs by Ludvigh (1941) and Wertheim (1894).

Parameters of the stimulus:

Reading performance using the SLO has been studied previously (Timberlake et al, 1987b), but the work described in the present study has, for the first time, used scrolled rather than stationary text. The scrolling feature of our text-generation programme has a number of advantages. The subject does not search for adjacent letters and therefore the retinal area under examination is accurately maintained. The effects of complex and unpredictable eye movements is considerably reduced thereby providing a well defined relationship between text and retinal locus.

The movement of the text is analogous to the strategy attempted by some low vision patients when reading with a magnifying device. That is, the head and eye is held still and a page of text is moved past a fixed line of sight. This is sometimes known as the "steady eye strategy" (Collins, 1987). However, some patients do use eye movement to scan text, and future studies should be conducted to compare reading rates at the same retinal location using scanning eye movements and scrolled text.

Two similar methods of text presentation not using a SLO have been previously described. In the first, Legge et al (1985a; 1985b) used a TV monitor which was masked to provide a "window" across which a single line of text was scanned horizontally. In the second, successive words were presented in the centre of a monitor while the eye was held still by fixation, this is known as Rapid Serial Visual Presentation (RSVP) (Turano and Rubin, 1988; Rubin and Turano, 1990). The SLO has advantages over both of these methods in that it enables the observer to see precisely where the text is positioned on the fundus, and, as seen in our results, retinal text position is a crucial variable in reading performance.

For the present series of experiments, random sequences of capital letters were chosen as the test stimuli in preference to words. This allowed testing of basic letter recognition without the complication of higher cognitive functions necessary for reading. In future studies reading performance should be assessed using the presentation of both individual words and complete sentences.

Previous findings indicate that to maximise reading speed, at least 4 characters should be presented within the window at any time (Legge et al, 1985a), and in normal reading as many as 15 characters to the right of fixation are necessary (Rayner et al, 1980). Since a fundamental aspect of our investigation was probing differences in function of various small retinal areas, we deliberately limited the window to 4.3 degrees in the horizontal dimension. This enabled us to present 4 letters of text 30 min arc in size, but only 2 letters at 60 min arc, and 1.5 at 90 min arc. As a consequence of this chosen method of text presentation, "reading" speeds in our subjects may have been artificially limited. Capital letters instead of words were chosen for this task since for the latter errors increase significantly as the window is reduced (Poulton, 1962).

Two other parameters of the target influenced performance, scrolling speed (Figure 16, p120) and contrast (Figure 17, p121). In the case of the former, when letters were presented to the parafovea they became more difficult to identify at the faster speed. In normal subjects no difference in performance was noted with the two scrolling speeds investigated in this study at the fovea. These results are similar to those of Legge (1985a) who found foveal reading accuracy remained constant up to a critical scan rate of approximately 250 words/minute. Foveal reading performance only deteriorated at higher speeds (>300 words/minute) (Legge, 1985a). Direct comparison of Legge's data with our own is limited by the fact that use of words in his study involved cognitive processes which may themselves increase reading speed. Stimulus contrast is also an important parameter in target recognition as reported by van Nes and Jacobs (1981) and confirmed in the present study. Contrast sensitivity is known to decrease with increasing age (McGrath and Morrison, 1981; Greene and Madden, 1987). Measurements made in low vision observers with cloudy media show that white on black text can be read faster than black on white. The same is not true for low vision patients with clear media (Legge et al, 1985b).

Retinal location:

Visual performance is greatly influenced by retinal eccentricity. The organisation of the retina is therefore of fundamental importance. Topographical variations of photoreceptor density (Osterberg, 1935; Curcio et al, 1990; Jonas et al, 1992) are complemented by variations in ganglion cell distribution (Curcio and Allen, 1990) and receptive field size (Drasdo, 1989) which increase from the fovea to the periphery. Also, there is a disproportionate representation of the fovea in the cortex (Cowey and Rolls, 1974; Virsu et al, 1982). Each of these will contribute to reduction of acuity with eccentricity.

Acuity is often correlated with the distribution of rods and cones (Ludvigh, 1941; Harrison, 1953). Osterberg (1935) provided a classic description of cone distribution, but on one retina of an eighteen year old with limited counts. A more recent study by Curcio et al (1990) of eight human retinae of varying age indicates that while differences between individuals are significant, in general the distribution of cones is asymmetrical with the relative densities being dependent upon eccentricity. In the foveal region, temporal retina has the highest density whereas in more peripheral areas nasal retina density is greatest. However, in the peripheral retina, cones outnumber the ganglion cells and hence the latter may be responsible for limiting visual resolution (Anderson et al, 1992). The distribution of ganglion cells is asymmetric, with the density in the nasal retina exceeding the corresponding eccentricities in the temporal retina by 300% (Curcio and Allen, 1990). Similarly, densities in superior retina exceed the inferior by 60%.

In normal observers acuity is thought to be asymmetric in the different quadrants (Wertheim, 1894; Weymouth et al, 1928; Millodot and Lamont, 1974; Timberlake et al, 1987a) and performance differences may well have their origin in these morphological variations (Anderson et al, 1992). This aspect is discussed further in section 4.3.3.2. (p168). Time limitations prevented investigations into performance correlations with eccentricity although clearly such a study would be extremely

helpful in establishing associations between anatomical and psychophysical measurements.

In our patient with juvenile macular disease, although the whole of the posterior pole was affected, the degenerative changes appeared to be more severe in the superior region. The results showed that reading performance was not constant at equi-distant locations above and below the fovea (Figure 20, p125). However, we do not know the relative importance of the disease process compared to the physiological variations.

In normal observers high contrast targets were identified more easily than low contrast targets (Figure 17, p121). At any given contrast the area 2 degrees from the fovea gave a consistently better performance than the area at 6 degrees, and this is in agreement with other findings that contrast sensitivity decreases with retinal eccentricity (Rijsdijk et al, 1980; van Nes and Jacobs, 1981). The patient with juvenile macular disease gave a near-normal response at the fovea to a high contrast 60 min arc target, but showed a severe decrement in function with a low contrast target of the same size (Figure 21, p127).

Both of our low vision observers gave reduced performances for the text contrast experiments compared to the normal observer and this is consistent with previous observations (Lovie-Kitchin, 1989). However, in our experiments the normal and low vision observers were not age-matched and peripheral visual acuity is known to decrease with age (Collins et al, 1989). Some differences in performance may be related to light scatter in the ocular media, ageing changes in the retina (Weale, 1975; Marshall, 1987; Cerella, 1985; Johnson et al, 1989) and/or higher visual centres (Weale, 1982).

Given the variation in both the type and extent of lesions in ARMD, it is difficult to compare functional results between individual cases. In our patient the retinal locations assessed appeared normal, but they were immediately adjacent to a disciform lesion (and approximately 6 degrees from the fovea), and may have been affected by the disease process. Thus contribution to poor contrast sensitivity

could not be selectively allocated to either eccentricity or the disease. In a group of eight patients with ARMD a progressive loss of contrast sensitivity outside the normal range has been demonstrated at 0, 2, 5 and 10 degrees (Brown and Lovie-Kitchin, 1987). In ARMD retinal function at greater eccentricities may be comparable to normal, as at least one study looking at functional parameters in the periphery has shown normal responses (Sunness et al, 1985).

We found the responses to black or white letters on a background of fixed illuminance to be approximately symmetrical for the normal observers, and in agreement with the results of Legge (1985a).

In conclusion, the present study has demonstrated the value of using scrolled text in a SLO to assess reading performance at various retinal loci. This novel technique was used in the following clinical study in an attempt to find the optimal retinal locus for reading and to teach the patient to use this area effectively.

4.3 Clinical Study

4.3.1 Patients and attendance

Patients in the study were highly motivated although this was not a prerequisite to recruitment. Visual performance tasks and training exercises were carried out with enthusiasm both during appointments and, apparently, during practice sessions at home. Motivation is known to be one of the most important factors in low vision rehabilitation (Mehr and Fried, 1975), and as such it was imperative that individuals in this study were prepared to work hard. Their resolution was demonstrated by the fact that they continued to attend appointments even though travelling, often alone, was not easy and the training was hard work and tiring.

The intention was to undertake appointments in consecutive weeks, but in a few cases this was not feasible and the schedules were extended over a longer period of time. While it was important to reinforce the training techniques regularly, this extended period was not excessive and would have had little influence on the programme.

The length of time spent with a patient is a crucial element in training. In this study, total contact time with the research worker extended to at least six hours per patient and comprised of both the training and assessment elements. Published accounts of clinical low vision training programmes are not always clear about total time allocated for training (Backman and Inde, 1979; Collins, 1987; Fitzmaurice, 1992). The Swedish training model typically requires 25-30 hours of instructor input plus 80-100 hours of "independent" patient training (Backman, 1994). In one case study, a single patient was furnished with 96 hours of one-to-one tuition (Ighe, 1994). Other programmes quote a variable contact time ranging from 1 to 44 hours (average 16) depending on a client's needs (Fitzmaurice and Keast, 1984). The total training period requires further investigation. For any given individual the learning curve will vary but in all cases will reach saturation at a given time (Overington, 1976). For clinical cost effectiveness the latency, shape and overall learning curves for training should be established. In this study a six hour contact time was specified for both practical and economic reasons and was deemed to be applicable in a clinical forum should the results justify it.

Large differences between patients were found for all the visual tasks assessed in this study (eg. search times, fixation stability, etc.). Such differences between individuals were to be expected since the diverse nature of ARMD presents various levels of acuity and residual visual field. Other than noting the diversity in performance between patients, further comparison between individuals could not be made. Since the number of patients was limited, no attempt was made to relate performance differences to the spectrum of pathologies.

4.3.2 Clinical assessment of vision

There appeared to be a significant difference in distance visual acuity before and after training. It is important to note that the training undertaken was directed at reading not distance viewing. This suggests that skills learnt for a specific task may be transferable to other situations. Alternatively, it is possible that the

attention paid to patients provided some psychological benefit thereby encouraging improved performance. These aspects are discussed in greater detail below.

Even though individual patients showed wide variability in acuity, when the results were analysed overall, strong evidence emerged to demonstrate that near acuity improved during the course of the study. This means that at successive assessments, the trend was for patients to read smaller print. Two possible factors could explain this finding: First, the training techniques of eccentric viewing (EV) and steady eye strategy (SES) were being utilised and this caused a real improvement in visual performance. Second, psychological elements associated with attention (Mayo, 1945) encouraged patients to try harder thereby allowing them to realise their true reading ability.

With regard to reading speed, there was no definite improvement over the course of the study. Hence the training techniques and/or psychological influences did not play a significant role for this visual task. This was surprising since Collins (1987) states that with the established use of SES, "improvements from 40-60 wpm to 100-150 wpm can be expected".

In a technique analogous to the SES, Legge et al (1985a; 1985b) presented horizontally scanned text on a TV monitor and asked subjects to read the words aloud. Maximum reading rates for normals were about 300 wpm but performance was much worse for subjects with central field loss (median 25 wpm). Even though the experimental setup mimicked the SES, Legge did not find the high reading rates claimed by Collins (1987). In the present study, excluding the two patients who had residual foveal function, the range of reading speeds was 9 to 136 wpm (average 39) and the median value was 31 wpm. The results are similar to Legge's even though the methods are completely different.

In terms of basic elements of vision it seems that with training, pattern recognition (e.g. acuity) was improved both in the distance and at near. However, kinetic elements (e.g. reading speed) remained poor, irrespective of whether the eye or the text moved.

4.3.3 Functional assessment of vision using a scanning laser ophthalmoscope

4.3.3.1 Scotoma mapping

Microperimetry using a SLO has been advocated previously and for the first time allowed fundoscopy to be related to visual function (Timberlake et al, 1982; Mainster et al, 1982; Timberlake et al, 1989; Fletcher and Schuchard, 1994). In comparison to standard clinical methods of testing visual fields, SLO techniques offer considerable advantages, not least the monitoring of fixation throughout testing and the visualisation of the stimuli on the fundus.

Earlier in this study, alternative techniques for scotoma mapping with a SLO were considered but the Rodenstock commercial software was selected for this clinical study. Of those explored (see section 2.3.1.), this method was confirmed as the most practical for use with patients. It was relatively quick and easy to operate and patients were not too fatigued by the procedure. A further advantage was that eye movement compensation was undertaken during the mapping process.

It was essential to define accurately the position and extent of the lesion. The SLO provided sufficient resolution that the information could be used to select alternative retinal locations (see next section). In two patients foveal function was detected in an area that clinically should have had no function. In agreement with this finding, Hart and Burde (1983) using a threshold static perimetry technique without a SLO, demonstrated that 20% of patients with macular disease retain some foveal vision.

Research studies using patients with ARMD initially analyse the nature of the scotoma (Whittaker et al, 1988a). In some clinical programmes this aspect is not addressed in great detail (Backman and Inde, 1979: Nilsson and Nilsson, 1986) and as a consequence the information available to the rehabilitation officer, relative to SLO assessment details, is limited. Mackeben and Colenbrander (1994) have attempted to address this problem using a computer programme which presents single letters to different parts of the patient's visual field. The test was designed to provide information regarding the "optimal" retinal location to the low vision

specialist. This technique has the advantage of low cost, it is simple and quick to operate, however, it does not provide the same detailed knowledge of a patients' visual status as a SLO.

In this study, only one value was selected for the stimulus contrast (i.e. -90%). Although it would have been possible to define the scotomas using different contrasts, it was felt that a single contrast of -90% was of value as all our other tests were carried out at a similar contrast.

4.3.3.2 Identification of preferred and alternative retinal locations

Preferred retinal locations (PRLs):

Of the eleven patients, only one patient altered fixation in a non-systematic fashion between the foveal region and a single eccentric point. The other ten had a consistent preference for a single PRL. Of these, the PRLs were at the fovea in two cases and at a non-foveal location in eight. The predilection for the PRL appeared to be so strong as to have restricted patient investigation into the use of possible alternative locations.

In agreement with these findings most other studies have also found that patients with macular disease prefer a single, non-foveal retinal area (Cummings and Whittaker, 1985; Timberlake et al, 1986; White and Bedell, 1985 and 1990; Guez et al, 1993). However, a few studies have suggested that multiple retinal areas may be utilised by some patients (Schuchard, 1991), particularly if the macular lesion is large, eg. over 20 degrees (Whittaker et al, 1988a and 1988b). In the present study no evidence of multiple PRLs was found, not even in the patients with scotomas of the size examined by Whittaker et al (1988a).

All patients in the study had long-standing bilateral macular disease (over 12 months). The time course for development of PRLs has not been firmly established but there are indications that lesions need to be longstanding, eg. over 20 months (Timberlake et al, 1986; White and Bedell, 1990; Mackeben and Colenbrander, 1994). However, other evidence implies that PRLs may be established swiftly since monkeys who received bilateral foveal lesions by laser photocoagulation developed

a new fixation locus virtually overnight (Heinen and Skavenski, 1992). In the latter study a laser exposure destroyed central vision within a few milliseconds, a situation not found, for the most part, in humans with macular disease. In laser accidents in humans the exposure is predominantly uniocular (Boldrey et al, 1981; Gabel et al, 1989) and therefore direct comparative studies cannot be made. The insidious onset of many macular conditions coupled with a progressive change in scotoma geometry probably implies that PRL are mobile in active disease and develop over a time frame indicated by White and Bedell (1990). All lesions studied in this thesis were long-standing and therefore the PRLs were presumed to be static. As yet, we have not undertaken longitudinal studies to investigate development of PRLs in relation to changing visual status.

With regard to the retinal location of the PRL, it might be reasonable to assume that it would be positioned as close as possible to the fovea since visual acuity is related to distance from the fovea both in normals (Low, 1946; 1951) and in patients with macular disease (Randall et al, 1966; Weiter et al, 1984). This was found to be so in the majority of patients in the present study, but with one notable exception. Patient DS had a large dense central scotoma extending to include the region around the optic nerve head; instead of selecting a PRL adjacent to the macular lesion, she had abandoned retinal areas temporal to the disc and elected to use nasal retina (see Figure 25). Similarly, Timberlake et al (1986) found one of the three patients studied selected a PRL remote from the foveola and seemed to ignore viable retina of closer proximity.

Of the PRLs determined in this study, 2 patients utilised central retina (fovea), 2 superior retina, 5 nasal retina and 2 temporal retina. Notably inferior retina was not employed. These results confirm the findings of other studies. Guez et al (1993) using a SLO examined fixation in 24 patients (40 eyes) with macular disease and found PRL position was central in 6 cases, superior in 10, inferior in none, nasal in 14 and temporal in 10. The tendency to avoid the use of inferior retina was confirmed in a larger study by Fletcher and Schuchard (1994). In cases of nasal and

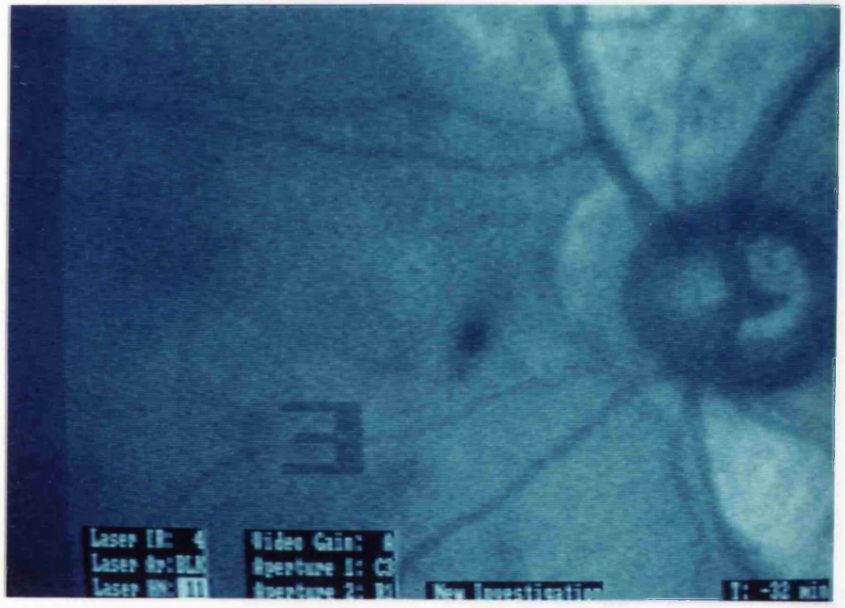


FIGURE 25: FUNDUS IMAGE OF PATIENT WITH AGE-RELATED MACULAR DISEASE SHOWING POSITION OF PREFERRED RETINAL LOCATION

temporal fixation the location of the PRL infers that any material to be read would extend into a scotomatous region (see below). If the method of classification of PRL location used in this thesis is applied to other studies similar results are obtained. For example, White and Bedell (1990) used a fundus camera and video recorder to investigate fixation in ten patients with ARMD and eleven patients with JMD with the following results; 10 used superior, 5 nasal, 6 temporal and none inferior retina. Although in the above studies PRLs are often displaced horizontally, some studies indicate that superior retina has a preference. Superior retina has been shown to be favoured in patients with macular holes (Acosta et al, 1991) and juvenile macular degeneration (Aulhorn, 1961; Dalgleish and Naylor, 1963) and in monkeys with an acute central loss of vision (Heinen and Skavenski, 1992).

Several reasons may exist for the placement of PRLs in specific retinal zones. The interesting concept that PRLs may be chosen on the basis of retinal correspondence for binocular viewing has been suggested recently (Schuchard and Fletcher, 1994). As yet, little work has been undertaken in this area and the mechanism is poorly understood. To date, the majority of information on PRLs relates to uniocular viewing.

The use of superior retina would appear to be logical since by rotating the eye upwards the patient displaces the visual field defect above the horizon. Under such circumstances navigation would become easier compared with displacement of the defect downwards. Another reason for selection of superior retina may be its improved visual function compared with inferior retina both in terms of visual acuity (Millodot and Lamont, 1974) and contrast sensitivity (Rijsdijk et al, 1980). In contrast to these psychophysical measurements, anatomical evidence shows that cone density in the midperipheral inferior retina is slightly greater than the equivalent location in superior retina (Curcio et al, 1990). However, the number of ganglion cells in the peripheral superior retina exceed those in the inferior retina by more than 60% (Curcio and Allen, 1990).

The reason for patients' frequent selection of PRLs in nasal or temporal retina may be related to better visual performance in the horizontal rather than the vertical meridian (Weymouth et al, 1928; Mandelbaum and Sloan, 1947; Anderson et al, 1992). Although not all studies have shown significant differences in performance along various meridians (Feinberg, 1949), Rijsdijk et al (1980) found temporal retina performed better in contrast sensitivity tasks while Merigan and Katz (1990) demonstrated the superiority of nasal retina for acuity in monkeys. The latter may be supported by the finding that cone density in humans is 45% higher in nasal compared to temporal retina at equivalent eccentricities (Curcio et al, 1990). Similarly, ganglion cells in nasal retina exceed those in temporal retina by more than 300% (Curcio and Allen, 1990). Hence, positioning of the PRLs may be as elementary as selection of the "best" retinal area. Differences between patients in precise location may be due to variations in peripheral acuity (Low, 1943), lesion size and position, and individual variability in cone density (Curcio et al, 1990) and ganglion cell numbers (Curcio and Allen, 1990).

Alternatively, preferred retinal locations may be chosen in relation to visual tasks, the position of scotoma or the growth axis in a developing scotoma. For example, one group has postulated that when attempting to read print in English, a scotoma situated to the right of fixation may allow the patient to locate the beginning of a line (Guez et al, 1993). But clearly such a field defect would interfere with the effective visual field (Rayner et al, 1980) and word recognition (Bouma, 1973). It would be of interest to determine PRLs in patients with macular lesions who routinely read from right to left (eg. Arabic) or up to down (eg. old-style Chinese). Unfortunately, our patient group did not allow such an investigation.

This is an important area for further work as six of our nine patients with eccentric PRL chose positions that forced them to read into a dense scotoma. Therefore, it might be reasonable to expect that low vision training would increase reading speed by encouraging the use of more suitable retinal locations in the superior or inferior retinal regions. This was done in the present study and ARLs

were determined in the vertical meridian but reading speed did not increase, although visual acuity did. However, when reading normal text under clinical conditions it is not possible to tell which retinal area the patient is utilising.

As might be expected, those patients in the study with residual foveal function utilised central vision. Patient GJ had reasonable foveal function providing corrected acuity in the distance of 6/19 and at near of N5. Reading speed was relatively good at about 100 wpm, although this was still below the maximum normal rate of about 300 wpm (Legge et al, 1985a). Early in the study it became apparent that this individual would not benefit from eccentric viewing training. Microperimetry demonstrated that the scotomata surrounded, but did not encroach upon, the fovea thereby allowing good reading vision and sufficient effective field of view. Conversely, in patient JD although the fovea resulted in reasonable visual acuity, the geometry of the lesion did not allow optimum performance. Central vision provided distance VA of 6/60 and reading VA of N6 with +20.00 magnifier. However, when attempting to read, a dense scotoma was projected to the right of fixation (see Figure 23, p134). The one patient (CP) who altered fixation between an eccentric location and the foveal region may have had some residual central vision function, although the detailed scotoma map derived from microperimetry does not support this theory.

Of the nine patients using an eccentric PRL, six (i.e. 67%) felt that they were viewing "straight ahead". The characteristics of oculomotor reference in patients with macular disease have been studied in detail by White and Bedell (1990). In agreement with the findings of the present study, White and Bedell found that seven out of ten patients with ARMD (i.e. 70%) had directional referencing to their PRL, i.e. the PRL gave rise to the sensation of direct viewing. In their discussion, the authors considered that this effect could have been real or may have been due to lack of understanding and compliance with the instructions and/or the patient's reluctance at aiming the eye in a manner that made the target indistinct.

Alternative retinal locations (ARLs):

Tentative suggestions for potential ARLs were made to the subject on the basis of retinal appearance and proximity to the fovea, with the further consideration of not reading into a scotoma. The patient's response would presumably be derived from an improvement or decrease in quality of vision. Ease of detection of the ARL, although not the basis for initial selection, was a consideration during training.

This approach and validation of chosen ARL sites was made relatively easy by the use of the SLO. In the absence of the SLO, such a task would be extremely difficult, if not impossible. All training programmes to date have tried to locate ARLs without the help of a SLO.

4.3.3.3 Acuity mapping

Standard clinical methods of measuring visual acuity give an indication of patients' performance but no information as to where the image is formed on the retina and no real disclosure as to optimisation of performance. By conventional testing an acuity value may be derived from patients either using a fovea compromised by disease or an eccentric retinal locus. Both of these sites would give poor performance but for different reasons. Hence, acuity testing using the SLO provides valuable insight into residual vision. Such measurements have been undertaken previously with both normal (Timberlake et al, 1987a) and low vision subjects (Timberlake et al, 1989). In the present study, this technique was used explicitly to compare performance between PRLs and ARLs.

Normal foveal resolving power under good experimental conditions can be of the order of 30 seconds but in the clinical environment an average individual is assumed to have acuity of approximately 1 minarc (Davson, 1980). Because of pixel limitations the smallest gap size that could be presented by this apparatus was 5.72 minarc (see p88). In practice this was not a problem because only one of our patients could demonstrate acuity of this order, whilst the rest could do no better

than 9 min arc (Table 20, p137).

One particular difficulty was experienced with the technique. The Snellen E, presented in the centre of crosshairs, was supposed to be the location fixated by the patient. However, on occasion, some patients found it difficult to maintain accurate fixation throughout the extended task, especially when attempting to utilise an ARL; hence, the E was sometimes presented to an adjacent retinal location. This could be observed on the TV monitor, but due to limitations of the programme, a repeat stimulus could not be presented to the correct location. To overcome this problem the programme had to be started again from the beginning. This was both time-consuming and tiring for the patient. This fault will be rectified for future studies by modification to the computer programme. Even given this problem, the results obtained were reasonably accurate.

In contrast to expectations the results suggested that the ARLs had similar acuity to the PRLs. Patients may choose PRLs on the basis of acuity, acuity plus location and/or stability of the acquired image. The current investigation was carried out with only high contrast targets. That the test worked is shown by the finding that there are significant differences between patients. In order to produce a more sensitive test variable contrast targets could be used as described by Timberlake et al (1987a).

Alternative reasons for selection of the PRL position, i.e. the ease of locating the ARLs and stabilising an image on the retina, are discussed below.

4.3.3.4 Fixation stability

With the exception of the patient who had good residual foveal vision, fixation stability was similar for the PRLs and ARLs. Again this finding was surprising since it could be expected that patients select their PRL on the basis of ability to maintain a specific eye position. This issue is analogous to that of choice of PRL with regard to acuity (discussed above). With the acuity mapping there was some contention about the proficiency of the test to detect small differences in performance. This is not true in the case of fixation stability when the

measurements of the BCEA were considered to be reliable (see System Assessment; sections 2.3.2, p63; 3.2.2, p104 and 4.2.2, p153). Therefore it appears that patients do not favour their PRL because of ease of maintenance of eye position.

Fixation stability improved during the course of the study. This is an important observation because it implies that learning and practice were a positive influence. Further, acquired skills dependent upon techniques in the training programme may have had a strong effect.

This is the only study to have addressed fixation stability throughout a low vision training programme. This is surprising given the importance of stability of an image on the retina when carrying out high visual acuity tasks. It should be emphasised, however, that without SLO technology this is an extremely difficult parameter to evaluate in the clinical setting.

In the experimental setting, studies have investigated fixation stability in both humans (Whittaker et al, 1988a) and monkeys (Heinen and Skavenski, 1992), see section 4.2.2. But in the former, longitudinal measurements were not undertaken. In the latter, after laser induced macular lesions, fixation stability improved to a stable value remarkably quickly, i.e. within two days. However, as previously stated, these lesions were small and instantaneous and therefore conclusions cannot be drawn in relation to training.

4.3.3.5 Search and identification

Patients' ability to search and identify a target improved during the study. Once again, this probably reflects a learning curve with two components, the first being acquired skills due to training and the second practice.

This is the first time that search and identification tasks have been addressed in a low vision training programme. This type of evaluation provides important information since patients need to be able to utilise their vision effectively and as such, locating a target with the correct area of retina is essential.

Although the primary aim of Schuchard's study (1991) was not in relation to training, he did investigate search times in a variety of subjects using a target of a cross with a gap in one of the four arms. By means of software, this stimulus was randomly located in one of twenty four locations in the SLO raster. In contrast, the present study utilised manual control of a letter instead of the cross and the stimulus was positioned anywhere in the raster. As would be expected, Schuchard found that normal observers were the quickest to identify the target (e.g. 0.5s), while patients with central scotomas, although slower (e.g. 2.5s) were able to perform better than those with peripheral field loss (5s). Search times in the present study were comparable to Schuchard's data (see Tables 23 and 24, p142-3).

The period taken to detect a target is almost certainly related to the size and location of the scotoma. Hence, it is easier to detect the presence of a target if the peripheral vision is intact. Even large central scotomas allow relatively quick detection (e.g. patient DR, 1s) provided the target is not presented within the field defect. Under less favourable circumstances, particularly when the patient is forced to view with a retinal area not normally utilised, the time taken can be extensive (e.g. patient CP, 80s).

Peripheral vision has a clear role in detection of a target but studies using normal observers with artificial central scotomas have demonstrated that foveal vision also plays an important part (Bertera, 1988; Murphy and Foley-Fisher, 1988). In summary, in patients with ARMD, peripheral vision has the essential role of detecting an object whereas the PRL is required to fixate and define it. The relative time course of these two may account for slower search times compared to normal observers.

In the present study the search and identification task provided the first piece of evidence that the PRLs had faster acquisition and recognition performance than ARLs. Speed of acquisition may underlie the patient's choice of PRL as anything that facilitates reading is clearly of benefit. In contrast, there was no difference in performance between the two ARLs.

4.3.3.6 Letter recognition

Performance outcomes for the task of reading scrolled letters in the SLO demonstrated that the PRLs had significantly superior capability compared to the ARLs. As with the search and identification task, patients may have selected the PRLs on the basis of good performance for a practical skill.

The ability to read letters correctly improved with time. As suggested for both fixation stability and the search and identification task, this may be due to better visual skills associated with training and their improvement with practice which lead to more efficient use of vision.

No previous low vision training study has used this modality to investigate patients' performance. Since the main aim of this study was to examine the concept that a training programme influences reading ability, this technique was of immense value in the comparison of "reading" performance at different retinal locations. The finding that PRL allows best performance and that reading ability improved with training is of great importance. A tentative conclusion is that eccentric viewing training programmes do improve reading ability but not for the reason assumed, i.e. not because the patient learns to utilise a different retinal area.

4.3.3.7 Speed of recognition

The visual task of identifying a unique letter in a sequence of similar letters was different from the letter recognition task in two ways. The first was advantageous to the patients in that because they did not have to read aloud, the possibility of mistakes due to inaccurate verbal responses was removed. The second was disadvantageous to the patients because it introduced the element of the crowding phenomenon which resulted from the letters being immediately adjacent to each other. The latter has been shown to cause significant effects in individuals with senile macular degeneration (Rubinstein and Underwood, 1985).

No other studies have addressed this visual task in a low vision training programme. In evaluating patients' visual performance it was a legitimate test since

most visual stimuli in the real world are presented in a complex visual environment. When undertaking this experiment, some patients commented on the level of difficultly due to the close proximity of adjacent letters.

Once again, in agreement with the above findings, the PRLs provided better performance than the ARLs. Similarly, performance for speed of recognition improved throughout the study. Both of these outcomes have been recognised in other practical tasks assessed in this study.

In summary, throughout the SLO assessment the PRLs never performed inferiorly to the ARLs. In addition, for the last three visual tasks assessed, which are perhaps the most important in terms of reading, the PRL performed significantly better. This is in direct contrast with claims made by published works that advocate the necessity of eccentric viewing training (Nilsson, 1990a).

4.3.3.8 Questionnaire

The purpose of this component of the investigation was not to assess the patients' psychological status but instead to gain some insight into the patients' responses to the training programme.

It was hoped that the promise of anonymity would result in realistic comments. If such a questionnaire was undertaken in the future, it would be improved by the use of multiple choice questions that could be scored and also by completed forms being returned to a third party such that the patient felt no obligation to be benevolent. Even so, the questionnaire utilised in the current study resulted in feedback which was both interesting and constructive (see Appendix V).

Nine of the eleven patients felt that they had "benefited" from the study. The benefits can be considered in two broad categories; psychological aspects and reading skills.

From the psychological point of view, several patients felt that advantages had been gained from the explanations, information and reassurance provided. Such issues should have been, and indeed may have been, addressed at an early stage in

the ophthalmological care; however, patients were inferring that they had not been covered adequately. With regard to reading skills, several patients remarked that vision had been improved by the use of the techniques taught. Indeed, the results of the study showed that near visual acuity improved, although reading speed did not.

According to patients' feedback, the programme had the effect of enhancing confidence and aiding adjustment to their disability. They were reassured that "someone was trying to help" and this indicated that inadequate support and rehabilitation had been offered previously. This is particularly disturbing because in order to be recruited for this study patients must have already attended a low vision clinic and been prescribed an appropriate magnifying device, i.e. the best the system can offer. Low vision provision in the UK is known to be inadequate (Bruce et al, 1991; Bruce and Hamlin, 1992). The messages these patients are giving is that current services are not providing sufficient psychological support. In many parts of the country the service is worse with no support whatsoever.

Constraints on time of the medical staff may lead to inadequate communication. Further, at the initial consultation patients are often shocked and little information is absorbed. This probably reflects the need for enhancement consultations which are basically informative and provide support in an informal fashion.

Other important comments were made; one patient remarked that the training programme was hard work both physically and mentally. The patient group targeted in this study was elderly and all aspects of the programme, including the appointments, travel, homework etc., represented a great deal of effort. As stated before, all the patients were motivated and completed the study. One patient commented that during appointments benefits due to eccentric viewing were experienced but at home the techniques were difficult to reproduce and visual improvement was not maintained. This may suggest that if training is appropriate, some patients may benefit from more extensive training, perhaps delivered in their home environment. The cost of such programmes, in relation to the learning curve, would have to be addressed carefully.

Another patient stated that during the training programme he had become a happier person and now enjoyed the challenge of reading. Such optimistic reports of training may be misleading if patients' comments are not supported by indepth assessment of visual function.

Two of the eleven questionnaires reported less enthusiastic responses. One patient found the experience "interesting" and was "grateful something has been attempted" but did not feel it was successful. Although the questionnaires were anonymous, this may have been the patient with residual foveal function for whom eccentric viewing was unproductive. The other patient did not feel that he had benefited in any way. Such negative reports validate the questionnaire since they demonstrate that patients were honest in their appraisal of the programme.

In any training programme there is an element of psychological support. The importance of psychological aspects in low vision care should not be underestimated (Morse, 1989; Negrin, 1989). Our patients appeared grateful for the time spent with them, for the information, explanations and reassurance that was provided. Such support is of tremendous value and perhaps could be provided in a more structured way by personnel from the social worker sector. However, psychological benefits of training must not be confused with a true improvement in visual performance. The potential advantages of training are discussed in detail below.

4.3.4 Low vision training with the scanning laser ophthalmoscope

The purpose of this clinical study was to develop and conduct a low vision training programme using the SLO. The most important part was to identify the retinal locations patients used for viewing and to characterise their performance. Other potential retinal locations with similar or better visual ability were also investigated. The aim was to use professional training methods to enhance the reading ability of these areas.

Some applications of SLOs have been demonstrated in previous studies, for

example, fixation (Timberlake et al, 1986; Schuchard and Raasch, 1992) and search tasks (Schuchard, 1991), but in the current thesis new and improved techniques for assessment of visual function have been achieved. The results show that accurate and repeatable measurements in patients with age-related macular disease can be accomplished.

In order to determine the effectiveness of a low vision training programme the visual performances in the following areas were evaluated throughout the study as summarised below:

A. Standard clinical examination of

i) distance VA,

ii) near VA with patient's magnifying device and

iii) words read per minute with magnifying device.

B. SLO assessments of

iv) fixation stability,

v) time for search and identification of a target,

vi) percentage of letters read correctly and

vii) maximum speed of recognition.

During the course of the programme, performance improved significantly in all tasks except iii), i.e. reading speed. In general, these results would appear to agree with previous claims of benefits with training (Backman and Inde, 1979; Nilsson and Nilsson, 1994a, 1994b), even though the methods utilised for eccentric viewing and assessment were different. However, more specifically, it does not endorse claims of improved reading speed (Collins, 1987).

Reasons for such "success" in the present study must be examined carefully. At least three possible explanations could account for the observed results. First, skill acquisition through practise could have improved patient's results. Second, psychological factors could have enhanced patients' wellbeing and in turn affected their performance. Third, true visual improvement could have taken place due to patients' learnt use of a retinal area that had better performance than the PRL.

As discussed earlier, the impact of learning and practise on performance is well known (Overington, 1976). The visual tests in this study, although not difficult, represented unfamiliar tasks for the patients. Elderly patients with visual deficits may take longer to adjust to unusual tasks, particularly in a highly technical environment. Even young partially sighted patients have been shown to improve their visual performance with continued practise (Overbury and Bross, 1978).

Concentration and attention are other important aspects that may influence such assessments. In normal observers, peripheral acuity (Low, 1943; Saugstad and Lie, 1964), general perceptual ability (Bruce and Low, 1951) and motion detection (Johnson and Leibowitz, 1974) can be enhanced by training. Such achievements may be related to the ability to learn to shift attention from a central part of the field to the periphery. Our patients had longstanding loss of central vision, hence the need to shift attention had been long present. The learning effect in attention may be an important element in low vision training, but relative to normal observers this effect may be diminished. Conversely, a reduction in the size of useful field of view occurs with age but this may be recovered partially with practise (Ball et al, 1988). Patients with ARMD are relatively elderly and since they need to obtain information at some distance from the fovea, they may indeed benefit from training.

Psychological support almost certainly has an substantial role in low vision training (Goodrich and Mehr, 1986). Increased levels of achievement may been obtained if individuals are in a suitable psychological state. In any clinical trail placebo effects are well known, they are often psychological in origin but may manifest in measurable effects. A phenomenon known as the Hawthorne Effect exists where individuals perform better if given attention (Mayo, 1945). In the present study the significance of the psychological aspect can not be isolated from other influences. In order to do this, a further study would be required involving a larger patient base, a trained group and two control groups. In the first control, patients would receive psychological support but no vision training, in the second,

patients would receive no "treatment". All subjects would undergo full visual assessment using SLO technology. In this manner, the relative influence of psychological and training elements would be determined.

The present study has been directed particularly towards investigation of the potential benefits of eccentric viewing. The patients' choice of PRL is of great consequence because if the "optimal" retinal area is selected then training to reposition the angle of view is unnecessary. This is the first time that a study has endeavoured to address this issue. In order to determine the suitability of patients' choice of PRLs it was necessary to compare the performances of various retinal locations. The data show that, for the group as a whole, ARLs did not achieve significantly better results than the PRLs in any of the tasks assessed. More specifically, no difference in performance for the PRLs and ARLs was found for the visual tasks of acuity measured with the SLO and fixation stability. In the three other tasks assessed (search and identification of a target, percentage of letters read correctly and maximum identification speed) PRLs demonstrated significantly better performances. This suggests that training patients to change their angle of view is futile and superfluous. Even when the PRL was situated in the horizontal meridian and the patient was attempting to read into a scotoma, training to reposition the angle of view did not allow faster reading speed.

The finding that PRLs performed at least as well if not better than the ARLs is highly relevant to eccentric viewing training. Even in the present study, with the benefit of sophisticated equipment, it was not possible to locate retinal areas that performed better than the PRLs. Studies which have less information on patients' visual status would presumably have less opportunity for successfully identifying more optimal retinal areas. In all previous clinical training programmes advocating eccentric viewing techniques, two severe limitations are present: First, limited information is available when locating the viewing position. For example, an Amsler grid has been advocated as "a useful aid for refining and identifying the exact angle of best view" (Collins, 1987). Relative to SLO technology this is an

extremely crude technique. Second, the trainer is unaware of the exact retinal location utilised by a patient during any given task. This is further complicated by the fact that some patients appear to have directional referencing to their PRL, making them unable to report accurately on their true eye position.

That ARLs do not produce significantly better performance than PRLs is apparent when the results are analysed for the whole group. However, individual cases can be cited where response to the ARLs seemed to be positive. For example, with patient JD the PRL was positioned at the fovea. Prior to entering the study she had investigated the possibility of eccentric viewing and found that her vision seemed to improve. This was confirmed by the SLO acuity test where acuity was found to be better at ARLs than the PRL (see Table 20, p137). Similarly, fixation stability and percentage of letters read correctly was slightly better at an ARL. Further, when the patient used her PRL for reading a scotoma was projected to the right of fixation on the visual field. Logically the ARL was better placed for reading and therefore it might be expected that her reading speed would improve - but this was not found to be the case on reading normal text. It cannot be discounted that, when attempting a task where her fixation position could nolonger be monitored, this patient returned to using her PRL. Other commitments on the SLO did not allow this aspect to be pursued in detail.

Low vision training techniques:

The term "training" covers many techniques all aimed at successful rehabilitation. Programmes may involve nothing more technical than basic instructions relating to dealing with the limitations of low vision and magnifying devices (Mehr and Fried, 1975; Faye, 1976; Kelleher, 1976). Such rehabilitation methods have obvious value. This practical advice also offers psychological support. In the current study these aspects were not under review, although our patients' responses to the questionnaires indicate how much this form of rehabilitation would be appreciated by patients in the UK.

Eccentric viewing training is a specialised area of rehabilitation. Since its

conception in the early 1970s the approach has been to direct the damaged fovea towards an area above or below the text to be read (Backman and Inde, 1979). Also, it has been somewhat dogmatically promulgated that "few patients can learn eccentric viewing effectively by themselves" (Nilsson and Nilsson, 1986). Recent more objective findings, both in the present thesis and other studies, have demonstrated that many patients self-acquire eccentric viewing and often have a strong preference for a single retinal location (Timberlake et al, 1986; Guez et al, 1993). In addition, some appear to have directional referencing to the PRL (White and Bedell, 1990). As discussed earlier, although overall the effect of training was to improve visual performance, this benefit was not derived from changing the patient's viewing angle.

The criteria defining whether or not an individual patient would benefit from training have not yet been identified. In some studies a number of patients are assigned to undergo no eccentric viewing training (Nilsson and Nilsson, 1986; Ighe, 1994), but unfortunately the reason for retaining centric viewing even though severe visual loss has occurred is not discussed. As Faye (1976) remarked with regard to basic instruction on handling a magnifier, not every patient needs a training programme to learn to use his aids. The same may be true in eccentric viewing, not all patients can be trained, or indeed, need to be.

Extremes are easily identified, for example, benefit can not be derived from training of patients with Alzheimer's disease or individuals with good central vision. Outside those extremes the definition of boundary conditions become more difficult. A reasonable IQ to facilitate comprehension and a suitable level of manual dexterity are helpful. Whilst, from first principles, the size and the position of a field defect may seem important, this must have a relatively low priority since many patients choose to read into a scotoma.

In this study, benefits were evident from training as a result of multi-factorial elements. These included the acquisition and perfection of new visual techniques and improvement in patients' well-being. The timing of intervention with training

may be important since changes in the visual system and psychological status may occur over a period of time. System changes may also occur, e.g. cortical adaptation. White and Bedell (1990) have suggested that training in SES may be unhelpful for patients with recent loss of vision since visual acuity correlates with saccadic rather than fixational eye movements and suppression of saccadic eye movements may prolong adaptation to the new visual status. The psychological status of the patient has a significant role since hope and expectation for recovery may affect motivation. The rate of loss of vision has influence since patients are shocked by a rapid decrease but may adapt to the situation if progression is slow (Schulz, 1977). Hence, there may be a critical period where training may be most beneficial.

The successful use of the SLO for assessment of residual vision in patients with macular disease and for low vision training has been demonstrated by this study. Detailed evaluation of central visual function and the identification of specific retinal areas would not be possible without the SLO. The major part of this thesis was concerned with the development and standardisation of techniques and software required to provide useful data in the assessment of clinical problems. Specific software has been developed and tested and the results have been promulgated within the scientific community (Culham et al, 1992; Culham et al, 1993; see Appendices VI and VII). Following this study, large numbers of patients need to be assessed and from that boundary conditions for training can be defined. Advanced training procedures can be developed and those patients who may benefit could be identified.

PART 5: CONCLUSIONS

Conclusions

In this study, the techniques developed, modified and utilised with the scanning laser ophthalmoscope have allowed the following conclusions to be drawn:

5.1. Scotoma mapping

1. Microperimetry was able to define accurately the size and location of retinal lesions in patients with macular disease.
2. In some patients, residual visual function was detected in retinal areas that appeared to be non-functioning.
3. In normal observers, correcting for eye movements made no significant difference to the reproducibility of scotoma maps.

5.2 Assessment of fixation

4. The ability to maintain steady fixation varied significantly among normal individuals and, more so, in patients with central field loss.
5. Fixation stability was affected by the size but not the complexity of form or the polarity of the fixation target.
6. Fixation was most accurately maintained on an isolated stationary target. It was less well maintained when a stationary target was used in the presence of scrolling text. Fixation was not influenced by the speed of scrolling text, nor by the retinal location of such text.

5.3 Letter recognition using scrolling text

7. This novel technique has proved to be valuable in the assessment of residual vision in patients with macular disease.
8. In normal observers, the ability to read text at different retinal locations declined with increasing retinal eccentricity and decreasing text contrast.
9. The reading performance of patients with macular disease was often worse than normal observers utilising similar retinal locations.

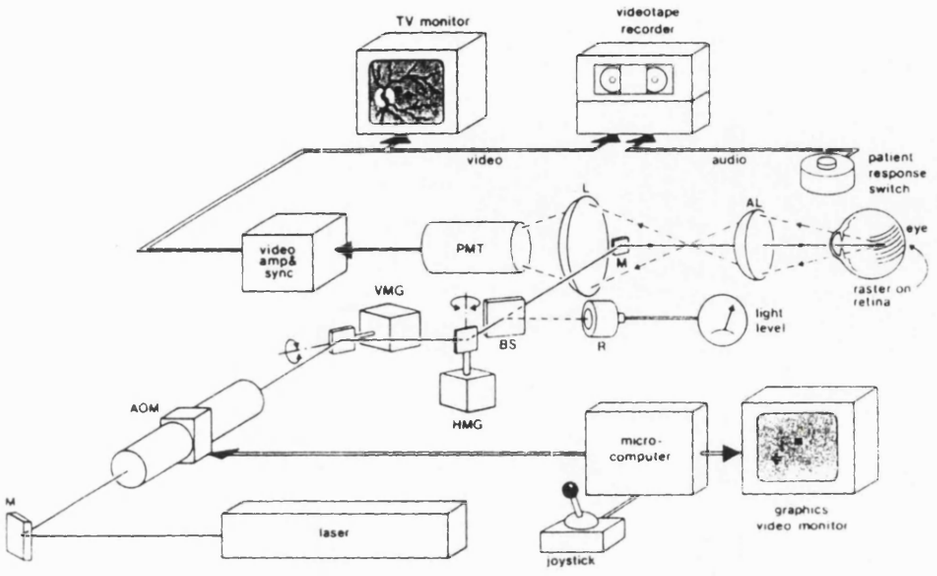
10. Most patients had a consistent preference for a single retinal area. In cases where there was no foveal function, this locus was situated eccentrically.

11. The preferred retinal location performed at least as well, if not better than any alternative retinal area assessed.

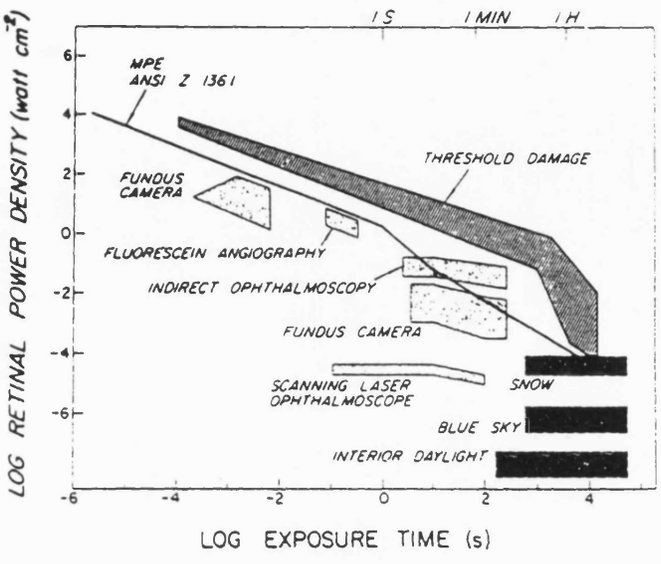
12. In comparison to alternative retinal locations, the patients' preferred retinal areas performed significantly better at specific visual tasks including letter recognition, speed of recognition and search and identification.

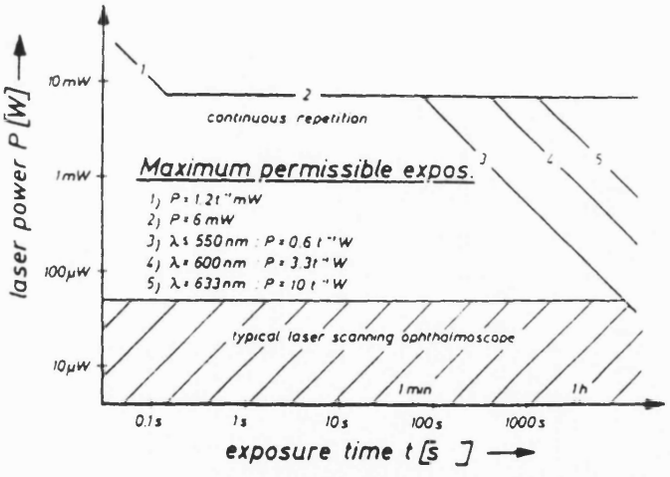
13. The low vision training programme used in this study improved patients' visual performance. This improvement was due not to instructing patients to utilise retinal areas with previously unidentified superior performance, but instead to psychological benefits associated with training and the acquisition and perfection of new visual strategies.

PART 6: APPENDICES



APPENDIX I: SCHEMATIC ILLUSTRATION OF THE SCANNING LASER OPHTHALMOSCOPE
FROM: TIMBERLAKE ET AL (1986)





APPENDIX II: SAFETY ASPECTS OF LASER SCANNING OPHTHALMOSCOPES
FROM: KLINGBEIL (1986)

APPENDIX III: TEXT FOR TESTS OF READING SPEED; SELECTED EXAMPLES

During the past few minutes he had become aware of the sound of dripping water coming from somewhere above him. There was nothing to be seen in the roof immediately above where he stood, and yet the sound was so close. He raise his torch once more but the light went out. Shaking it hard, he tried again and flashed the light in an arc around him.

It was close to four o'clock, and the others at the tunnel mouth would not be kept waiting about after the real darkness fell. For a moment he wondered if he were really awake. It seemed to him that he was in the middle of a forest - a forest of pale stone. Many tall columns stretched in all directions and for the first time he felt frightened.

But he also did not want to go back; not until he had explored a little more. He could still hear the sound of dripping water and he wanted to find out where it came from.

The room in which they were sitting might have been called a playroom, schoolroom or nursery by most people. But to the Greens it was known as the Office. It was at the very top of the house so that they could make as much noise as they wished. In one corner of the room stood an old upright piano that always looked offended, for some reason, and whose rack was littered with sheets of music all patched and held together with tape.

In addition to various chairs, tables and toy cupboards, there was a big dingy sofa and a blackboard. The Greens seemed to go on collecting precious articles that they could never bear to throw away. The Office was their pride and joy, and what it lacked in tidiness it more than made up for in colour and comfort.

It was also full of landmarks; any child could have told you that the scars on the floor had been made by Tom trying out a pair of skates.

Tom came to the turning which was the corner point and searched in the dark for the shed. He saw a faint glow and supposed there was a bonfire in the convent's grounds. Fancy adding smoke to the confusion, he thought with annoyance. He heard someone running in the distance and wondered how they could see well enough to proceed so fast. Then the red glow became stronger and felt smoke in the back of his throat and in his nose.

The glow was in front of him now and it took the form of flames; it crackled and spat out sparks of fire. And it was not in the convent ground. It was at the end of the road - in Joe's shed. He heard his heart pounding madly, people shouting and the whine of a dog.

Coming closer, suddenly quite calm, he looked more carefully. Smoke was coming out of the window, flames licked up the padlocked door. The whole of the front of the shed was on fire.

In that crowded hall, the only object that Tom recognised was the grandfather clock. He moved towards it, not to read its face, but simply to touch it - to reassure himself that this at least was as he knew it. His hand was nearly on it, when he heard a little breath behind him that was the maid passing back the way she had come. For some reason, she did not seem to make as much sound as before.

She was making for the door through which she had first come, and, as Tom followed her with his eyes, he received a curious impression: she reached the door, her hand was upon the knob, and then she seemed to go. That was it exactly; she went, but not through the door. She simply thinned out, and went.

He looked round sharply, and caught the hall in the act of emptying itself of furniture and rugs and pictures. They were not positively going but rather beginning to fail to be there.

The grandfather clock was still there, and must tell him the true time. It must be either twelve or one: there was no hour between. There is no thirteenth hour. His attention was distracted by the opening of a door down the hall - the door of the groundfloor front flat. A maid trotted out.

Tom had seen housemaids only in pictures, but he recognised the white apron, cap and cuffs, and the black stockings. He was not expert in fashions, but the dress seemed to him to be rather long for her. She was carrying paper, wood and a box of matches.

He did not feel afraid of the maid; as she came nearer, he saw that she was only a young girl. To warn her of his presence without startling her, Tom gave a cough; but she did not seem to hear it. She still came on. He moved forward into her line of vision; she looked through him. His heart jumped in a way he did not understand.

It was to his shop I went one Friday afternoon to have my hair cut. My dad had been nagging me that much about it, until he got fed up and said that he would not give me Friday's sixpence until it had been cut. I hated the idea because, apart from the ordeal of plucking and itching and keeping still, there was always something warm about having long thick hair covering your neck and hanging like a fringe over your jersey collar.

There was no getting out of it, except to go without spending money, so at half past four I went into Rag Bob's. The saloon, as it was called, was the front room of an ordinary two-up and two-down cottage.

It had no fancy equipment; and the stone floor was white and your clogs made a nice clack when walking over it. The gaslight was on all the time because of the big spinning-mill just across the narrow street cast a cool dark shadow.

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APPENDIX IV: RAW DATA FROM FIXATION STUDY (SECTION 3.2.2)

TABLE 1 EXPERIMENT I Fixation stability data of normal subjects viewing different stationary target arrays

SUBJECT	TARGET	RETINAL LOCATION	PRL	SIZE (min arc)	CONTRAST (%)	SD(H)	SD(V)	ANGLE (deg)	BCEA (min arc^2)
CJ (normal):									
1st sitting									
	E	fovea	y	20x20	-25	7	10	58	356
	E	fovea	y	20x20	+25	4	4	50	99
	E	fovea	y	160x160	-25	5	6	133	165
	E	fovea	y	160x160	+25	4	8	114	158
	TH+LH	fovea	y	100x20	-25	4	3	143	79
	TH+LH	fovea	y	100x20	+25	4	4	80	124
CJ:									
2nd sitting									
	E	fovea	y	20x20	-25	3	6	109	91
	E	fovea	y	20x20	+25	2	3	83	47
	E	fovea	y	160x160	-25	3	4	74	66
	E	fovea	y	160x160	+25	4	8	103	214
	TH+LH	fovea	y	100x20	-25	3	3	126	80
	TH+LH	fovea	y	100x20	+25	4	4	40	97
CL (normal):									
	E	fovea	y	20x20	-25	3	4	109	92
	E	fovea	y	20x20	+25	3	5	101	101
	E	fovea	y	160x160	-25	5	8	180	304
	E	fovea	y	160x160	+25	4	4	124	113
	TH+LH	fovea	y	100x20	-25	4	6	107	162
	TH+LH	fovea	y	100x20	+25	4	6	109	155

PK (normal):								
	E	fovea	y	20x20	-25	4	2	10	63
	E	fovea	y	20x20	+25	5	4	149	142
	E	fovea	y	40x40	-25	9	7	9	464
	E	fovea	y	40x40	+25	9	6	147	273
	TH+LH	fovea	y	100x20	-25	4	1	173	42
	TH+LH	fovea	y	100x20	+25	2	4	97	40
EM (normal):									
	E	fovea	y	20x20	-25	17	5	177	581
	E	fovea	y	20x20	+25	6	4	163	189
	E	fovea	y	40x40	-25	22	9	176	1405
	E	fovea	y	40x40	+25	18	11	151	955
	TH+LH	fovea	y	100x20	-25	6	4	167	202
	TH+LH	fovea	y	100x20	+25	11	5	17	344
DS (normal):									
	E	fovea	y	20x20	-25	3	3	65	79
	E	fovea	y	80x80	-25	7	3	171	162
	TH+LH	fovea	y	100X20	-25	4	4	146	94
	+	fovea	y	20x20	-25	5	4	166	123
	Grid	fovea	y	100X100	-25	2	3	64	53
IM (normal):									
	E	fovea	y	20x20	-25	3	2		29
	E	fovea	y	80x80	-25	5	4		103
	TH+LH	fovea	y	100X20	-25	4	2		47
	+	fovea	y	20x20	-25	3	4		53
	Grid	fovea	y	100X100	-25	2	2		23

AP (normal):								
	E	fovea	y	20x20	-25	3	3	103	71
	E	fovea	y	80x80	-25	4	3	152	83
	TH+LH	fovea	y	100X20	-25	1	3	92	26
	+	fovea	y	20x20	-25	2	1	8	21
	Grid	fovea	Y	100X100	-25	4	2	164	67
JS (normal):									
	E	fovea	y	20x20	-25	7	5	17	232
	E	fovea	y	80x80	-25	14	4	10	365
	TH+LH	fovea	y	100X20	-25	4	2	167	75
	+	fovea	y	20x20	-25	7	3	167	126
	Grid	fovea	y	100X100	-25	7	4	18	182
PJ (normal):									
	E	fovea	y	20x20	-25	3	2	162	56
	E	fovea	y	80x80	-25	4	3	174	78
	TH+LH	fovea	y	100X20	-25	2	3	113	41
	+	fovea	y	20x20	-25	2	3	78	44
	Grid	fovea	y	100X100	-25	3	1	3	30
AM (normal):									
	E	fovea	y	20x20	-25	8	3	9	129
	E	fovea	y	80x80	-25	14	4	1	369
	TH+LH	fovea	y	100X20	-25	8	4	2	233
	+	fovea	y	20x20	-25	8	2	2	126
	Grid	fovea	y	100x100	-25	7	2	1	115
Different instructions:									
	E	fovea	y	20	-25	4	3	147	87
	E	fovea	y	80	-25	6	3	169	112

DD (normal):								
	E	fovea	y	20x20	-25	3	3	44	58
	E	fovea	y	80x80	-25	4	4	134	98
	TH+LH	fovea	y	100x20	-25	3	3	60	53
	+	fovea	y	20x20	-25	1	3	91	33
	Grid	fovea	y	100x100	-25	13	4	175	368
AJ (normal):									
	E	fovea	y	20x20	-25	9	6	177	373
	E	fovea	y	80x80	-25	8	10	55	498
	TH+LH	fovea	y	100x20	-25	6	5	145	164
	+	fovea	y	20x 20	-25	6	3	1	123
	Grid	fovea	y	100x100	-25	5	3	174	88

TABLE 2 EXPERIMENT I Fixation stability of low vision patients viewing stationary targets

TARGET	RETINAL LOCATION Degrees	Clock position	PRL	SIZE (min arc)	CONTRAST (%)	SD(H)	SD(V)	ANGLE (deg)	BCEA (min arc^2)
EF (fundus flavimaculatus):									
E	fovea		y	80x80	-85	10	9	27	628
E	fovea		y	80x80	+75	4	2	12	63
TH+LH	fovea		y	400x80	-85	4	2	0	51
TH+LH	fovea		y	400x80	+75	6	5	140	150
JW (geographic atrophy):									
E	2	5	y	80x80	-50	16	6	167	495
E	2	12	n	80x80	-50	28	15	179	2888
TH+LH	2	5	y	400x80	-50	11	8	154	603
AA (atypical Stargardts):									
TH+	6	12	y	240x80	-95	41	46	87	13367
TH+	6	2	n	240x80	-95	70	33	172	15903
NH (Bull's eye maculopathy):									
E	6	11	y	40x40	-50	15	12	26	1247
E	6	11	y	40x40	+50	7	11	92	553
E	6	11	y	80x80	-50	8	16	74	874
E	6	11	y	80x80	+50	14	26	79	2613
TH+LH	6	11	y	400x80	-50	7	8	76	374
TH+LH	6	11	y	400x80	+50	6	26	95	1012

DB (disciform degeneration):

E	6	3	y	80x80	-50	9	4	161	174
E	6	3	y	80x80	+50	17	4	171	348
E	6	10	n	80x80	-50	4	8	105	208
E	6	10	n	80x80	+50	5	6	52	176
E	6	2	n	80x80	-50	8	4	157	140
E	6	2	n	80x80	+50	11	4	166	214
E	6	3	y	160x160	-50	12	3	169	222
E	6	3	y	160x160	+50	4	3	161	70
E	6	10	n	160x160	-50	6	7	130	170
E	6	10	n	160x160	+50	5	9	89	332
E	6	2	n	160x160	-50	15	4	175	365
E	6	2	n	160x160	+50	18	2	178	295
TH+	6	3	y	240x80	-50	7	9	122	381
TH+	6	3	y	240x80	+50	10	4	171	263
TH+	6	10	n	240x80	-50	4	5	123	121
TH+	6	10	n	240x80	+50	6	3	176	135
TH+	6	2	n	240x80	-50	9	3	122	187
TH+	6	2	n	240x80	+50	16	3	8	289

KA (macular hole):									
E	fovea		y	40x40	-50	7	4	160	168
E	fovea		y	40x40	+50	7	2	3	99
E	3.5	12	n	40x40	-50	17	7	165	625
E	3.5	12	n	40x40	+50	26	16	150	1602
TH+LH	fovea		y	300x60	-50	7	4	9	185
TH+LH	fovea		y	300x60	+50	9	4	168	227
HW (Neovascular membrane):									
E	fovea		y	40x40	-25	7	5	155	198
E	fovea		y	40x40	+25	8	2	3	138
E	fovea		y	80x80	-25	2	4	97	69
E	fovea		y	80x80	+25	9	5	10	301
TH+LH	fovea		y	200x40	-25	4	4	45	99
TH+LH	fovea		y	200x40	+25	2	3	107	36

TABLE 3 EXPERIMENT III Fixation stability of normal subjects viewing scrolled stimuli of speeds 1, 2 and 3 at different retinal locations

SUBJECT	RETINAL LOCATION (deg)	SPEED 1 ANGLE (deg)	SPEED 1 BCEA (min arc^2)	SPEED 2 ANGLE	SPEED 2 BCEA	SPEED 3 ANGLE	SPEED 3 BCEA
CJ (normal):							
CONTRAST -/+ 25%; LETTER SIZE 20 MIN ARC							
	Fovea	169	117	136	121	15	440
		106	84	9	103	164	103
	2	78	58	90	160	97	596
		80	72	97	72	1	67
	4	75	74	103	113	137	197
		82	55	100	285	175	608
	6	91	41	105	213	169	408
		50	111	112	179	59	234
CL (normal):							
CONTRAST -/+ 25%; LETTER SIZE 20 MIN ARC							
	Fovea	141	305	175	594	174	359
		155	204	149	167	161	179
	2	156	126	86	165	146	281
		142	197	9	135	118	1384
	4	106	251	110	262	120	875
		125	75	88	97	52	280
	6	156	189	146	211	162	175
		96	139	74	164	84	226

PK (normal):
CONTRAST -/+ 25%; LETTER SIZE 20 MIN ARC

Fovea	179	252	99	112	171	509
	163	403	169	336	119	110
2	86	221	52	4778	92	81
	88	656	175	343	173	331
4	7	65	76	660	45	73
	58	240	78	79	100	173
6	55	1871	115	232	77	197
	11	323	35	163	167	136

TABLE 4 EXPERIMENT III Fixation stability data for normal subjects viewing scrolled stimuli of speeds 1, 3 and 4 at different retinal locations

SUBJECT	RETINAL LOCATION (DEG)	SPEED 1 ANGLE	SPEED 1 BCEA	SPEED 3 ANGLE	SPEED 3 BCEA	SPEED 4 ANGLE	SPEED 4 BCEA
DS (normal):							
CONTRAST -25%; LETTER SIZE 20 MIN ARC							
	Fovea	175	232	17	232	142	1124
	2	82	558	11	142	80	179
	4	18	251	123	645	131	167
	6	128	645	103	139	33	297
IM (normal):							
CONTRAST -25%; LETTER SIZE 20 MIN ARC							
	Fovea	11	184	180	135	2	71
	2	7	173	11	132	56	101
	4	7	138	3	140	82	636
	6	46	105	127	90	164	137
AP (normal):							
CONTRAST -25%; LETTER SIZE 20 MIN ARC							
	Fovea	178	144	16	124	175	289
	2	149	80	83	329	69	1928
	4	90	2504	64	996	86	9054
	6	151	171	172	84	85	9643

JS (normal):
CONTRAST -25%; LETTER SIZE 20 MIN ARC

Fovea	8	435	7	388	105	441
2	176	172	94	367	66	624
4	70	4313	99	44	129	194
6	130	182	126	547	80	832

PJ (normal):
CONTRAST -25%; LETTER SIZE 20 MIN ARC

Fovea	19	923	102	167	159	260
2	174	120	97	145	5	203
4	77	249	89	438	79	181
6	156	140	9	371	3	151

AM (normal):
CONTRAST -25%; LETTER SIZE 20 MIN ARC

Fovea	2	290	174	695	2	560
2	54	879	4	205	16	86
4	13	179	2	267	2	199
6	15	126	6	316	20	157

DD (normal):
CONTRAST -25%; LETTER SIZE 20 MIN ARC

Fovea	166	123	3	460	180	279
2	42	963	7	372	107	2111
4	118	533	101	3002	32	392
6	123	557	91	3043	66	757

AJ (normal):
CONTRAST -25%; LETTER SIZE 20 MIN ARC

Fovea	25	176	174	692	20	241
2	80	2929	102	1948	26	511
4	107	432	164	553	158	636
6	119	550	171	683	14	1237

TABLE 5 EXPERIMENT III Fixation stability data of low vision patients viewing scrolling stimuli of speeds 1,2 and 3 at different retinal locations

PATIENT	RETINAL LOCATION (deg)	SPEED 1 ANGLE	SPEED 1 BCEA	SPEED 2 ANGLE	SPEED 2 BCEA ($min\ arc^2$)	SPEED 3 ANGLE	SPEED 3 BCEA
EF (fundus flavimaculatus):							
CONTRAST -85/+75%; LETTER SIZE 80 MINS							
	Fovea	12	1865	116	2254	170	5424
		18	524	173	3842	10	2024
	2	140	292	2	710	116	657
		136	3343	168	670	101	102
	4	2	478	169	253	103	1767
		169	1141	148	2124	148	419
	6	141	156	136	483	1	840
		8	4645	172	342	5	371
NH (Bull's eye maculopathy):							
CONTRAST -/+ 50%; LETTER SIZE 60 MIN ARC							
	Fovea	13	3120	78	995	180	494
		102	2182	133	10256	53	1118
	2	75	1803	178	9554	16	1866
		81	5694	104	2634	146	1286
	4	135	3054	56	5296	149	5929
		71	28343	85	15202	79	3705
	6	12	1364	112	1306	16	3673
		7	3810	80	4276	13	3738

KA (macular hole):
CONTRAST -/+ 90%; LETTER SIZE 80 MIN ARC

Fovea	51	274	180	445	5	304
	177	227	140	400	12	208
2	11	167	74	265	5	256
	167	196	5	253	1	268
4	179	278	56	144	153	223
	101	127	20	362	44	787
6	5	116	90	1218	33	214
	138	599	165	138	38	315

HW (subretinal neovascular membrane):
CONTRAST -/+ 25%; LETTER SIZE 40 MIN ARC

Fovea	157	104	1	208	134	129
	156	117	160	219	66	219
2	120	270	95	72	85	159
	119	145	96	130	97	173
4	162	133	109	72	73	68
	179	417	90	105	166	198
6	86	259	153	509	105	135
	157	450	145	384	77	319

APPENDIX V: PATIENTS' RESPONSES TO QUESTIONNAIRE

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

Please comment:
Yes, Miss L. Culham was very patient and helpful in explaining the problem, I am very pleased that I attended.

2. Do you think that the study made any difference to your vision?

Please comment:
Yes, the training to use the part of the Retina which was not damaged, was a great benefit to my vision.

3. Has your understanding of your eye problem changed?

Please comment:
Yes, as things have been explained to me in full.

4. Do you feel any differently about yourself or your eyes?

Please comment:
Yes, I feel more confident, more independent than when I first started the study, the time was well spent.
The Research was a great, great benefit.

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

   Please comment: Most certainly. I understand my problem now.

2. Do you think that the study made any difference to your vision?

   Please comment: Yes, I can use my eyes now to the best advantage

3. Has your understanding of your eye problem changed?

   Please comment: Yes I'm not quite so frustrated.

4. Do you feel any differently about yourself or your eyes?

   Please comment: I have covered the question as above.

5. Are there any other remarks you wish to make? Sonia Coleman is a most satisfactory 'teacher' and I should like to convey my thanks.

D. J. Sutton

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

   Please comment: yes, because of the information that part of the retina was still useable.

2. Do you think that the study made any difference to your vision?

   Please comment: Yes having been shown how to use the active part of the retina properly

3. Has your understanding of your eye problem changed?

   Please comment: yes in the knowledge of the information given at each visit

4. Do you feel any differently about yourself or your eyes?

   Please comment: Yes as the result of 2, 3, + 4 above.

5. Are there any other remarks you wish to make?

I feel privileged to have been selected for this study & the comfort I feel from the way I was treated at each visit made my trips to the hospital so worth-while.

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

   Please comment: YES.

2. Do you think that the study made any difference to your vision?

   Please comment: Yes. I have been made more aware of the potential offered by developing my peripheral vision. I am not sure how much (as yet) it has actually improved my vision.

3. Has your understanding of your eye problem changed?

   Please comment: Not really, although I found it helpful to know that in my left eye I have some central vision left. Also to know where I can best "pick up" peripheral vision.

4. Do you feel any differently about yourself or your eyes?

   Please comment: Yes, I have more confidence that in spite of damage to my central vision as a whole, there is the wider field of peripheral vision to be worked on - hopefully developed.

5. Are there any other remarks you wish to make?

   My thanks for being given the opportunity to be included in this study, and for Miss Culham's guidance.

JQ220

14. 2. 94.

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

   Please comment: yes, psychologically.

2. Do you think that the study made any difference to your vision?

   Please comment: yes. Reading skills improved.

3. Has your understanding of your eye problem changed?

   Please comment: No.

4. Do you feel any differently about yourself or your eyes?

   Please comment: Feel reassured.

5. Are there any other remarks you wish to make?

   Express thanks that someone is trying to help.

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

   Please comment: It has given me confidence and incentive to read.

2. Do you think that the study made any difference to your vision?

   Please comment: Most certainly! Vision is becoming clearer, Am adapting naturally to a new way of viewing.

3. Has your understanding of your eye problem changed?

   Please comment: YES! am using my eyes to the best advantage.

4. Do you feel any differently about yourself or your eyes?

   Please comment: Both! I feel a much happier person, and can now enjoy the challenge of reading again, which has very much improved.

5. Are there any other remarks you wish to make?

   It is most gratifying to know that research is being carried out in this field!

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

Please comment:

Yes, I have gained more confidence in understanding my problem.

2. Do you think that the study made any difference to your vision?

Please comment:

Yes, I did not realise that using other areas of my correct peripheral vision could improve my sight, and this has enabled me to read more easily.

3. Has your understanding of your eye problem changed?

Please comment:

Yes, I realise that the damaged macular is not the whole of the eye, and that my sight cannot be lost altogether.

4. Do you feel any differently about yourself or your eyes?

Please comment:

Yes, before the study I was unaware of the amount of people suffering from this disability, and finding out that it is not a rare occurrence has made it easier to come to terms with it.

5. Are there any other remarks you wish to make?

By taking part in this study it may help other people in the future to come to terms with their disability, and I think the study has been very worthwhile.

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

   Please comment: Yes. I was encouraged by the improvement reached by the 6th week.

2. Do you think that the study made any difference to your vision?

   Please comment: Only in making me realize that there is a possibility of using other parts of the peripheral retina with practice

3. Has your understanding of your eye problem changed?

   Please comment: as last comment.

4. Do you feel any differently about yourself or your eyes?

   Please comment: Not really. I'm still navigating well !!! reasonably optimistic & am

5. Are there any other remarks you wish to make?

Yes, it's jolly hard work !!!

I still slip into using the 1st exercise place automatically

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

   Please comment:
   my eyes feel more comfortable when trying to to read but the actual vision has not improved generally

2. Do you think that the study made any difference to your vision?

   Please comment:
   Slightly.

3. Has your understanding of your eye problem changed?

   Please comment:
   Yes.

4. Do you feel any differently about yourself or your eyes?

   Please comment:
   No - just as frustrated.

5. Are there any other remarks you wish to make?

   During the visit to the Hospital, I felt as though there was some benefit from the visit, but this seemed to fad at home, despite my attempts to repeat the advice given.

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

   Please comment: BY ATTENDING THE STUDY I AM ABLE TO READ BETTER BY LOOKING STRAIGHT AT THE PRINT

2. Do you think that the study made any difference to your vision?

   Please comment: THE STUDY HAS NOT CHANGED MY VISION

3. Has your understanding of your eye problem changed?

   Please comment: NO. I HAD MY PROBLEM EXPLAINED PREVIOUSLY BY A DOCTOR

4. Do you feel any differently about yourself or your eyes?

   Please comment: NO

5. Are there any other remarks you wish to make? NO

Thank you very much for participating in the study.

I would appreciate your comments on the study so that the structure of the training programme can be improved.

Please answer the following questions (truthfully!). To remain anonymous, do not put your name on the form.

Many thanks.

1. Do you feel that you have benefited from attending the study?

   Please comment: YES

2. Do you think that the study made any difference to your vision?

   Please comment: NO, but do realise that this is not possible in my case.

3. Has your understanding of your eye problem changed?

   Please comment: YES. I found the whole study course very interesting.

4. Do you feel any differently about yourself or your eyes?

   Please comment: Not really.

5. Are there any other remarks you wish to make?

   I am grateful that something has been attempted even if not successful.

Use of scrolled text in a scanning laser ophthalmoscope to assess reading performance at different retinal locations*

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(Received 16 July 1991, in revised form 20 September 1991)

A new technique is described for assessing reading performance using a scanning laser ophthalmoscope. Letters of different sizes and contrasts were projected onto specific retinal locations of normal and low vision observers. Successive letters were scrolled in a horizontal direction at different speeds through a 'window'. Throughout the experiments the subjects' fundus and the retinal location of the stimuli could be visualized. With this scanning laser ophthalmoscope text-scrolling computer program the subject does not search for adjacent letters, and because the eye is held relatively stationary the tedious eye movement analysis incurred in other studies is reduced. Five retinal areas were investigated in two normal observers. The percentage of letters correctly identified decreased with eccentricity, increased velocity of the text and reduced text contrast. The reading performance of two patients, one with age-related macular degeneration and the other with juvenile macular disease, was investigated. Decrements in performance were related to morphology of the lesions.

Age-related macular degeneration (ARMD) may cause permanent loss of vision[1]. In England during 1980/81, diseases of the macula and posterior pole were responsible for over 40% of new cases of registered blindness in individuals aged 65 and over[2]. The incidence of blindness in the general elderly population due to macular disorders may be even higher. No treatment is available for geographic atrophy associated with ARMD[3], and laser therapy is appropriate in only a minority of cases with the exudative form of ARMD[4,5]. When treatment is successful severe visual loss is temporarily suppressed, but the high recurrence rate of new vessel formation in approximately 50% of cases causes further deterioration within two years[4]. Therefore, the majority of individuals with macular disease rely on low vision services and social services to provide rehabilitation and support.

Patients with macular disease frequently request help with reading. This is an important daily task which becomes increasingly difficult if the condition progresses. Magnification and control of illumination are established rehabilitation techniques. Although they are beneficial in many cases, those patients who do not use optimally functioning retina will not maximize their visual potential. The scanning laser ophthalmoscope (SLO) technique described here may help in the identification of functioning retinal areas. If patients could be taught to use optimal areas proficiently, reading performance may be enhanced.

The SLO is a relatively new instrument with some unique features. Originally it was designed to image the ocular fundus using low light levels[6,7]. Further development has provided facilities to perform other procedures including angiography[8], tomographic analysis of the retina[9], measurement of eye rotations[10], densitometry[11], visually evoked potentials[12,13] and psychophysical testing[14–16]. For the latter, the main advantage is that the operator can see the retinal position of stimuli and thus study visual function in relation to retinal lesions while viewing a continuous and real-time television image of the fundus. A high degree of correlation of function with retinal location can be achieved because stimuli are seen concurrently with the retinal image, and subsequent analysis of video-recorded images allows compensation for eye movements. Therefore, scotomatous areas and fixation strategies can be investigated accurately and the visual potential of specific retinal loci can be assessed[14,15].

The purpose of our work was to use the SLO to investigate normal visual function of the fovea and parafovea. Further, we wished to identify functioning and non-functioning retinal areas in patients with loss of central vision, and to use the system to probe and define retinal locations which could be used for optimal reading performance.

We have developed a computer program which allows the operator to restrict text presentation to a defined retinal location. In this program visual stimuli of various sizes can be generated so that individuals with different acuity can be tested. The text can be varied from black to white so that the effects of negative and positive contrast can be investigated. Although a relatively

*Based on material presented at the Second International Conference on Laser Scanning Ophthalmoscopy, Boston, MA, USA, November 1990.

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extensive area of retina was constantly visualized, text was scrolled through a small 'window' within this area much like neon advertising displays. This facility is important in the measurement of reading speed at specific retinal locations, or in the determination of visual function at a location the patient would not normally choose. The angular speed of text movement through the window could be varied so that the effects of reading speeds could be investigated.

Materials and methods

Scanning laser ophthalmoscope

The principles of the optical system of SLOs have been described in detail elsewhere[17,18]. For our work, a Rodenstock (Ottobrun, Germany) prototype SLO incorporating a helium–neon laser (633 nm) was modified by the addition of an infrared diode laser (Sharp Corporation, Osaka, Japan, LT-021MD, 782 nm, 20 μW)[19]. Images of the fundus using the He–Ne laser at the chosen background levels were of low contrast, and to view an image of high contrast the fundus was scanned simultaneously with both the IR and the He–Ne lasers. The IR laser was not visible to the subjects at the intensities used.

The raster generated by both laser beams measured 15° vertically by 16° horizontally. The chosen background retinal irradiance of the He–Ne laser was 12 μW cm^{-2}. At no time were accepted maximum permissible exposures levels exceeded[20].

Visual stimuli

Any monochrome video graphics which can be displayed on a visual display unit (VDU) can be projected onto the fundus by modulating the He–Ne beam by means of an acousto-optic modulator (AOM). The AOM varies the intensity of the beam in response to electronic signals from an Acorn Archimedes (Cambridge, UK) computer with Wild Vision (Tyne and Wear, UK) frame grabber, thereby causing certain picture elements (pixels) in the raster to appear brighter or darker.

Two sorts of stimuli were used; relatively bright or dark letters on a constant background. These will be referred to as positive and negative contrast respectively. Contrast of the visual stimuli was calculated by[21]

$$\text{contrast} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

where L = luminance.

Although the letters presented in the SLO could range in size from 10 to 900 min arc, in these experiments the letters used were 30, 60 and 90 min arc. This size corresponds to both the vertical and horizontal dimension. Only the letters E, H, I, L, T, F, were used so that aliasing effects due to producing curved or diagonal lines in the raster were avoided. The sequence of letters was generated randomly. Each adjacent letter was separated by one character space of equivalent size, in an attempt to avoid the effects of the 'crowding phenomenon'[22] (*Figure 1*).

Text was presented in a window measuring 4.3° horizontally, the vertical dimension of which varied with the letter size. This window could be located anywhere within the raster under the direct control of the operator.

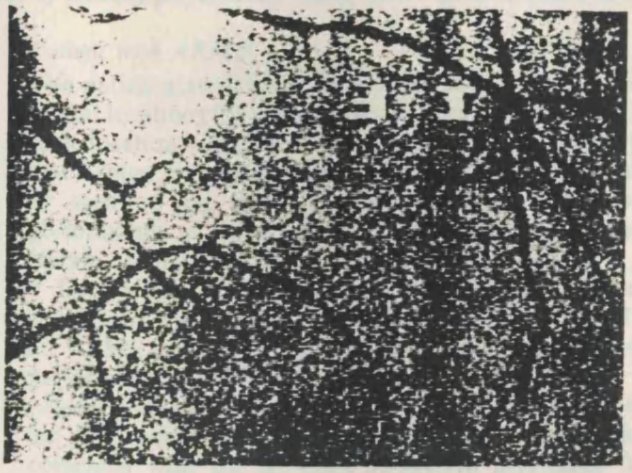

Figure 1 Scanning laser ophthalmoscope image showing the observer's fundus and the visual stimuli

Within the window, letters first appeared on the right and were scrolled through to the left. The angular velocity, or scrolling speed at the retina was varied from 0.74 to 3.8 deg s^{-1}. This represents 44 to 228 letters per min for letters of 30 min arc, and 22 to 114 letters per min for 60 min arc.

Subjects

The subjects were two ocularly normal female observers (25- and 32-years-old) both with Snellen acuity of 6/6, one male patient (75 years) with ARMD (longstanding disciform degeneration) with visual acuity of 3/60, and one female patient (35 years) with juvenile macular disease (fundus flavimaculatus) with visual acuity of 6/18.

Procedure

The non-test eye was patched. Once placed comfortably in the headrest, the subject was directed to fixate a stationary target. The sizes of the text in each experiment were determined for the subject by pilot measurements. A sequence of six letters was presented at each location. Subjects were required to read the letters aloud, paying attention to the accuracy rather than the speed of their response. They were encouraged to make a 'best guess' if they were unsure. The operator typed the responses into the computer, the data were printed at the end of the experiment and the percentage read correctly was calculated. At each location up to ten separate presentations were made to allow calculation of standard error of the mean.

Each of the two patients underwent one session of testing lasting approximately 2½ h. The investigation on the normal observers took 4–5 h in total and was spread over three sessions. Regular breaks during the testing period were necessary to prevent fatigue.

Results

Normal observers

Figure 2 shows the percentage of letters read correctly at five retinal locations displaced sequentially in 2° steps superior to the fovea. The letters were 30 min arc in size with a contrast of 55%. Two scrolling speeds were used; 1.5 and 3.8 deg s^{-1}.

The two individuals showed similar performance. At

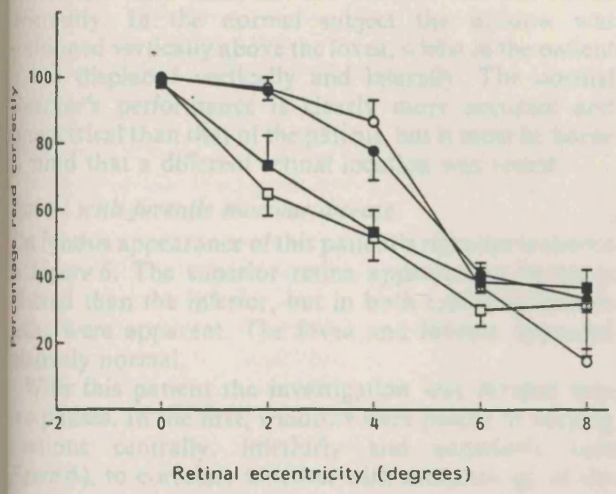

Figure 2 Percentage of letters read correctly at five superior retinal eccentricities by normal observers. Subjects D.W. = ●, ■; L.C. = ○, □; ○, ●, scrolling speed of 1.5 deg s^{-1}; □, ■, 3.8 deg s^{-1}. Letter size 30 min arc wih contrast of +55%

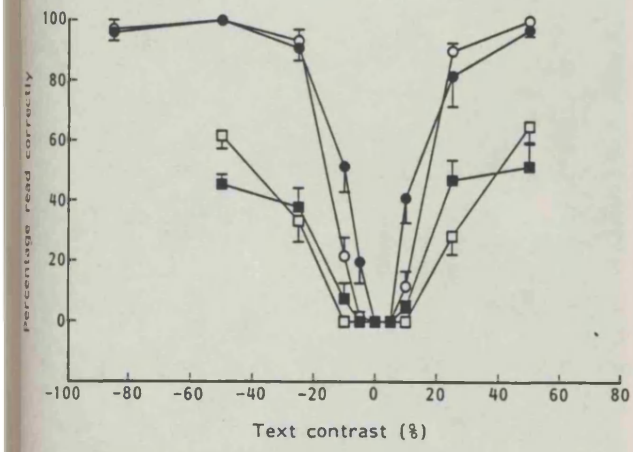

Figure 3 Percentage of letters of variable contrast read correctly by normal observers. Subjects D.W. = ●, ■; L.C. = ○, □; ○, ●, 2° retinal eccentricity; □, ■, 6°; Letter size 30 min arc; speed 1.5 deg s^{-1}

the fovea (i.e. 0 degrees retinal eccentricity) 100% of letters were read correctly, but visual performance declined rapidly with increasing eccentricity, falling to 50% at 5°. This pattern was more marked with the faster scrolling speed of 3.8 deg s^{-1}. For example, 4° from the fovea, less than 60% of letters were read correctly at the faster speed, but accuracy was over 80% with the slower speed. The latter speed was used for all subsequently experiments described here.

The effects of letter contrast at 2° and 6° eccentricity in the superior retina were investigated (*Figure 3*). The results from the two individuals were similar. At 55% contrast, either positive or negative, both observers attained 100% accuracy for letters presented at 2°, but only 45–60% accuracy at 6°. The location closer to the fovea allowed 90% accuracy to be maintained for contrasts above + and −25%. Below this contrast there was a rapid drop in visual performance. Within the range of contrasts we used, performance across the positive/negative contrasts appeared to be symmetrical.

Patient with ARMD

This patient stated that he commonly used three different retinal locations for various visual tasks. The position of each location was determined by asking the patient to read a letter in the SLO raster, the retinal area used could be seen on the monitor (see *Figure 4*). The visual performance of these locations was investigated using 90 min arc letters of variable contrast (*Figure 5*).

There was a small difference in performance, with area A allowing the best performance at +25%. Conversely, at −25% contrast all three locations provided poor performance. The identification of retinal area A (*Figure 5*) as the most appropriate area of the three tested for the specific visual task used in this experiment coincided with the patient's subjective preference for reading normal print with his optical magnifier.

To compare this patient's visual performance to that of a normal observer the experiment was repeated with a normal subject (*Figure 5*). The same stimulus

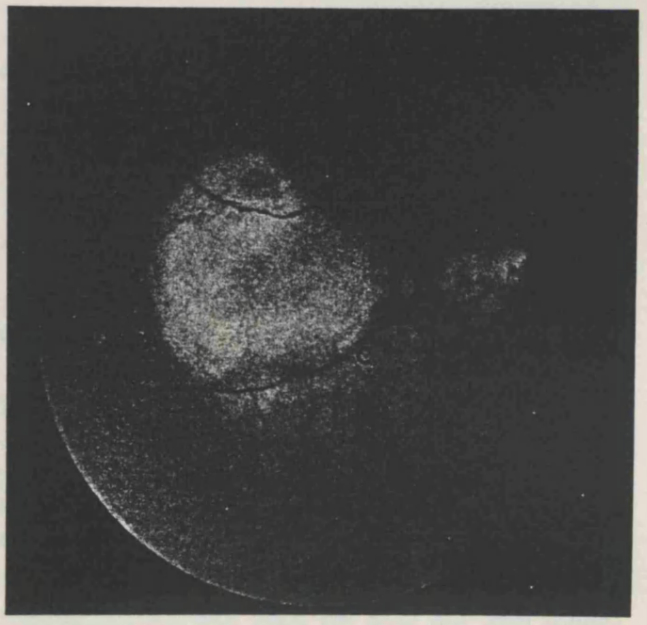

Figure 4 Fundus photograph of right eye of patient with age-related macular degeneration (patient D.B.). The retinal areas examined are labelled A, B and C

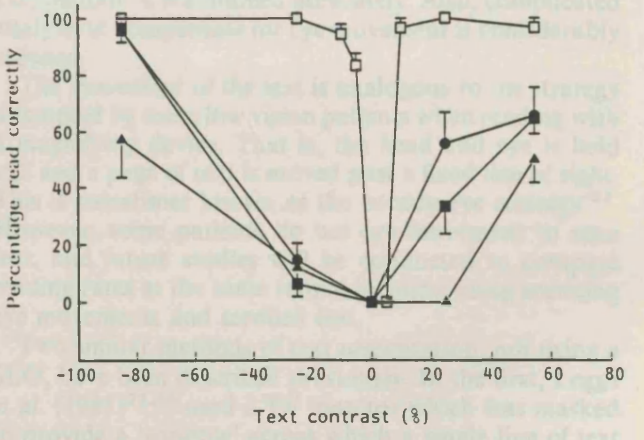

Figure 5 Percentage of letters of variable contrast read correctly by patient D.B. and normal observer. Retinal locations A = ●, B = ■, C = ▲; normal observer (6° eccentricity) = □; letter size 90 min arc; speed 1.5 deg s^{-1}

parameters were used, but the window was positioned differently. In the normal subject the window was positioned vertically above the fovea, whilst in the patient it was displaced vertically and laterally. The normal observer's performance is clearly more accurate and symmetrical than that of the patient, but it must be borne in mind that a different retinal location was tested.

Patient with juvenile macular disease

The fundus appearance of this patient's right eye is shown in *Figure 6*. The superior retina appeared to be more affected than the inferior, but in both typical yellowish flecks were apparent. The fovea and foveola appeared relatively normal.

With this patient the investigation was divided into two phases. In the first, windows were placed in varying locations centrally, inferiorly and superiorly (see *Figure 6*), to correlate function with morphology of the lesions. In the second, a more extensive investigation of foveal function using different letter contrast was undertaken. The results of phase one for a 60 min arc target are illustrated in *Figure 7*. A near-normal response

Figure 6 Fundus photograph of right eye of patient with juvenile macular disease (patient E.F.), showing the 0, 2, 4, 6, 8° locations examined

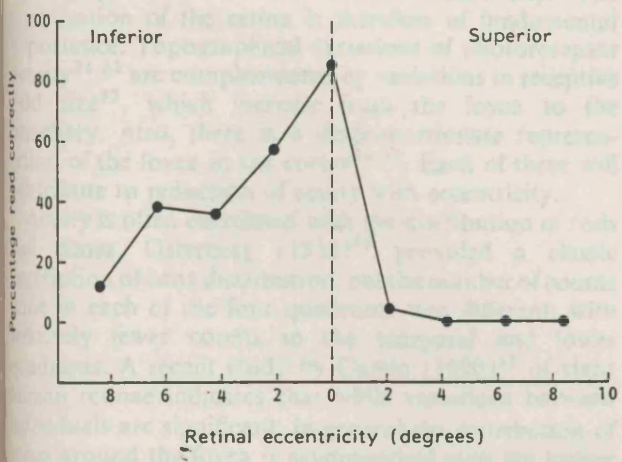

Figure 7 Percentage of letters read correctly at different retinal locations by patient E.F.; letter size 60 min arc; speed 1.5 deg s^{-1}

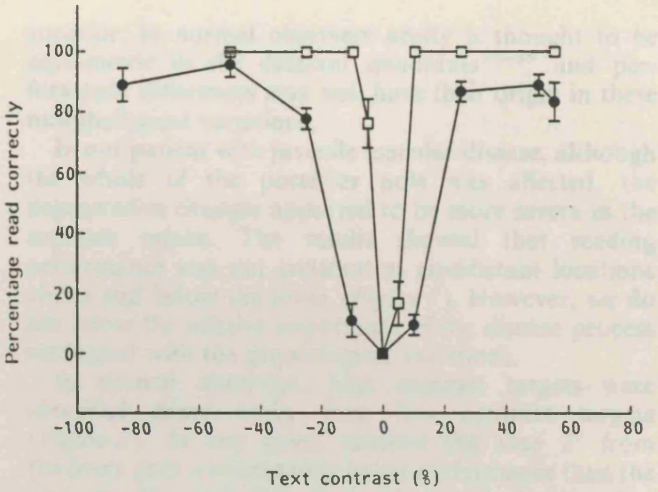

Figure 8 Percentage of letters of variable contrast read correctly by patient E.F. and normal observer using the fovea. E.F. = ●; normal observer = □; letter size 60 min arc; speed 1.5 deg s^{-1}

was demonstrated at the fovea while the retina below the fovea allowed considerably better performance than that above. For example, with the stimulus 2° inferiorly, 55% of letters were read correctly, but at 2° superiorly the accuracy was almost 0. The results of the second phase, for foveal function was illustrated in *Figure 8*. At this location, responses to positive and negative contrast appeared to be approximately symmetrical, however, when compared with those of a normal observer, the patient's responses appeared abnormal in the lower contrast range (i.e. + and −5 to 20%).

Discussion

Visual performance depends upon both the retinal location of the image and the nature of the image. In the following discussion, we will first review the stimulus, and then aspects of retinal location.

Stimulus

Reading performance using the SLO has been studied previously[16], but the work described here has, for the first time, used scrolled rather than stationary text. The scrolling feature of our text-generation program has a number of advantages. The subject does not search for adjacent letters and therefore the retinal area under examination is maintained accurately. Also, complicated analysis to compensate for eye movement is considerably reduced.

The movement of the text is analogous to the strategy attempted by some low vision patients when reading with a magnifying device. That is, the head and eye is held still and a page of text is moved past a fixed line of sight. This is sometimes known as the 'steady eye strategy'[23]. However, some patients do use eye movement to scan text, and future studies will be conducted to compare reading rates at the same retinal location using scanning eye movements and scrolled text.

Two similar methods of text presentation, not using a SLO, have been described previously. In the first, Legge *et al.* (1985)[21,24] used a TV monitor which was masked to provide a 'window' across which a single line of text was scanned horizontally. In the second, successive words were presented in the centre of a monitor while the eye

was held still by fixation, this is known as rapid serial visual presentation (RSVP)[25,26]. The SLO has advantages over both of these methods in that it enables the observer to see precisely where the text is positioned on the fundus, and, as seen in our results, retinal position is a crucial variable in reading performance.

For the series of experiments presented in this paper random sequences of capital letters were chosen as the test stimuli in preference to words. This allowed testing of basic letter recognition without the complication of higher cognitive functions necessary for reading. In future studies it is our intention to assess reading performance resulting from the presentation of both words and sentences.

Previous findings indicate that to maximize scrolled text reading speed, at least 4 characters should be presented within the window at any time[21], and in normal reading as many as 15 characters to the right of fixation are necessary[27]. Since a fundamental aspect of our investigation was probing differences in function of various small retinal areas, we deliberately limited the window to 4.3° in the horizontal dimension. This enabled us to present 4 letters of text 30 min arc in size, but only 2 letters at 60 min arc, and 1.5 at 90 min arc. Consequently the reading speeds of our subject may have been limited.

Two other parameters of the target influenced performance, scrolling speed (*Figure 2*) and contrast (*Figure 3*). In the case of the former, when letters were presented to the parafovea they became more difficult to identify at the faster speed. In normal subjects, no difference in performance was noted with the two scrolling speeds investigated in this study at the fovea. These results are similar to those of Legge[21] who found foveal reading accuracy remained constant up to a critical scan rate of approximately 250 words/min. Foveal reading performance only deteriorated at higher speeds (>300 words/min)[21]. Direct comparison of Legge's data with our own is limited by the fact that use of words in his study involved cognitive processes which may themselves increase reading speed. Target contrast is an important parameter since it may affect recognition in both the fovea and extrafovea[28], and contrast sensitivity is known to vary with age[29,30].

Position

In this and future studies we hope to be able to relate reading performance with retinal eccentricity. The organization of the retina is therefore of fundamental importance. Topographical variations of photoreceptor density[31,32] are complemented by variations in receptive field size[33], which increase from the fovea to the periphery. Also, there is a disproportionate representation of the fovea in the cortex[34,35]. Each of these will contribute to reduction of acuity with eccentricity.

Acuity is often correlated with the distribution of rods and cones. Osterberg (1935)[31] provided a classic description of cone distribution, but the number of counts done in each of the four quadrants was different, with relatively fewer counts in the temporal and lower quadrants. A recent study by Curcio (1990)[32] of eight human retinae indicates that while variations between individuals are significant, in general the distribution of cones around the fovea is asymmetrical with the higher densities being in the nasal compared with the temporal retina, and the midperipheral inferior compared with the superior. In normal observers acuity is thought to be asymmetric in the different quadrants[36–39] and performance differences may well have their origin in these morphological variations.

In our patient with juvenile macular disease, although the whole of the posterior pole was affected, the degenerative changes appeared to be more severe in the superior region. The results showed that reading performance was not constant at equidistant locations above and below the fovea (*Figure 7*). However, we do not know the relative importance of the disease process compared with the physiological variations.

In normal observers, high contrast targets were identified more easily than low contrast targets (*Figure 3*). At any given contrast the area 2° from the fovea gave a consistently better performance than the area at 6°, and this is in agreement with other findings that contrast sensitivity decreases with retinal eccentricity[28,40]. The patient with juvenile macular disease gave a near-normal response at the fovea to a high contrast 60 min arc target, but showed a severe decrement in function with a low contrast target of the same size (*Figure 8*).

Both of our low vision observers gave reduced performances for the text contrast experiments compared with the normal observer and this is consistent with previous observations[41]. However, in our experiments the normal and low vision observers were not age-matched, and some differences in performance may be related to light scatter in the ocular media, ageing changes in the retina[42–44] or higher visual centres[45].

Given the variation in both the type and extent of lesions in ARMD, it is difficult to compare functional results between individual cases. In our patient the retinal locations examined appeared normal, but they were immediately adjacent to a disciform lesion (and approximately 6° from the fovea), and may have been affected by the disease process. Thus poor contrast sensitivity could not definitely be ascribed to the eccentricity or the disease. In a group of 8 patients with ARMD a progressive loss of contrast sensitivity outside the normal range has been demonstrated[46] at 0, 2, 5 and 10°. Retinal function at greater eccentricities may be comparable to normal, as at least one study looking at functional parameters in the periphery has shown normal responses[47].

We found the responses to black or white letters on a background of fixed illuminance to be approximately symmetrical for the normal observers, and in agreement with the results of Legge[21]. Our patient with ARMD performed slightly better with positive contrast letters; this needs to be investigated further. The results presented here are for a limited number of subjects, but further planned studies will include more patients.

Conclusions

Our study has demonstrated the value of using scrolled text in a SLO to assess reading performance at various retinal loci, with the therapeutic aim of finding an optimal area and teaching the patient to use it effectively. The results show that there may be considerable gain in doing this.

The aim of this work was to develop a technique for quantitative assessment of reading performance using the SLO. Our results demonstrate that basic performance of

isolated retinal areas can be evaluated using visual stimuli or various sizes and contrasts.

It is hoped that further probing of visual function in patients with central field defects will ultimately provide the facility for optimizing their reading potential.

Acknowledgements

We gratefully acknowlege the financial support of the Royal National Institute for the Blind. We would like to thank the Eye Research Institute, Boston, MA, USA for the use of their software during our initial studies, and Mrs A. Patmore for technical assistance.

This work is in part fulfilment of a PhD degree for the University of London by L. E. Culham.

References

1. Lovie-Kitchin J. E., Farmer, E. J. and Bowman, K. J. *Senile Macular Degeneration: the Effects and Management*. Department of Optometry, Queensland Institute of Technology, Australia (1982).
2. DHSS. *Causes of Blindness and Partial Sight among Adults in 1976/77 and 1980/81, England*. HMSO, London, UK (1988).
3. Bressler N. M., Bressler, S. B. and Fine, S. L. Major review: age-related macular degeneration. *Surv. Ophthalmol.* **32**, 375–413 (1988).
4. The Moorfields Macular Study Group. Treatment of senile disciform macular degeneration: a single-blind randomised trial by argon laser photocoagulation. *Br. J. Ophthalmol.* **66**, 745–753 (1982).
5. Macular Photocoagulation Study Group. Argon laser photocoagulation for senile macular degeneration. Results of a randomized clinical trial. *Arch. Ophthalmol.* **100**, 912–918 (1982).
6. Webb, R. H., Hughes, G. W. and Pomerantzeff, O. Flying spot TV ophthalmoscope. *Appl. Opt.* **19**, 2991–2997 (1980).
7. Webb, R. H. and Hughes, G. W. Scanning laser ophthalmoscope. *IEEE Trans. Biomed. Eng.* **BME-28**, 488–492 (1981).
8. Gabel, V. P., Birngruber, R. and Nasemann, J. Fluorescein angiography with the scanning laser ophthalmoscope (SLO). *Lasers and Light in Ophthalmol.* **3**, 35–40 (1988).
9. Bartsch, D. U., Intaglietta, M., Bille, J. F., Dreher, A. W., Gharib, M. and Freeman, W. R. Confocal laser tomographic analysis of the retina in eyes with macular hole formation and other focal macular disease. *Am. J. Ophthalmol.* **108**, 277–287 (1989).
10. Ott, D. and Lades, M. Measurement of eye rotations in three dimensions and retinal stimulus projection using scanning laser ophthalmoscopy. *Ophthal. Physiol. Opt.* **10**, 67–71 (1990).
11. van Norren, D. and van de Krassts, J. Imaging retinal densitometry with confocal scanning laser ophthalmoscope. *Vision Res.* **29**, 1825–1830 (1989).
12. Le Gargasson, J. F., Lamare, M., Rigaudiere, F., Corno, F., Grall, Y., Charlier, J. and Simon, J. Scanning laser ophthalmoscope and visually evoked potentials. *J. Med. Nucl. Biophys.* **13**, 343–354 (1989).
13. Katsumi, O., Timberlake, G. T., Hirose, T., Van de Velde, F. J. and Sakaue, H. Recording pattern reversal visual evoked response with the scanning laser ophthalmoscope. *Acta Ophthalmol.* **67**, 243–248 (1989).
14. Timberlake, G. T., Mainster, M. A., Webb, R. H., Hughes, G. W. and Trempe, C. L. Retinal localization of scotomata by scanning laser ophthalmoscopy. *Invest. Ophthalmol. Visual Sci.* **22**, 91–97 (1982).
15. Timberlake, G. T., Mainster, M. A., Peli, E., Augliere, R. A., Essock, E. A. and Arend, L. E. Reading with a macular scotoma. I. Retinal location of scotoma and fixation area. *Invest. Ophthalmol. Visual Sci.* **27**, 1137–1147 (1986).
16. Timberlake, G. T., Peli, E., Essock, E. A. and Augliere, R. A. Reading with a macular scotoma. II. Retinal locus for scanning text. *Invest. Ophthalmol. Visual Sci.* **28**, 1268–1274 (1987).
17. Plesch, A. and Klingbeil, U. Optical characteristics of a scanning laser ophthalmoscope. *SPIE* **1161**, 390–398 (1989).
18. Woon, W. H., Fitzke, F. W., Chester, G. H., Greenwood, D. G. and Marshall, J. The scanning laser ophthalmoscope. Basic principles and applications. *J. Ophthalmic Photography* **12**, 17–23 (1990).
19. Fitzke, F. W., Woon, H., Timberlake, G. Robinson, L., Marshall, J. and Bird, A. C. Optical modifications to a scanning laser ophthalmoscope for high magnification, narrow optical imaging. *Lasers and Light in Ophthalmol.* **4**, 7–14 (1991).
20. British Standards Institution. BS 4803: Part 3 (1983).
21. Legge, G. E., Pelli, D. G., Rubin, G. S. and Schleske, M. M. Psychophysics of reading. I. Normal vision. *Vision Res.* **25**, 239–252 (1985).
22. Rubinstein, M. P. and Underwood, J. The crowding phenomenon and its significance in senile macular degeneration. *Br. Orthopt. J.* **42**, 45–53 (1985).
23. Collins, J. Coping with the rising incidence of partial sight. *Optom. Today* **27**, 772–779 (1987).
24. Legge, G. E., Rubin, G. S., Pelli, D. G. and Schleske, M. M. Psychophysics of reading. II. Low vision. *Vision Res.* **25**, 253–266 (1985).
25. Turano, K. and Rubin, G. S. Reading performance with peripheral viewing using rapid serial visual presentation. *Optical Society of America Topical Meeting on Noninvasive Assessment of the Visual System, 1988. Technical Digest Series* **3**, 192–195 (1988).
26. Rubin, G. S. and Turano, K. Normal and low vision reading using rapid serial visual presentation. *Invest. Ophthalmol. Visual Sci.* **31(Suppl)**, 599 (1990).
27. Rayner, K., Well, A. D. and Pollatsek, A. Asymmetry of the effective visual field in reading. *Percept. Psychophysics* **27**, 537–544 (1980).
28. van Nes, F. L. and Jacobs, J. C. The effect of contrast on letter and word recognition. *IPO Annual Progress Report* **16**, 72–80 (1981).
29. McGrath, C. and Morrison, J. D. The effects of age on spatial frequency perception in human subjects. *Quart. J. Exper. Physiol.* **66**, 253–261 (1981).
30. Greene, H. A. and Madden, D. J. Adult age differences in visual acuity, stereopsis, and contrast sensitivity. *Am. J. Optom. Physiol. Opt.* **64**, 749–753 (1987).
31. Osterberg, G. Topography of the layer of rods and cones in the human retina. *Acta Ophthalmol.* **13**, 1–103 (1935).
32. Curcio, C. A., Sloan, K. R., Kalina, R. E. and Hendrickson, A. E. Human photoreceptor topography. *J. Comp. Neurol.* **292**, 497–523 (1990).
33. Curcio, C. A. and Allen, K. Topography of gangion cells in human retina. *J. Comp. Neurol.* **300**, 5–25 (1990).
34. Cowe, A. and Rolls, E. T. Human cortical magnification factor and its relation to visual acuity. *Exp. Brain Res.* **21**, 447–454 (1974).
35. Virsu, V., Rovamo, J., Laurinen, P. and Nasanen, R. Temporal contrast sensitivity and cortical magnification. *Vision Res.* **22**, 1211–1217 (1982).
36. Wertheim, T. H. Uber die indirekte Sehscharfe. *Ztschr. Psychol. Physiol. Sinnesorg.* **7**, 172 (1894).
37. Millodot, M. and Lamont, A. Peripheral visual acuity in the vertical plane. *Vision Res.* **14**, 1497–1498 (1974).
38. Weymouth, F. W., Hines, D. C., Acres, L. H., Raaf, J. E. and Wheeler, M. C. Visual acuity within the area centralis and its relation to eye movements and fixation. *Am. J. Ophthalmol.* **12**, 947–960 (1928).
39. Timberlake, G. T., Peli, E. and Augliere, R. A. Visual acuity measurements with a second generation scanning laser ophthalmoscope. *Optical Society of America Topical Meeting on Noninvasive Assessment of Visual System, 1987. Technical Digest Series* **5**, 4–7 (1987).
40. Rijsdijk, J. P., Kroon, J. N. and van der Wildt, G. J. Contrast sensitivity as a function of position in the retina. *Vision Res.* **20**, 235–241 (1980).
41. Lovie-Kitchin, J. E. High contrast and low contrast visual acuity in age-related macular degeneration. *Clin. Exp. Optom.* **72**, 79–83 (1989).
42. Marshall, J. The ageing retina: physiology or pathology. *Eye* **1**, 282–295 (1987).
43. Cerella, J. Age-related decline in extrafoveal letter perception. *J. Gerontol.* **40**, 727–736 (1985).
44. Johnson, C. A., Adams, A. J. and Lewis, R. A. Evidence for a neural basis of age-related visual field loss in normal observers. *Invest. Ophthalmol. Visual Sci.* **30**, 2056–2064 (1989).
45. Weale, R. A. *A Biography of the Eye*. Lewis, London, UK, pp. 255–263 (1982).
46. Brown, B. and Lovie-Kitchin, J. Contrast sensitivity in central and paracentral retina in age-related maculopathy. *Clin. Exp. Optom.* **70**, 145–148 (1987).
47. Sunness, J. S., Massof, R. W., Johnson, M. A., Finkelstein, D. and Fine, S. L. Peripheral retinal function in age-related macular degeneration. *Arch. Ophthalmol.* **103**, 811–816 (1985).

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Clin. Vision Sci. Vol. 8, No. 6, pp. 551–561, 1993

0887-6169/93 $6.00 + 0.00

ASSESSMENT OF FIXATION STABILITY IN NORMAL SUBJECTS AND PATIENTS USING A SCANNING LASER OPHTHALMOSCOPE

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(Received 5 April 1993; in revised form 7 October 1993)

Summary—1. In this study we have investigated the ability of normal and low vision subjects to (a) fixate stationary targets and (b) to maintain fixation on a stationary target while text was scrolled at different retinal locations.

2. Test stimuli were visualized directly on the fundus with the scanning laser ophthalmoscope (SLO), and relative eye movements were evaluated using digitized images. Target arrays consisted of single and multiple letters which were either stationary or scrolled in a horizontal direction. The retinal area selected by the subject to view the target was determined, and the stability of fixation calculated as a bivariate contour ellipse area (BCEA).

3. The ability to maintain steady fixation varied between individuals; this variability was particularly notable in the low vision patients. In the normal group, fixation was affected by the size of the stationary target but not by the form or polarity. In both the normal and patient groups stationary targets allowed more accurate fixation compared to scrolling text. The speed of scrolling text and the retinal location did not influence fixation stability.

Key words—Scanning laser ophthalmoscope; fixation stability; low vision; preferred retinal location.

INTRODUCTION

The primary aim of this study was to investigate the potential of the scanning laser ophthalmoscope (SLO) for the visual rehabilitation of low vision patients. In particular we were interested in exploring the possibility of improving the reading performance of patients with macular disease and decreased central vision. Macular disease is the major cause of visual disability in developed countries (Swann and Lovie-Kitchin, 1990; Department of Health and Social Security, 1988) and with an aging population in the west the number of sufferers is increasing (RNIB, 1984). Clinical intervention is appropriate and successful in only a limited number of cases (Moorfields Macular Study Group, 1982; Macular Photocoagulation Study Group, 1982). A large number of patients are untreatable and even those treated may ultimately lose foveal function (Macular Photocoagulation Study Group, 1989), hence there is a need to utilize fully the residual vision. Popular rehabilitation methods attempt to improve the retinal image by means of magnification and control of illumination, but ignore the fact that the image may not be at the optimal retinal locus. Such loci should not only be capable of useful acuity but also of fixating and stabilizing a desired image. The present study attempted to investigate fixation stability using different targets in normal subjects and low vision patients.

Even when a normal subject attempts to fixate the eyes are in constant motion as a result of small eye movements (Yarbus, 1967). Such movements can be categorized into three main types (Ditchburn, 1973a): (1) "drifts", periods of fairly slow movement of median amplitude 2–5 min arc; (2) saccades (flicks), occasional sharp movements usually <10 min arc; (3) tremor, small irregular oscillatory movements of amplitude of 1 min arc or less. Drifts and saccades determine the accuracy of fixation since they produce larger movements than tremor. In low vision subjects fixation stability is usually less good than in normals (Timberlake *et al.*, 1986; Whittaker *et al.*, 1988) and a detailed assessment of this function is helpful

because without a reasonably stable image reading ability is compromised.

Fixation has been studied previously, but mainly using stationary disk-type (Steinman, 1965; Rattle, 1969; Sansbury *et al.*, 1973) or square (Kosnik *et al.*, 1986) target arrays, cross targets (Alder and Fliegelman, 1934; Nachmias, 1959; Schuchard and Raasch, 1992), vernier hyper-acuity targets (Lakshminarayanan *et al.*, 1992) or single letters (Whittaker *et al.*, 1988). The present study was designed to examine the quality of fixation at various retinal locations in both normal and low vision subjects using a variety of visual stimuli. This investigation was divided into three parts. The first part was designed to study the effect of the size and form of a target array on fixation. Stationary targets were used to identify the retinal locations that individual subjects routinely utilize for fixation. The subjects' ability to hold the eye steady using the preferred retinal location (PRL, i.e. the area that the patient chooses to utilize) was assessed. In the second part of the experiment alternative retinal locations (ARLs, i.e. areas that are not the patient's first choice) were investigated in selected patients. The third part of the experiment was designed to determine the effect of moving, textual stimuli on fixation stability and the variation in stability when the text was scrolled at different retinal locations. Since our objective was to improve understanding of reading performance in low vision patients the stimuli chosen for this study were related to reading: a single letter, a Snellen E; a fixation cross embedded in capital letters; a fixation cross (for comparison); a "grid" pattern of letters and scrolling capital letters.

Scrolled text in a SLO has been used to assess reading performance at different retinal locations (Culham *et al.*, 1992) and has the advantage that the subject is not required to make voluntary saccadic eye movements in order to read successive letters. However, fixation stability is important because the text must be maintained at the required retinal location. By measuring excursions of the PRL some indication of the area of retina being utilized to interpret scrolled letters can be determined.

The SLO is a useful instrument for psychophysical experiments such as this because the investigator can monitor the subject's visual behaviour by viewing the test stimuli on the continuous real-time image of the monocular fundus (Mainster *et al.*, 1982; Timberlake *et al.*, 1987). The stimuli, which can be located precisely on the fundus, can be altered in character, size, contrast and velocity such that residual function of the retina can be determined.

METHOD AND MATERIALS

Scanning laser ophthalmoscope

The optical principles and operational characteristics of SLOs have been described previously (Webb *et al.*, 1980; Webb and Hughes, 1981; Plesch and Klingbeil, 1989; Woon *et al.*, 1990). In this study a Rodenstock prototype SLO, employing a helium–neon (He–Ne, 633 nm) laser as the primary source, was used. The system had been modified by the addition of an infrared diode (IR, 792 nm) laser. The IR laser allowed high contrast images of the subject's fundus to be acquired while the subject viewed a dim, red raster. The He–Ne laser produced the visual stimuli ranging in contrast from -90 to $+90\%$ on the dim IR background. Even with both lasers operating the irradiance falling upon the retina never exceeded maximum permissible exposure limits (BSI Standards, 1992).

The SLO laser beam raster was calibrated by projecting it onto a diffuse reflecting surface and measuring the angular subtence at 1 m. The raster measured 19 × 14 deg and each pixel (picture element) represented 4 min arc in the horizontal and 3 min arc in the vertical.

Visual stimuli

Visual stimuli were produced by modulation of the He–Ne beam via an acoustooptic modulator which was controlled by an Acorn Archimedes computer. The contrast of the stimuli was calculated using the Michelson definition (Michelson, 1927)

$$\text{contrast} = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

where L_{max} and L_{min} are the maximum and minimum luminance values respectively. In the contrast value, a minus sign referred to black (negative) stimuli on a fixed background whereas a plus sign referred to bright (positive) stimuli on the same background. The IR laser luminance was not included in this calculation because of its low visual efficiency.

The stimuli could be placed anywhere within the SLO raster under the direct control of the operator. With low contrast targets it was often difficult to discriminate the stimuli against the background image of the fundus and as a result we developed a second method of positioning

the stimuli by means of a calibrated grid on the computer screen. A cursor on the TV monitor allowed location of retinal features on the grid which was calibrated in degrees in the horizontal and vertical meridians. The stimuli were positioned at the appropriate retinal location by reference to the grid.

In the case of scrolling text, the stimuli were presented within a small portion of the raster, termed the "window". The method of using a window to control the extent of the text presented was similar to the technique described by Legge *et al.* (1985a) whereby a TV monitor was masked to provide windows of different sizes. In this study the window was 4.5 deg horizontally and the vertical dimension varied with the size of text. The size of the window limited the area of retina used and was important in discriminating function at specific locations.

Fixation

To examine fixation stability we acquired images of the subjects' fundus throughout a period of fixation of 7.5 s. In all subjects there was sufficient contrast in these images that retinal features such as blood vessels could be used as landmarks for comparison between images. Images were stored on video tape (sVHS) and sample images were acquired by means of a Wild Vision frame grabber and digitized by the computer. Images were digitized in sequence of 44 images at a rate of 6 per s. Of these the first 32 frames of good quality, e.g. unaffected by blinks, were used. Thus 5.5 s of fixation were sampled. One image of the sequence, usually the first, was taken as a "master", to which the other images were manually aligned by the operator using the computer mouse to superimpose prominent features. This alignment procedure was achieved using the "flicker method" in which the master image and the image to be aligned were presented on the monitor alternately at a frequency of 11 frames/s. In the manner of a flick cartoon, movement was seen in misaligned images, whereas correct alignment resulted in a stationary picture.

Hence registration of the digitized images resulted in measurements of image mismatch on both the X- and Y-axes which were recorded in pixels. With care it was possible to align the fundus images to within 1 pixel. In order to determine the repeatability of these measurements one sequence of images was aligned three times on one day and once again 4 weeks later. The range of mean pixel values of X and Y varied by 0.13 and 0.43 respectively. One pixel in the digitized image represented $19 \times 14\ \mu m$ on the retina.

The X, Y values provided the measurement of eye movement and these were used to calculate the bivariate contour ellipse area (BCEA) (Steinman, 1965; Ditchburn, 1973a; Timberlake *et al.*, 1986), which allowed comparison of our data with existing literature. The BCEA is a two-dimensional ellipse which describes the portion of retinal surface within which the centre of the target was imaged 68% of the time, and it is expressed in min arc^2. The standard deviations of the eye positions in the horizontal and vertical meridians were also calculated. The BCEA statistic is appropriate only in cases of unimodal distribution. In the present study, measurements for each subject related to a single retinal locus. This was confirmed by observing the subject's fundus throughout testing.

The shape and orientation of the bivariate contour ellipse, as shown on the graphs in the Results, depended upon the type of eye movements that occurred while the subject was maintaining fixation. The angle of the ellipse was defined as the orientation of the major axis and its description was limited to a positive value ranging from 0 to 180 deg. If the horizontal and vertical eye movements were identical in size and frequency then the ellipse would appear circular. However, if the observer made large horizontal scanning movements when reading the scrolling text then the ellipse would be extended horizontally. Similarly, if vertical eye movements were predominant, e.g. during letter recognition of a large target, then the ellipse would be vertically orientated.

The BCEAs were analysed using the t-test and analysis of variance (ANOVA) with multifactorial structure. As the data set was unbalanced the ANOVA required adjustment (Montgomery, 1984).

Procedure

The subject was positioned in a headrest specifically designed to minimize head movement.

Experiment I

This experiment was designed to investigate the influence of target form and size on fixation stability.

The fixation stability of four normal and seven low vision subjects were studied using the following visual stimuli.

(i) "Basic" Snellen E. For normal subjects the letter size was 20 min arc, for low vision patients the basic size (i.e. minimum resolvable) varied up to 80 min arc.
(ii) Enlarged Snellen E. This was larger than the basic E by a factor of 2, 4 or 8 and was used to study the effect of a larger stimulus on the fixation stability.
(iii) Fixation cross embedded in letters, e.g. TH + LH. This target was used to investigate the effect of contrast and texture around the fixation point.

For each individual, the size and contrast (both positive and negative) of the basic Snellen E and the embedded cross were selected such that the targets were easily recognized.

The PRL was determined by asking the subject to fixate the stimulus. The operator then observed the retinal location of the stimulus on the fundus image displayed on the TV monitor.

This experiment was completed on two separate occasions on subject CJ.

In addition, eight normal observers were studied using targets of negative contrast only.

(i)–(iii) as above.
(iv) A single cross, i.e. +, sized 20 min arc.
(v) Multiple Hs (five horizontally by five vertically) extending 100 × 100 min arc with a fixation cross in the centre, i.e. a grid pattern.

All subjects were directed to "watch the target carefully and steadily".

Experiment II

This experiment investigated fixation stability in patients who were not permitted to utilize their PRL.

In four patients (JW, AA, DB and KA) a series of further observations were made, using targets (i) or (iii) above, in that they were encouraged to fixate with ARLs either of their own choice or determined by the investigator.

Experiment III

This experiment investigated subjects' ability to maintain fixation in the presence of moving text.

In the third part of the experiment the stimuli were scrolled horizontally through a window and four retinal locations were examined. Subjects were directed to hold fixation on a small (10 min arc) stationary fixation target within the SLO raster while sequences of random letters were scrolled at the fovea, and 2, 4 and 6 deg superiorly. In practice, those patients with gross central scotomas were unable to locate the small fixation target. This group were instructed to fix their gaze on an alternative fixation target that was the smallest they could see.

In the first set of measurements both positive and negative contrast text was used and the velocities were 0.6, 1.1 and 1.7 deg/s (these are referred to as speed 1, 2 and 3 respectively). After analysis of these data, a group of normal observers were examined with negative stimuli with velocities of 0.6, 1.7 and 4.4 deg/s (i.e. speeds 1, 3, 4).

In a previous study we have addressed accuracy of letter recognition by instructing subjects to read text aloud (Culham *et al.*, 1992). This technique invokes greater fixation variability. Hence, in the present study subjects were required to attend to the letters as they were scrolled at different retinal locations but no attempt was made to quantify the accuracy of letter recognition.

Subjects

Twelve observers with no known ocular problems and seven patients with macular disease were examined (Table 1).

Table 1. Summary of subjects' details

Subject age/gender	Eye tested	VA	Condition
Normals			
CJ/36/M	R	6/6	
CL/28/M	R	6/6	
PK/51/F	R	6/6	
EM/27/F	R	6/6	
DS/32/M	R	6/6	
IM/32/M	R	6/6	
AP/27/F	R	6/6	
JS/71/M	R	6/6	
PJ/33/M	R	6/6	
AM/58/M	R	6/6	
DD/59/M	R	6/6	
AJ/25/F	R	6/6	
Patients			
EF/35/F	L	6/18	Fundus flavimaculatus
JW/72/F	R	6/60	Geographic atrophy
AA/61/M	L	6/60	Atypical Stargardt's
DB/75/M	R	3/60	Disciform degeneration
NH/35/M	R	6/60	Bull's Eye maculopathy
HW/61/M	R	6/9	Neovascular membrane
KA/68/M	L	6/12	Macular hole

M, male; F, female, R, right eye; L, left eye.

Table 2. Experiment I—averaged fixation stability data for 12 normal subjects viewing different stationary target arrays

Target	Letter size (min arc)	Contrast (%)	SD (H)	SD (V)	BCEA
E	20	−25	6	4	183
E	20	+25	4	4	116
E	160	−25	8	6	350
E	160	+25	7	7	343
TH + LH	20	−25	4	3	102
TH + LH	20	+25	5	5	152
+	20	−25	4	3	81
Grid	100	−25	5	3	116

SD, standard deviation of horizontal (H) or vertical (V) eye movements.

RESULTS

Experiment I

Averaged results from all the normal subjects are shown in Table 2; individual patient results are shown in Table 3.

There was a large inter-subject variability (F-test), both within the normal group and between patients. In the normal group the fixation stability varied unsystematically for older and younger subjects, therefore it did not appear to correlate with age. The measurements on CJ were repeated on two separate occasions but the small improvement in fixation stability demonstrated in the second sitting was not statistically significant (t-test; $P > 0.05$).

In normal subjects the enlarged Snellen E (up to 160 min arc) induced significantly less stable fixation compared with the basic sized E of 20 min arc (F-test, $P = 0.012$). The results for the single fixation cross, fixation cross embedded in letters and the grid pattern were not significantly different compared with the basic E (t-test; $P > 0.05$).

In normal subjects the standard deviation of horizontal eye position during fixation was significantly greater than the standard deviation of vertical eye position (t-test; $P < 0.01$). The polarity of contrast of the targets had no significant effect on the fixation stability of either normal subjects or patients (t-test; $P > 0.05$).

Table 3. Experiment I—fixation stability data of low vision patients viewing stationary targets

Target	Retinal location (deg/clock position)	Letter size (min arc)	Contrast magnitude	SD (H)	SD (V)	Angle (deg)	BCEA
EF (fundus flavimaculatus)							
E	Fovea	80	80	7	6	27/12	346
TH + LH	Fovea	80	80	5	4	180/140	101
JW (geographic atrophy)							
E	2 5	80	50	16	6	167	495
TH + LH	2 5	80	50	11	8	154	603
AA (atypical Stargardts)							
TH+	6 12	80	95	41	46	87	13367
DB (disciform degeneration)							
E	6 3	80	50	13	4	161/171	261
E	6 3	160	50	8	3	169/161	146
TH+	6 3	80	50	9	7	121/171	322
NH (Bull's Eye maculopathy)							
E	6 11	40	50	11	12	26/92	900
E	6 11	80	50	11	21	74/79	1744
TH + LH	6 11	80	50	7	17	76/95	693
KA (macular hole)							
E	Fovea	40	50	7	3	160/3	134
TH + LH	Fovea	60	50	8	4	9/168	206
HW (neovascular membrane)							
E	Fovea	40	25	8	4	155/3	168
E	Fovea	80	25	6	5	97/10	185
TH + LH	Fovea	40	25	3	4	45/107	68

Retinal location of the PRL is described in terms of degrees from the foveola in a clockface position. Angle of ellipse is described in degrees for the negative/positive targets.

Table 4. Experiment II—fixation stability data of patients using ARLs for viewing stationary targets

Target	Retinal location (deg/clock position)		Letter size (min arc)	Contrast magnitude	SD (H)	SD (V)	Angle (deg)	BCEA
JW (geographic atrophy)								
E	2	12	80	50	28	15	179	2888
AA (atypical Stargardts)								
TH+	6	2	80	95	70	33	172	15903
DB (disciform degeneration)								
E	6	10	80	50	5	7	105/52	192
E	6	2	80	50	10	4	157/166	177
E	6	10	160	50	6	8	130/89	251
E	6	2	160	50	17	3	175/178	330
TH+	6	10	80	50	5	4	123/176	128
TH+	6	2	80	50	13	3	173/8	238
KA (macular hole)								
E	3.5	12	40	50	22	12	164/150	1114

Retinal location of the ARL is described in terms of meridian and degrees from the foveola. Angle of ellipse is described in degrees for the negative/positive targets.

All normal subjects used the foveola to fixate the targets. Patients EF, KA and HW used the residual elements of their foveas for viewing, whereas patients JW, AA, DB, and NH utilized a non-foveal PRL.

Experiment II

Fixation stability using the ARLs (Table 4) was equivalent or notably worse when compared with the PRL.

Experiment III

Averaged BCEAs for normal subjects viewing scrolled text are shown in Table 5 and results for individual patients are shown in Table 6.

A typical example of BCEAs for a normal subject is shown in Fig. 1; examples of patients with relatively poor and good fixation stability are shown in Figs 2 and 3. In each figure four bivariate contour ellipses are shown; one of these ellipses (A) is for a stationary Snellen E target. This ellipse is included to demonstrate changes in relative size and orientation of the other three ellipses (e.g. 1, 2, 3) which represent the increasing scrolling speeds.

In both the normal and patient groups the best fixation was achieved with the stationary targets ($P < 0.001$). Using ANOVA, the speed of the text did not significantly affect the fixation stability ($P > 0.05$); neither did the retinal position of the presented stimuli ($P > 0.05$). There was no significant difference between the horizontal and vertical standard deviations for any of the four speeds ($P > 0.05$).

In our patient group, each individual had a different condition, consequently there was no systematic variation between subjects in size or orientation of the ellipses at different speed. For

Table 5. Experiment III—averaged fixation stability data for normal subjects viewing scrolled stimuli of speeds 1, 2, 3 and 4 at different retinal locations

Retinal location (deg)	Speed 1 BCEA	Speed 2 BCEA	Speed 3 BCEA	Speed 4 BCEA
Fovea	277	239	328	408
2	515	942	456	718
4	669	249	592	1432
6	368	194	475	1651

Contrast −25%; letter size 20 min arc.

Table 6. Experiment III—fixation stability of individual patients viewing scrolled stimuli of speeds 1, 2 and 3 at different retinal locations

Retinal location (deg)	Speed 1 BCEA	Speed 2 BCEA	Speed 3 BCEA
EF (fundus flavimaculatus)			
Contrast −85/+75%; letter size 80 min arc			
Fovea	1195	3048	3724
2	1818	690	380
4	810	1189	1093
6	2401	413	606
NH (Bull's Eye maculopathy)			
Contrast ±50%; letter size 60 min arc			
Fovea	2651	5626	806
2	3749	6094	1576
4	15699	10249	4817
6	2587	2791	3706
KA (macular hole)			
Contrast ±90%; letter size 80 min arc			
Fovea	251	423	256
2	182	259	262
4	203	253	505
6	358	723	265
HW (subretinal neovascular membrane)			
Contrast ±25%; letter size 40 min arc			
Fovea	111	214	174
2	208	101	166
4	275	89	133
6	355	447	227

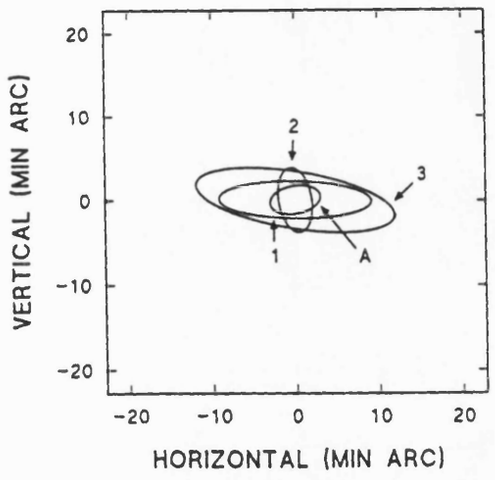

Fig. 1. Graph showing a typical example of fixation stability of normal subject for negative targets which are stationary (A) and scrolling at speeds 1, 2 and 3.

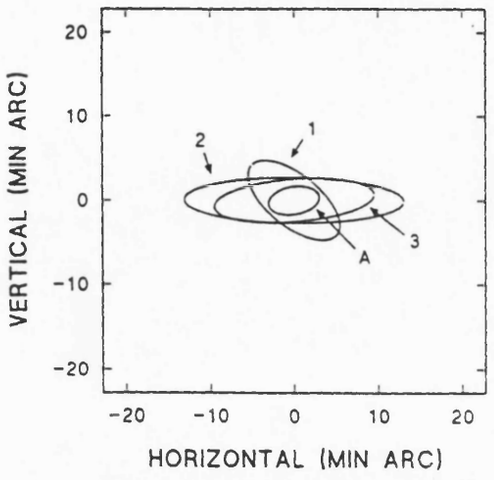

Fig. 3. Graph showing the relatively good fixation stability of patient KA for negative targets which are stationary (A) and scrolling at speeds 1, 2 and 3.

patient EF fixation stability was worse when the text was scrolled across the fovea, i.e. the region of maximum vision. At the retinal locations of 2, 4 and 6 deg, where vision was more compromised, fixation was more stable. That is, the distracting stimulus had less influence in regions where vision was poor. In contrast, the patient with Bull's Eye maculopathy demonstrated worst stability in a region of poor vision (4 deg), where he could only just recognize the letters and made searching eye movements in order to read them. When the letters were scrolled across the fovea, where he was unaware of them, fixation was relatively good. It remained at the same level when the text was scrolled at 6 deg location which was his PRL.

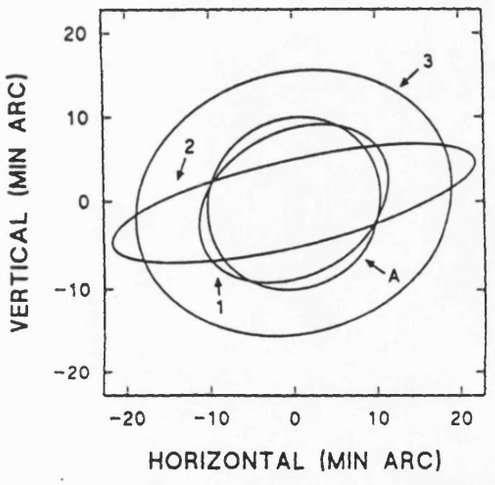

Fig. 2. Graph showing the relatively poor fixation stability of patient NH for negative targets which are stationary (A) and scrolling at speeds 1, 2 and 3.

DISCUSSION

In agreement with other more conventional tests of visual acuity (Kitchin and Bailey, 1981) and contrast sensitivity (Brown and Lovie-Kitchin, 1987), we found that in our visually compromised observers both parameters had to be increased, compared with normals, in order to provide recognizable targets. For each subject the size and contrast of the stimuli used in the SLO had been determined by pilot measurements.

The stimuli in this study were specifically chosen to investigate the effects of reading related targets on fixation. For comparative purposes the Snellen E, 20 min arc in size, was used as a standard target. In the normal group fixation stability was influenced by target size. When the Snellen E increased in size, up to a maximum of 160 min arc, the fixation stability decreased. This is in general agreement with previous observations. In a study by Steinman (1965), normal subjects fixated the centre of disks of different sizes, i.e. 1.9–87.2 min arc, and known luminance. One subject increased eye movements with increased size; the other subject, who exhibited less stable fixation for all targets, was not so influenced by the size. In another study (Rattle, 1969), subjects fixated the centre of a disk ranging in size from 19 to 240 min arc. While fixation remained stable for targets 19–78 min arc eye movements increased for stimuli 140–240 min arc. However, fixation was notably worse with targets of approximately the same diameter as the fovea, e.g. 10 min arc. In respect of contrast, shape and

form the stimuli in the present study differ markedly from those of Steinman and Rattle. However, all three sets of stimuli were of similar size and therefore it is of interest that the results are comparable.

In order to examine the possibility of effects on fixation by the target surround we used arrays with multiple stimuli. By doing so we were able to assess any effects of contrast, texture and crowding (Rubenstein and Underwood, 1985). No significant effects were observed in either our normal or patient groups.

For stationary targets in this study the overall standard deviation of horizontal eye movements was greater than the standard deviation of vertical eye movements and this is in agreement with previous results (Kosnik *et al.*, 1986). Unlike most previous studies which used bright targets of known luminance and of simple geometric construction, i.e. a square or a circle, in the present study all fixation targets had contrast within them. In both the normal and patients groups the polarity of contrast, i.e. black on white or white on black, did not have any measurable influence on fixation performance. This lack of influence of contrast polarity was perhaps not surprising since reverse contrast has not been reported to have an effect on reading related tasks in either normals (Legge *et al.*, 1987) or patients with central loss but with clear media (Legge *et al.*, 1985b). This observation should not be confused with the fact that in practice reverse contrast (white on black) is often more comfortable for low vision patients, perhaps because of the absence of glare (Genensky *et al.*, 1972; Mehr *et al.*, 1973).

Although studies have reported a change in macular function (Elliott and Whitaker, 1991) and a progressive loss of foveal photoreceptors (Gartner and Henkind, 1981) with age, we did not find accuracy of fixation to be age dependent, confirming previous psychophysical observations (Kosnik *et al.*, 1986). Age-related deficits in acuity have been demonstrated (Greene and Madden, 1987) but whether there is an age-related correlation between acuity and fixation stability remains to be determined.

Any individual undertaking a psychophysical task progresses through a period of learning. The initial phase of this is often determined by both the pretest explanation and the performance instructions. The subjects in this study were directed to "watch the target carefully and steadily". The instruction "hold the eye still on one specific point on the target" may have altered the results. This concept has been demonstrated by Steinman *et al.* (1967). Learning and experience after the initial phase appeared to have little effect on the results, as indicated by consecutive experiments with subject CJ.

Given the diversity of macular lesions in our small patient group the wide range in responses was not unexpected (Table 3). The three patients who fixated with their fovea had abnormal foveal function, as reflected by their visual acuity, but all demonstrated relatively normal fixation. Of the four patients that did not use the fovea for fixation, all had pathologies which resulted in an absolute central scotoma. In this group by using their PRL, two patients showed performance within the normal range and two did not. The former were age-related macular lesions and the latter were juvenile macular conditions. Psychophysical tests would suggest that with increased size of central scotoma fixation stability would decrease (Whittaker *et al.*, 1988), however, the problem is complicated. Such complexity may be displayed in the variation in individual patient's responses. For example, patient DB viewed eccentricity in order to avoid the large, long standing discform scar, and the PRL was positioned at 6 deg eccentrically. His fixation stability under these conditions was remarkably good, e.g. 261 min arc^2 (Table 3). In contrast, patient AA, who had longstanding juvenile macular disease and a PRL at equivalent degrees eccentricity, had considerably worse fixation stability, e.g. 13,367 min arc^2. In future studies more patients will be investigated so that correlations can be made between fixation stability and nature of disease, size of scotoma, retinal meridians and rod/cone survival.

While scrolled text may be an unusual stimulus with which to study fixation stability, we considered that this novel modality may be of help in rehabilitation of patients with compromised vision. The measurement of the BCEA indicated the amount of retina stimulated by the centre of the text. Although we had expected that scrolling text through a fixation point may act as a distraction and therefore increase the BCEA, data from our normal subjects showed that this was not the case. Also, no increase was noted in the normal group at different eccentric retinal locations. Further, in our limited patient group no systematic variation was found.

Given the predominance of horizontal eye movements in the fixation of stationary stimuli

it was surprising to observe that these eye movements did not increase with scrolled text and that they were also unaffected by text speed. However, in the majority of subjects the temptation to track the target was suppressed and therefore only small saccadic movements were observed and these did not influence the size of the BCEA. In the normal group all individuals stated that reading became more difficult as the scrolling speed increased. At the fastest speed difficulty was expressed by some observers even when stimuli transgressed the fovea. While we could have increased the speed still further, in an attempt to deliberately provoke horizontal tracking movements, this was beyond the scope of the present paper. Given the degree of compromised vision in the patient group we elected to use the three slower speeds only.

Patients KA (macular hole) and HW (neovascular membrane) had good fixation for both stationary and scrolled text (Tables 3 and 6). Visual acuity was better than 6/18 and the damage to the macula was of limited extent. These two individuals seemed able to fixate as effectively as normals and in doing so they appeared to overcome their visual deficiency. The BCEA of these patients may suggest that fixation was not directly related to acuity. This is particularly so in the case of KA who was unable to see the centre of the target due to foveal loss but could perceive its upper and lower edges. Therefore, his fixation was equivalent to viewing between two points. When KA was encouraged to abandon this technique and instead use an ARL his fixation stability became notably worse (Tables 3 and 4).

The fixation stability of NH (Bull's eye maculopathy) and AA (Stargardts') was considerably worse for all targets. In addition NH was relatively more distracted by the scrolling stimuli than were the other patients and normal observers. The relatively poor performance of NH may be related not only to the large central scotoma but also to wide spread compromised receptor cell function. Before testing commenced NH described his vision as "decreased detail in the central region" but he was unaware of the large absolute central scotoma. He was surprised when targets placed on the fovea disappeared. This suggested that he did not usually attempt to utilize direct vision, but instead routinely utilized a "pseudo-fovea", which was situated at approx. 6 deg eccentricity in the superior retina.

Several methods of measuring eye movements in digitized images are available. Timberlake *et al.* (1986) utilized a registration procedure whereby each frame was marked at several points using computer graphics. One mark was placed on the stationary target and at least two other marks were located on different retinal features. Eye movements were calculated by measuring relative changes in position of the marked retinal features. Both methods of analysis are time consuming, but the flicker method is slightly faster, although it cannot resolve fully torsional eye movements. Currently we are developing an automatic flicker alignment programme which should minimize data processing time.

Classical methods for recording eye movements have been reviewed by Ditchburn (1973b); the more common ones include such devices as search coil eyetracker (Robinson, 1963), Purkinje-image eyetracker (Crane and Steele, 1978), and contact lens techniques (Ratliff and Riggs, 1950; Nachmias, 1959). The resolution of the SLO is lower than these techniques which can provide accuracy of up to 10 sec arc; however, measurements with the SLO are adequate to determine fixation ability in normal and low vision observers. The main advantage of the SLO system is that the visual stimuli are viewed continuously on the subject's fundus image, i.e. fixation is assessed directly by comparing stimulus position with retinal features.

CONCLUSIONS

There are five main findings in this study. First, the ability to maintain steady fixation varied significantly in normal subjects. Second, in a limited patient population large variations were observed. Third, in normal subjects fixation was affected by the size of stationary targets but not by the form or polarity. Fourth, in both normal and patient groups stationary targets allowed more accurate fixation compared with fixating a stationary stimulus in the presence of scrolled text. Fifth, the speed of scrolling text and the retinal location did not influence fixation stability.

Acknowledgements—We gratefully acknowledge the financial support of the Royal National Institute for the Blind and the Medical Research Council. We would like to thank too Dr Robert Kempson for statistical advice and the subjects for taking part. This work is in part fulfilment of a PhD degree for the University of London by L. E. Culham.

REFERENCES

Adler F. H. and Fliegelman M. (1934) Influence of fixation on the visual acuity. *Archs Ophthal.* **12**, 475–483.

British Standards Institution (1992) BSEN 60825.

Brown B. and Lovie-Kitchin J. (1987) Constrast sensitivity in central and paracentral retina in age-related maculopathy. *Clin. exp. Opt.* **70**, 145–148.

Crane H. D. and Steel C. M. (1978) Accurate three-dimensional eye tracker. *Appl. Opt.* **17**, 691–705.

Culham L. E., Fitzke F. W., Timberlake G. T. and Marshall J. (1992) The use of scrolled text in a scanning laser ophthalmoscope to assess reading performance at diffe ent retinal locations. *Opthal. physiol. Opt.* **12**, 281–286.

Department of Health and Social Security (1988) *Causes of Blindness and Partial Sight among Adults in 1976/77 and 1980/81 England*. HMSO, London.

Ditchburn R. W. (1973a) Kinematic description of small eye movements. In *Eye-movements and Visual Perception*. Clarendon Press, Oxford.

Ditchburn R. W. (1973b) Methods of recording eye movements (1) and (2). In *Eye-movements and Visual Perception*. Clarendon Press, Oxford.

Elliott D. B. and Whitaker D. (1991) Changes in macular function throughout adulthood. *Documenta Ophthal.* **76**, 251–259.

Gartner S. and Henkind P. (1981) Aging and degeneration of the human macula. I. Outer nuclear layer and photoreceptors. *Br. J. Ophthal.* **65**, 23–28.

Genensky S. M., Petersen H. E., Moshin H. L., Clewett R. W. and Yoshimura R. I. (1972) Advances in closed circuit TV systems for the partially sighted. Rand R1040-HEW/RC.

Greene H. A. and Madden D. J. (1987) Adult age differences in visual acuity, stereopsis, and contrast sensitivity. *Am. J. Optom. Physiol. Opt.* **64**, 749–753.

Kitchin J. E. and Bailey I. (1981) Task complexity and visual acuity in senile macular degeneration. *Aust. J. Optom.* **64**, 235–242.

Kosnik W., Fikre J. and Sekuler R. (1986) Visual fixation stability in older adults. *Invest. Ophthal. visual Sci.* **27**, 1720–1725.

Lakshminarayanan V., Knowles R. A., Enoch J. M. and Vasudevan R. (1992) Measurement of fixational stability while performing a hyper-acuity task using the scanning laser ophthalmoscope. *Clin. Vision Sci.* **7**, 557–563.

Legge G. E., Rubin G. S. and Luebker A. (1987) Psychophysics of reading. V. The role of contrast in normal vision. *Vision Res.* **27**, 1165–1177.

Legge G. E., Pelli D. G., Rubin G. S. and Schleske M. M. (1985a) Psychophysics of reading. I. Normal vision. *Vision Res.* **25**, 239–252.

Legge G. E., Rubin G. S., Pelli D. G. and Schleske M. M. (1985b) Psychophysics of reading. II. Low vision. *Vision Res.* **25**, 253–266.

Macular Photocoagulation Study Group (1982) Argon laser photocoagulation for senile macular degeneration. Results of a randomized clinical trial. *Archs Ophthal.* **100**, 912–918.

Macular Photocoagulation Study Group (1989) Persistent and recurrent neovascularization after krypton laser photocoagulation for neovascular lesions of ocular histoplasmosis. *Archs Ophthal.* **107**, 344–352.

Mainster M. A., Timberlake G. T., Webb R. H. and Hughes G. W. (1982) Scanning laser ophthalmoscopy—clinical applications. *Ophthalmology* **89**, 852–857.

Mehr E. B., Frost A. B. and Apple L. E. (1973) Experience with closed circuit television in the blind rehabilitation program of the veterans administration. *Am. J. Optom.* **50**, 458–469.

Michelson A. A. (1927) *Studies in Optics*, p. 113. University of Chicago Press, Chicago, Ill.

Montgomery D. C. (1984) *Design and Analysis of Experiments*. Wiley, New York.

Moorfields Macular Study Group (1982) Treatment of senile disciform macular degeneration: a single-blind randomised trial by argon laser photocoagulation. *Br. J. Ophthal.* **66**, 745–753.

Nachmias J. (1959) Two-dimensional motion of the retinal image during monocular fixation. *J. opt. Soc. Am.* **49**, 901–908.

Plesch A. and Klingbeil U. (1989) Optical characteristics of a scanning laser ophthalmoscope. *SPIE* **1161**, 390–398.

Ratliff F. and Riggs L. A. (1950) Involuntary motions of the eye during monocular fixation. *J. exp. Psychol.* **40**, 687–701.

Rattle J. D. (1969) Effect of target size on monocular fixation. *Optica Acta* **16**, 183–192.

RNIB. (1984) *Initial Demographic Study. A Review of Available Data on the Visual Disabled Population*. Shankland Cox, London.

Robinson D. A. (1963) A method of measuring eye movement using a scleral search coil in a magnetic field. *IEEE Trans. Biomed. Electron.* **10**, 137–145.

Rubinstein M. P. and Underwood J. (1985) The crowding phenomenon and its significance in senile macular degeneration. *Br. orthopt. J.* **42**, 45–53.

Sansbury R. V., Skavenski A., Haddad G. M. and Steinman R. (1973) Normal fixation of eccentric targets. *J. opt. Soc. Am.* **63**, 612–614.

Schuchard R. A. and Raasch T. W. (1992) Retinal locus for fixation: pericentral fixation targets. *Clin. Vision Sci.* **7**, 511–520.

Steinman R. M. (1965) Effect of target size, luminance, and color on monocular fixation. *J. opt. Soc. Am.* **55**, 1158–1165.

Steinman R. M., Cunitz R. J., Timberlake G. T. and Herman M. (1967) Voluntary control of microsaccades during maintained monocular fixation. *Science* **155**, 1577–1579.

Swann P. J. and Lovie-Kitchin J. E. (1990) Age related maculopathy. I. A review of its morphology and effects on visual function. *Ophthal. physiol. Opt.* **10**, 149–158.

Timberlake G. T., Peli E., Essock E. A. and Augliere R. A. (1987) Reading with a macular scotoma. II. Retinal locus for scanning text. *Invest. Ophthal. visual Sci.* **28**, 1268–1274.

Timberlake G. T., Mainster M. A., Peli E., Augliere R. A., Essock E. A. and Arend L. E. (1986) Reading with a macular scotoma. I. Retinal location of scotoma and fixation area. *Invest. Ophthal. visual Sci.* **27**, 1137–1147.

Webb R. H. and Hughes G. W. (1981) Scanning laser ophthalmoscope. *IEEE Trans. Biomed. Engng* **BME-28**, 488–492.

Webb R. H., Hughes G. W. and Pomerantzeff O. (1980) Flying spot TV ophthalmoscope. *Appl. Opt.* **19**, 2991–2997.

Whittaker S. G., Budd J. and Cummings R. W. (1988) Eccentric fixation with macular scotoma. *Invest. Ophthal. visual Sci.* **29**, 268–278.

Woon W. H., Fitzke F. W., Chester G. H., Greenwood D. G. and Marshall J. (1990) The scanning laser ophthalmoscope. Basic principles and applications. *J. Ophthal. Photogr.* **12**, 17–23.

Yarbus A. L. (1967) Eye movements during fixation on stationary objects. In *Eye Movements and Vision*. Plenum Press, New York.

Glossary of Terms

AOM - Acoustooptic modulator; reference in text p37.

ARMD - Age-related macular degeneration; reference in text p17.

ARL - Alternative retinal location; reference in text p36.

BCEA - Bivariate contour ellipse area; reference in text p64.

DHSS - Department of Health and Social Security; reference in text p21.

ERI - Eye Research Institute, Boston; reference in text p54.

EV - eccentric viewing; reference in text p40.

He-Ne - Helium-neon; reference in text p24.

IR - Infra-red; reference in text p24.

log MAR - logarithm of minimum angle of resolution; reference in text p126.

minarc - minutes of arc; reference in text p34.

MPE - maximum permissible exposure; reference in text p56.

NVM - neovascular membrane; reference in text p19.

pixel - picture element; reference in text p57.

PRL - preferred retinal location; reference in text p36.

raster - the apparent rectangular pattern produced by a rapidly scanning spot of laser light; reference in text p57.

RPE - retinal pigment epithelium; reference in text p18.

SES - steady eye strategy; reference in text p40.

SLO - Scanning laser ophthalmoscope; reference in text p36.

REFERENCES

Adams AJ, Wong LS, Wong L and Gould B. Visual acuity changes with age: some new perspectives. Am J Optom Physiol Opt 1988;65:403-406.

Acosta F, Lashkari K, Reynaud X, Jalkh A, Van de Velde F and Chedid N. Characterization of functional changes in macular holes and cysts. Ophthalmology 1991;98:1820-1823.

Adler FH and Fliegelman M. Influence of fixation on visual acuity. Arch Ophthalmol 1934;12:475-483.

Amsler M. Earliest symptoms of diseases of the macula. Brit J Ophthalmol 1953;37:521-537.

Anderson RS, Wilkinson MO and Thibos LN. Psychophysical localization of the human visual streak. Optom Vis Sci 1992;69:171-174.

Anstis SM. A chart demonstrating variations in acuity with retinal position. Vision Res 1974;14:589-592.

Aulhorn E. "Perimetrische Untersuchengen bei Kranken mit Zentralskotom". Grundungstg, Sachs-Thuring. Ges. Augenheilk, 1961. Cited in Mackensen G. Diagnosis and phenomenology of eccentric fixation. Int Ophthalmol Clin 1966;6:397-409.

Backman O. Reading skills, reading training and technology for the visually handicapped - prospects for the 1990es. In "Low Vision - Research and New Developments in Rehabilitation". Studies in Health Technology and Informatics, Vol II. Eds. Kooijman AC, Looijestijn PL, Welling JA and Van der Wildt GJ. IOS Press, Amsterdam, 1994, p251-254.

Backman O and Inde K. Low Vision Training. LiberHermods, Malmo, Sweden, 1979.

Bailey IL and Lovie JE. New design principles for visual acuity letter charts. Am J Optom Physiol Opt 1976;53:740-745.

Bailey IL and Lovie JE. The design and use of a new near-vision chart. Am J Optom Physiol Opt 1980;57:378-387.

Ball KK, Beard BL, Roenker DL, Miller RL and Grigg DS. Age and visual search: expanding the useful field of view. J Opt Soc Am 1988;5:2210-2219.

Banks CN. Integrated ophthalmic services - visual rehabilitation. Aust J Ophthalmol 1980;8:231-233.

Bartley SH. Psychological aspects of aging. In "Vision of the Aging Patient". Eds Hirsch MJ and Wick RE. Chilton, New York, 1960, p26.

Bennett AG. Ophthalmic test types. Br J Physiol Opt 1965;22:236-271.

Bennett AG and Rabbetts RB. "Clinical Visual Optics". Second ed. Butterworths, 1989.

Bertera JH. The effect of stimulated scotoma on visual search in normal subjects. Invest Ophthalmol Vis Sci 1988;29:470-475.

Blank HR. Psychoanalysis and blindness. Psychoanal Q 1957;26:1-24.

Blumenkranz MS, Russell SR, Robey MC, Kott-Blumenkranz R and Penneys N. Risk factors in age-related maculopathy complicated by choroidal neovascularization. Ophthalmology 1986;93:552-557.

Boldrey EE, Little HL, Flocks M and Vassiliadis A. Retinal injury due to industrial laser burns. Ophthalmology 1981;88:101-107.

Boulton LM. Palmerston North low vision aid clinic. Trans Ophthalmol Soc NZ 1977;29:59-61.

Bouma H. Visual interference in the parafoveal recognition of initial and final letters of words.. Vision Res 1973;13:767-782.

Bouma H, Legeïn CHP, Melotte HEM and Zabel L. Is large print easy to read? Oral reading rate and word recognition of elderly subjects. IPO annual progress report 1982;17:84-90.

Bressler NM, Bressler SB and Fine SL. Major review: Age-related macular degeneration. Surv Ophthalmol 1988;32:375-413.

British Standards Institution. Radiation safety of laser products, equipment classification, requirements and user's guide. BS EN 60825;1992.

Brown B and Lovie-Kitchin J. Contrast sensitivity in central and paracentral retina in age-related maculopathy. Clin Exp Optom 1987;70:145-148.

Bruce I and Hamlin D. The RNIB Needs Survey. Optometry Today 1992;April:8-9.

Bruce RH and Low FN. The effect of practise with brief-exposure techniques upon central and peripheral visual acuity and a search for a brief test of peripheral acuity. J Exp Psychol 1951;41:275-280.

Bruce I, McKennell A and Walker E. "Blind and Partially Sighted Adults in Britain: the RNIB Survey". HMSO, London, 1991.

Campbell FW and Green DG. Optical and retinal factors affecting visual resolution. J Physiol 1965;181:576-593.

Campbell FW and Gubisch RW. Optical quality of the human eye. J Physiol 1966;186:558-578.

Cerella J. Age-related decline in extrafoveal letter perception. J Gerontol 1985;40:727-736.

Chan CWC and Billson FA. Visual disability and major causes of blindness in NSW: A study of people aged 50 and over attending the Royal Blind Society 1984 to 1989. Aust N Z J Ophthalmol 1991;19:321-325.

Cohen JM and Waiss B. Reading speed through different equivalent power low vision devices with identical field of view. Optom Vis Sci 1991;68:795-797.

Collins J. Coping with the rising incidence of partial sight. Optometry Today 1987;27:772-779.

Collins MJ, Brown B and Bowman KJ. Peripheral visual acuity and age. Ophthalmic Physiol Opt 1989;9:314-316.

Coscas G and Soubrane G. Photocoagulation des neo-vaisseaux sous retiniens dans la degenerescence maculaire senile par le laser a argon. Resultats de l'etude randomisee de 60 cas. Bull Mem Soc Fr Ophtalmol 1983;94:149-154.

Cowey A and Rolls ET. Human cortical magnification factor and its relation to visual acuity. Exp Brain Res 1974;21:447-454.

Crane HD and Steel CM. Accurate three-dimensional eye tracker. Appl Opt 1978;17:691-705.

Culham LE. "Evaluation of a Low Vision Training Programme". M Phil thesis, University of London, 1991.

Culham LE, Fitzke FW, Timberlake GT and Marshall J. The use of scrolled text in a scanning laser ophthalmoscope to assess reading performance at different retinal locations. Ophthalmic Physiol Opt 1992;12:281-286.

Culham LE, Fitzke FW, Timberlake GT and Marshall J. Assessment of fixation stability in normal subjects and patients using a scanning laser ophthalmoscope. Clin Vision Sci 1993;8:551-561.

Cullinan TR. The epidemiology of visual disability. Studies of visual disabled people in the community. Health Services Research Unit: Report No.28, University of Kent, Canterbury, 1977.

Cummings RW and Whittaker SG. Development of eccentric fixation following loss of macular vision. ARVO Abstracts. Invest Ophthalmol Vis Sci 1985;26(suppl):216.

Curcio CA, Sloan KR, Kalina RE and Hendrickson AE. Human photoreceptor topography. J Comp Neurol 1990;292:497-523.

Curcio CA, Sloan KR, Packer O, Hendrickson AE and Kalina RE. Distribution of cones in human and monkey retina: Individual variability and radial asymmetry. Science 1987;236:579-582.

Curcio CA and Allen K. Topography of ganglion cells in human retina. J Comp Neurol 1990;300:5-25.

Dalgleish R and Naylor EJ. Bilateral eccentric fixation with no ocular deviation in a case of heredo-macular degeneration. Br J Ophthalmol 1963;47:11.

Daniel PM and Whitteridge D. The representation of the visual field on the cerebral cortex in monkeys. J Physiol 1961;159:203-221.

Davson H. "Physiology of the Eye". 4th ed. Churchill Livingstone, 1980, p191.

Delaney W and Oates R. Senile macular degeneration: A preliminary study. Ann Ophthalmol 1982;14:21-24.

Delori FC, Parker JS and Mainster MA. Light levels in fundus photography and fluorescein angiography. Vision Res 1980;20:1099-1104.

Department of Health and Social Security. "Causes of Blindness and Partial Sight among Adults in 1976/77 and 1980/81 England". London, HMSO, 1988.

Department of Health and Social Security. "Registered Blind and Partially Sighted persons as of 31st March 1988 England". London, HMSO, 1989.

Ditchburn RW. Kinematic description of small eye movements. In "Eye Movements and Visual Perception", Clarendon Press, Oxford, 1973a, p78-107.

Ditchburn RW. Methods of recording eye movements (1) and (2). In "Eye Movements and Visual Perception", Clarendon Press, Oxford, 1973b, p36-77.

Dorey CK, Wu G, Ebenstein D, Garsd A and Weiter JJ. Cell loss in the aging retina. Invest Ophthalmol Vis Sci 1989;30:1691-1699.

Drasdo N. Receptive field densities of the ganglion cells of the human retina. Vision Res 1989;29:985-988.

Elliott DB and Whitaker D. Changes in macular function throughout adulthood. Doc Ophthalmol 1991;76:251-259.

Elsner AE, Burns SA and Weiter JJ. Retinal and sub-retinal changes in age-related macular degeneration patients measured with infrared light. ARVO Abstract. Invest Ophthalmol Vis Sci 1992;33 (suppl):803.

Emerson DL. Facing loss of vision: the response of adults to vision impairment. J Vis Impairment Blind 1981;Feb:41-5.

Erdmann RL and Neal AS. Word legibility as a function of letter legibility, with word size, word familiarity, and resolution as parameters. J Appl Psychol 1968;52:403-409.

Faes FF. A study of successful and unsuccessful low vision rehabilitation patients. Am J Optom Physiol Opt 1981;58:404-7.

Farrall H. "Optometric Management of Visual Handicap". Blackwell Scientific Publications, 1991, p147-153.

Faye EE. Adjustment to low vision corrections: Instructing patients who lose vision as adults. In "Clinical Low Vision". Little, Brown and Co, Inc. 1976, p123-128.

Ferris FL. Senile macular degeneration: a review of epidemiological features. Am J Epidemiol 1983;118:132-51.

Feinberg R. A study of some aspects of peripheral visual acuity. Am J Optom 1949;26:105-119.

Fine AM, Elman MJ, Ebert JE, Prestia PA, Starr JS and Fine SL. Earliest symptoms caused by neovascular membranes in the macula. Arch Ophthalmol 1986;104:513-514.

Fitzke FW, Woon H, Timberlake GT, Robinson L, Marshall J and Bird AC. Optical modifications to a scanning laser ophthalmoscope for high magnification, narrow optical section imaging. Lasers Light Ophthalmol 1991;4:7-14.

Fitzmaurice K. Reading efficiency of visually impaired students - Review of pilot program. Aust Orthop J 1985;22:57-59.

Fitzmaurice K. Eccentric viewing position as a predictor of potential level of near visual acuity. Aust Orthop J 1992;28:29-32.

Fitzmaurice K. The efficacy of eccentric viewing as a rehabilitation strategy for patients with age-related macular degeneration. Transactions of International Mobility Conference, Melbourne, 1994.

Fitzmaurice K and Keast J. The effect of a reading efficiency program on visually impaired tertiary students - A pilot study. Aust Orthop J 1984;21:33-37.

Fitzmaurice K, Kinnear JF and Chen Y. A computer generated method of training eccentric viewing. Aust Orthop J 1993;29:13-17.

Fletcher DC and Schuchard RA. Scanning laser ophthalmoscope macular perimetry and applications for low vision rehabilitation clinicians. Ophthalmol Clin North Am 1994;7:257-265.

Forster KI. Visual perception of rapidly presented word sequences of varying complexity. Percept Psych 1970;8:215-221.

Frangieh GT, Green WR and Engel HM. A histopathologic study of macular cysts and holes. Retina 1981;1:311-336.

Freeman PB and Jose RT. "The Art and Practice of Low Vision". Butterworth-Heinemann, 1991.

Gabel VP, Birngruber R, Lorenz B and Lang GK. Clinical observations of six cases of laser injury to the eye. Health Phys 1989;56:705-710.

Gabel VP, Birngruber R and Nasemann J. Fluorescein angiography with the scanning laser ophthalmoscope (SLO). Lasers Light Ophthalmol 1988;2:35-40.

Gartner S and Henkind P. Aging and degeneration of the human macula. I. Outer nuclear layer and photoreceptors. Br J Ophthalmol 1981;65:23-28.

Gass JDM. "Stereoscopic Atlas of Macular Diseases: Diagnosis and Treatment". 3rd Ed. CV Mosby, St Louis 1987, p236-238: 256-261: 264-266: 684-693.

Gass JDM and Joondeph BC. Observations concerning patients with suspected impending macular holes. Am J Ophthalmol 1990;109:638-646.

Genensky SM, Petersen HE, Moshin HL, Clewett, RW and Yoshimura RI. Advances in closed circuit TV systems for the partially sighted. Rand R1040-HEW/RC, 1972, p62.

Goodrich GL and Mehr EB. Eccentric viewing training and low vision aids: current practice and implications of peripheral retinal research. Am J Optom Physiol Opt 1986;63:119-26.

Goodrich GL and Quillman RD. Training eccentric viewing. J Vis Impairment Blind 1977;71:377-81.

Greene HA and Madden DJ. Adult age differences in visual acuity, stereopsis, and contrast sensitivity. Am J Optom Physiol Opt 1987;64:749-753.

Guez JE, Le Gargasson JF, Rigaudiere F and O'Regan JK. Is there a systematic location for the pseudo-fovea in patients with central scotoma. Vision Res 1993;33:1271-1279.

Harris MJ, Robins D, Dieter JM, Fine SL and Guyton DL. Eccentric visual acuity in patients with macular disease. Ophthalmology 1985;92:1550-1553.

Harrison ER. Visual acuity and the cone cell distribution of the retina. Br J Ophthalmol 1953;37:538-542.

Hart WM and Burde RM. Three-dimensional topography of the central visual field. Ophthalmology 1983;90:1028-1038.

Heinen SJ and Skavenski AA. Adaptaion of saccades and fixation to bilateral foveal lesions in adult monkey. Vision Res 1992;32:365-373.

Henfi W. Helping the partially sighted. Bull Ophthalmol Soc Egypt 1969;62:403-8.

Hochheimer BF. Angiography of the retina with indocyanine green. Arch Ophthalmol 1971;86:564-565.

Holden AL and Fitzke FW. Image size in the fundus: structural evidence for wide field retinal magnification factor. Br J Ophthalmol 1988;72:228-230.

Holcomb JG and Goodrich GL. Eccentric viewing training. J Am Optom Assoc 1976;47:1438-43.

Hyman LG, Lilienfeld AM, Ferris FL and Fine SL. Senile macular degeneration: a case-control study. Am J Epidemiol 1983;118:213-227.

Inde K. Low vision training in Sweden. J Vis Impairment Blind 1978;Oct:307-10.

Ighe S. Reading training - four cases. In "Low Vision - Research and New Developments in Rehabilitation". Studies in Health Technology and Informatics, Vol II. Eds. Kooijman AC, Looijestijn PL, Welling JA and Van der Wildt GJ. IOS Press, Amsterdam, 1994, p255-258.

Jalkh AE, Availa MP, Trempe CL, McMeel JW and Schepens CL. Choroidal neovascularization in the fellow eyes of patients with advanced senile macular degeneration. Role of laser photocoagulation. Arch Ophthalmol 1983;101:1194-1197.

Jennings JAM and Charman WN. Off-axis image quality in the human eye. Vision Res 1981;21:445-455.

Johnson CA, Adams AJ and Lewis RA. Evidence for a neural basis of age-related visual field loss in normal observers. Invest Ophthalmol Vis Sci 1989;30:2056-2064.

Johnson CA and Leibowitz HW. Practise, refractive error, and feedback as factors influencing peripheral motion thresholds. Percept Psych 1974;15:276-280.

Jonas JB, Schneider U and Naumann GOH. Count and density of human retina photoreceptors. Graefes Arch Clin Exp Ophthalmol 1992;230:505-510.

Kanski JJ. "Clinical Ophthalmology". 2nd Ed. Butterworths, 1989.

Kelleher DK. Training low vision patients. J Am Optom Assoc 1976;47:1425-1427.

Kelly NE and Wendel RT. Vitreous surgery for idiopathic macular holes. Arch Ophthalmol 1991;109:654-659.

Khan HA, Leibowitz HM, Ganley JP, Colton T, Nickerson R and Dawder TR. The Framingham Eye Study. I. Outline and major prevalence findings. Am J Epidemiol 1977;106:17-32.

Khan HA, Leibowitz HM, Ganley JP et al. The Framingham Eye Study. II. Association of ophthalmic pathology with single variables previously measured in the Framingham Heart Study. Am J Epidemiol 1977;106:33-41.

Kini MM, Leibowitz HM, Colton T and Nickerson RJ. Prevalence of senile cataract, diabetic retinopathy, senile macular degeneration and open-angle glaucoma in the Framingham Eye Study. Am J Ophthalmol 1978;85:28-34.

Kitchin JE and Bailey I. Task complexity and visual acuity in senile macular degeneration. Aust J Optom 1981;64:235-242.

Klingbeil U. Safety aspects of laser scanning ophthalmoscopes. Health Phys 1986;51:81-93.

Kornzweig AL and Feldstein M. Studies of the eye in old age. II. Hole in the macula: a clinico-pathologic study. Am J Ophthalmol 1950;33:243-247.

Kosnik W, Fikre J and Sekuler R. Visual fixation stability in older adults. Invest Ophthalmol Vis Sci 1986;27:1720-1725.

Kothe AC, Lovasik JV and Faubert J. Visual function in partial and full thickness macular holes. Clin Eye Vision Care 1992;4:55-60.

Krischer CC, Nat R, Meissen R and Ing. Reading speed under real and simulated visual impairment. J Vis Impair Blind 1983;Oct:386-388.

Legge GE, Pelli DG, Rubin GS and Schleske MM. Psychophysics of reading. I. Normal vision. Vision Res 1985a;25:239-252.

Legge GE, Rubin GS, Pelli DG and Schleske MM. Psychophysics of reading. II. Low vision. Vision Res 1985b;25:253-266.

Legge GE, Rubin GS and Luebker A. Psychophysics of reading. V. The role of contrast in normal vision. Vision Res 1987;27:1165-1177.

Leibowitz HM, Krueger DE, Maunder LR et al. The Framingham Eye Study Monograph. Surv Ophthalmol 1980;24(suppl):335-610.

Loshin DS and White J. Contrast sensitivity. The visual rehabilitation of the patient with macular degeneration. Arch Ophthalmol 1984;102:1303-1306.

Lovie-Kitchin JE. High contrast and low contrast visual acuity in age-related macular degeneration. Clin Exp Optom 1989;72:79-83.

Lovie-Kitchin JE and Brown B. Reaction time in age-related maculopathy. Am J Optom Physiol Opt 1986;63:366-371.

Lovie-Kitchin JE, Farmer EJ and Bowman KJ. "Senile Macular Degeneration: The Effects and Management". Queensland Institute of Technology, 1982, p5-20.

Low FN. The peripheral visual acuity of 100 subjects. Am J Physiol 1943;140:83-88.

Low FN. Some characteristics of peripheral visual performance. Am J Physiol 1946;146:573-584.

Low FN. Peripheral visual acuity. Arch Ophthalmol 1951;45:80-99.

Ludvigh E. Extrafoveal visual acuity as measured with Snellen test-letters. Am J Ophthalmol 1941;24:303-310.

Lui P, Choi JC and Frambach DA. Retinal capillary potential measurement with a scanning laser ophthalmoscope. Invest Ophthalmol Vis Sci 1992;33:811.

Mackeben M and Colenbrander A. Mapping the topography of residual vision after macular loss. In "Low Vision - Research and New Developments in Rehabilitation". Studies in Health Technology and Informatics, Vol II. Eds. Kooijman AC, Looijestijn PL, Welling JA and Van der Wildt GJ. IOS Press, Amsterdam, 1994, p59-67.

Macular Photocoagulation Study Group. Argon laser photocoagulation for senile macular degeneration. Results of a randomized clinical trial. Arch Ophthalmol 1982;100:912-918.

Macular Photocoagulation Study Group. Argon laser photocoagulation for neovascular maculopathy. Three-year results from randomised clinical trials. Arch Ophthalmol 1986a;104:694-701.

Macular Photocoagulation Study Group. Choriodal neovascularization after argon laser photocoagulation for neovascular maculopathy. Arch Ophthalmol 1986b;104:503-512.

Mainster MA, Timberlake GT, Webb RH and Hughes GW. Scanning laser ophthalmoscopy - clinical applications. Ophthalmology 1982;89:852-857.

Maltzman BA, Mulvihill MM and Greenbaum A. Senile macular degeneration and risk factors: a case-control study. Ann Ophthalmol 1979;11:1197-1201.

Mandelbaum J and Sloan LL. Peripheral visual acuity. Am J Ophthalmol 1947;30:581-588.

Maplesden C. A subjective approach to eccentric viewing training. J Vis Impairment Blind 1984;Jan:5-6.

Marron JA and Bailey IL. Visual factors and orientation-mobility performance. Am J Optom Physiol Opt 1982;59:413-426.

Marshall J. Radiation and the ageing eye. Ophthalmic Physiol Opt 1985;5:241-263.

Marshall J. The ageing retina: Physiology or pathology. Eye 1987;1:282-295.

Mayo E. "The Social Problems of an Industrial Civilization". Division of Research, Graduate School of Business Administration, Harvard University, Boston, 1945, p68-86.

McConkie GW and Rayner K. Asymmetry of the perceptual span in reading. Bull Psychonom Soc 1976;8:365-368.

McGrath C and Morrison JD. The effects of age on spatial frequency perception in human subjects. Q J Exp Physiol 1981;66:253-261.

Mehr EB and Fried AN. "Low Vision Care". Professional Press, Chicago, 1975.

Mehr EB, Frost AB and Apple LE. Experience with closed circuit television in the blind rehabilitation program of the veterans administration. Am J Optom 1973;50:458-469.

Mehr HM, Mehr EB and Ault C. Psychological aspects of low vision rehabilitation. Am J Opt Arch Am Acad Opt 1970;47:605-12.

Mein CE and Flynn HW. Recognition and removal of the posterior cortical vitreous during vitreoretinal surgery for impending macular holes. Am J Ophthalmol 1991;111:611-613.

Merigan WH and Katz LM. Spatial resolution across macaque retina. Vision Res 1990;30:985-991.

Michelson AA. "Studies in Optics". Univ Chicago Press, 1927, p113.

Millodot M and Lamont A. Peripheral visual acuity in the vertical plane. Vision Res 1974;14:1497-1498.

Mishkin M and Forgays DG. Word recognition as a function of retinal locus. J Exp Psychol 1952;43:43-48.

Mitra S. Spatial contrast sensitivity in macular disorders. Doc Ophthalmol 1985;59:247-267.

Montgomery DC. "Design and Analysis of Experiments". Wiley, 1984.

Moorfields Macular Study Group. Treatment of senile disciform macular degeneration: a single-blind randomised trial by argon laser photocoagulation. Br J Ophthalmol 1982;66:745-753.

Morse JL. Psychosocial aspects of low vision. In "Understanding Low Vision". Ed. Jose RT. American Foundation for the Blind, New York, 1989, p43-54.

Murphy K and Foley-Fisher JA. Visual search with non-foveal vision. Ophthalmic Physiol Opt 1988;8:345-348.

Nachmias J. Two-dimensional motion of the retinal image during monocular fixation. J Opt Soc Am 1959;49:901-908.

Nasemann JE and Muller M. Scanning laser angiography. In "Scanning Laser Ophthalmoscopy and Tomography". Eds. Nasemann JE and Burk ROW. Quintessenz Verlag, 1990, p63-80.

Negrin S. Psychosocial aspects of aging and visual impairment. In "Understanding Low Vision". Ed. Jose RT. American Foundation for the Blind, New York, 1989, p55-59.

Newson K. "The Art of English 2". Schofield and Sims Limited, Huddersfield, 1970.

Nilsson UL. Visual rehabilitation of patients with advanced diabetic retinopathy. Doc Ophthalmol 1986;62:369-382.

Nilsson UL. Visual rehabilitation of patients with advanced stages of glaucoma, optic atrophy, myopia or retinitis pigmentosa. Doc Ophthalmol 1989;70:363-383.

Nilsson UL. "Results of Low Vision Rehabilitation". PhD thesis. Linkoping University Medical Dissertations No.313, 1990a.

Nilsson UL. Visual rehabilitation with and without educational training in the use of optical aids and residual vision. A prospective study of patients with advanced age-related macular degeneration. Clin Vision Sci 1990b;6:3-10.

Nilsson UL and Nilsson SEG. Rehabilitation of the visually handicapped with advanced macular degeneration. Doc Ophthalmol 1986;62:345-367.

Nilsson SEG and Nilsson UL. Educational training in the use of aids and residual vision is essential in rehabilitation of patients with severe age-related macular degeneration. I. Principles and methods. In "Low Vision - Research and New Developments in Rehabilitation". Studies in Health Technology and Informatics, Vol II. Eds. Kooijman AC, Looijestijn PL, Welling JA and Van der Wildt GJ. IOS Press, Amsterdam, 1994a, p147-150.

Nilsson UL and Nilsson SEG. Educational training in the use of aids and residual vision is essential in rehabilitation of patients with severe age-related macular degeneration. II. Results of a prospective study. In "Low Vision - Research and New Developments in Rehabilitation". Studies in Health Technology and Informatics, Vol II. Eds. Kooijman AC, Looijestijn PL, Welling JA and Van der Wildt GJ. IOS Press, Amsterdam, 1994b, p151-154.

Office of Population Censuses and Surveys London, St Catherine's House, 10 Kingsway, London WC2B 6JP, UK, 1983.

Osterberg G. Topography of the layer of rods and cones in the human retina. Acta Ophthalmol 1935;13:1-103.

Ott D and Eckmiller R. Ocular torsion measured by TV and scanning laser ophthalmoscopy during horizontal pursuits in humans and monkeys. Invest Ophthalmol Vis Sci 1989;30:58-66.

Ott D and Lades M. Measurement of eye rotations in three dimensions and retinal stimulus projection using scanning laser ophthalmoscopy. Ophthalmic Physiol Opt 1990;10:67-71.

Overbury O and Bross M. Improvement of visual acuity in partially and fully sighted subjects as a function of practice, feedback, and instructional techniques. Percept Mot Skills, 1978;46:815-822.

Overington I. "Vision and Acquisition. Fundamentals of Human Visual Performance, Environmental Influences and Applications in Instrumental Optics". Pentech Press, London, 1976, p32-47.

Peli E. Contrast in complex images. J Opt Soc Am 1990;7:2032-2040.

Plesch A and Klingbeil U. Optical characteristics of a scanning laser ophthalmoscope. SPIE 1989;1161:390-398.

Post RB and Johnson CA. Motion sensitivity in central and peripheral vision. Am J Optom Physiol Opt 1986;63:104-107.

Poulton EC. Peripheral vision, refractoriness and eye movements in fast oral reading. Br J Psychol 1962;53:409-419.

Randall HG, Brown DJ and Sloan LL. Peripheral visual acuity. Arch Ophthalmol 1966;75:500-504.

Ratliff F and Riggs LA. Involuntary motions of the eye during monocular fixation. J Exp Psychol 1950;40:687-701.

Rattle JD. Effect of target size on monocular fixation. Optica Acta 1969;16:183-192.

Rayner K. Parafoveal identification during a fixation in reading. Acta Psychol 1975a;39:271-282.

Rayner K. The perceptual span and peripheral cues in reading. Cognitive Psychol 1975b;7:65-81.

Rayner K, Well AD and Pollatsek A. Asymmetry of the effective visual field in reading. Percept Psych 1980;27:537-544.

Rehkopf P, Friberg TR, Mandarino L, Warnicki J, Finegold D, Cappozi D and Horner J. Retinal circulation time using scanning laser ophthalmoscope-image processing techniques. In "Scanning Laser Ophthalmoscopy and Tomography". Eds. Nasemann JE and Burk ROW. Quintessenz, Verlag, 1990, p81-90.

Ridley H. Recent methods of fundus examination including electronic ophthalmoscopy. Trans Ophthalmol Soc UK 1952;LXXII:497-509.

Rijsdijk JP, Kroon JN and van der Wildt GJ. Contrast sensitivity as a function of position in the retina. Vision Res 1980;20:235-241.

Robinson DA. A method of measuring eye movement using a scleral search coil in a magnetic field. IEEE Trans Biomed Electronics 1963;10:137-145.

Robinson R, Deutsch J, Jones HS, Youngson-Reilly S, Hamlin DM, Dhurjon L and Fielder AR. Unrecognised and unregistered visual impairment. Br J Ophthalmol 1994;78:736-740.

Rosen ES. "Fluorescence Photography of the Eye". Butterworths, London, 1969.

Rosenbloom AA. Prognostic factors in low vision rehabilitation. Am J Optom 1970;47:600-605.

Rovamo J and Virsu V. An estimation and application of the human cortical magnification factor. Exp Brain Res 1979;37:495-510.

Rubin GS. Predicting reading performance in patients with age-related maculopathy. In "Low Vision Principles and Applications". Ed. Woo GC. New York, Springer-Verlag, 1986.

Rubin GS. Assessment of visual function in eyes with visual loss. In "Assessment of Visual Function for the Clinician". Ophthalmol Clin North Am 1989;2:357-367.

Rubin GS and Legge GE. Psychophysics of reading. VI. The role of contrast in low vision. Vision Res 1989;29:79-91.

Rubin GS and Turano K. Normal and low vision reading using rapid serial visual presentation. ARVO Abstracts. Invest Ophthalmol Vis Sci 1990;31(suppl):599.

Rubin GS and Turano K. Reading without saccadic eye movements. Vision Res 1992;32:895-902.

Rubinstein MP and Underwood J. The crowding phenomenon and its significance in senile macular degeneration. Br Orthopt J 1985;42:45-53.

Sansbury RV, Skavenski A, Haddad GM and Steinman R. Normal fixation of eccentric targets. J Opt Soc Am 1973; 63:612-614.

Sarks SH. Ageing and degeneration in the macular region: a clinico-pathological study. Br J Ophthalmol 1976;60:324-341.

Saugstad P and Lie I. Training of peripheral visual acuity. Scand J Psychol 1964;5:218-224.

Schatz H, Burton TC, Yannuzzi LA and Rabb MF. "Interpretation of Fundus Fluorescein Angiography". CV Mosby, St Louis, 1978.

Scheider A, Schrodel C and Plesch A. Indocyanine green angiography with a scanning laser ophthalmoscope. In "Scanning Laser Ophthalmoscopy and Tomography". Eds. Nasemann JE and Burk ROW. Quintessenz, Verlag, 1990, p97-102.

Schuchard RA. Retinal locus for identification in observers with vision loss. Optical Society of American Topical Meeting on Noninvasive Assessment of the Visual System 1991;Technical Digest 1:46-49.

Schuchard RA. Amsler grid perimetry and perceptual completion. ARVO Abstracts. Invest Ophthalmol Vis Sci 1992;33(suppl):970.

Schuchard RA. Validity and interpretation of Amsler grid reports. Arch Ophthalmol 1993;111:776-780.

Schuchard RA and Fletcher DC. Preferred retinal locus. A review with applications in low vision rehabilitation. Ophthalmol Clin North Am 1994;7:243-256.

Schuchard RA and Raasch TW. Retinal locus for fixation: Pericentral fixation targets. Clin Vision Sci 1992;7:511-520.

Schulz PJ. Reaction to the loss of sight. In "Psychiatric Problems in Ophthalmology". Ed. Pearlman JT, Adams GL and Sloan SH. Charles Thomas, Illinois, 1977, p38-67.

Sekuler R, Owsley C and Hutman L. Assessing spatial vision of older people. Am J Optom Physiol Opt 1982;59:961-968.

Sheedy JE, Bailey IL and Raasch TW. Visual acuity and chart luminance. Am J Optom Physiol Opt 1984;61:595-600.

Silver J. Visual aids in macular disease. Trans Ophthalmol Soc UK 1972;93:479-84.

Silverstone DE and Hirsch J. "Automated Visual Field Testing. Techniques of Examination and Interpretation". Appleton-Century-Crofts, Connecticut, 1986, p33-34.

Sloan LL. Variations of acuity with luminance in ocular diseases and anomalies. Doc Ophthalmol 1969;26:384-393.

Sloan LL. "Reading Aids for the Partially Sighted: A Systematic Classification and Procedure for Prescribing". Waverly Press, Inc., Baltimore, 1977, p103-9.

Sloan LL and Habel A. Reading speeds with textbooks in large and in standard print. Sight Saving Review 1973;43:107-111.

Smith RG, Hardman Lea SJ and Galloway NR. Visual performance in idiopathic macular holes. Eye 1990;4:190-194.

Soubrane G, Coscas G, Francais C and Koenig F. Occult subretinal new vessels in age-related macular degeneration. Natural history and early laser treatment. Ophthalmology 1990;97:649-657.

Steinman RM. Effect of target size, luminance, and color on monocular fixation. J Opt Soc Am 1965;55:1158-1165.

Steinman RM, Cunitz RJ, Timberlake GT and Herman M. Voluntary control of microsaccades during maintained monocular fixation. Science 1967;155:1577-1579.

Stone EM, Nichols BE, Streb LM, Kimura AE and Sheffield VC. Genetic linkage of vitelliform macular degeneration (Best's Disease) to chromosome 11q13. Nat Genet 1992;1:246-250.

Sunness JS, Massof RW, Johnson MA, Finkelstein D and Fine SL. Peripheral retinal function in age-related macular degeneration. Arch Ophthalmol 1985;103:811-816.

Sunness JS, Massof RW, Johnson MA, Bressler NM, Bressler SB and Fine SL. Diminished foveal sensitivity may predict the development of advanced age-related macular degeneration. Ophthalmology 1989;96:375-381.

Suppes P. Eye movement models for arithmetic and reading performance. In "Eye Movements and their Role in Visual and Cognitive Processes". Ed. E Kowler. Elsevier, New York, 1990.

Swann PJ and Lovie-Kitchin JE. Age related maculopathy. I. A review of its morphology and effects on visual function. Ophthalmic Physiol Opt 1990;10:149-158.

Swann PJ and Lovie-Kitchin JE. Age related maculopathy. II. The nature of the central visual field loss. Ophthalmic Physiol Opt 1991;11:59-70.

Tanaka T, Muraoka K and Shimizu K. Fluorescein fundus angiography with scanning laser ophthalmoscope. Visibility of leukocytes and platelets in perifoveal capillaries. Ophthalmology 1991;98:1824-1829.

Tatsuoka MM. Multivariate significance tests of group differences. In "Multivariate Analysis: Techniques for Education and Psychological Research". Wiley, New York, 1971, p62-73.

Timberlake GT, Mainster MA, Webb RH, Hughes GW and Trempe CL. Retinal localization of scotomata by scanning laser ophthalmoscopy. Invest Ophthalmol Vis Sci 1982;22:91-97.

Timberlake GT, Mainster MA, Peli E, Augliere RA, Essock EA and Arend LE. Reading with a macular scotoma. I. Retinal location of scotoma and fixation area. Invest Ophthalmol Vis Sci 1986;27:1137-1147.

Timberlake GT, Peli E and Augliere RA. Visual acuity measurements with a second generation scanning laser ophthalmoscope. Optical Society of America Topical Meeting on Noninvasive Assessment of Visual System 1987a;Technical Digest:4-7.

Timberlake GT, Peli E, Essock EA and Augliere RA. Reading with a macular scotoma. II. Retinal locus for scanning text. Invest Ophthalmol Vis Sci 1987b;28:1268-1274.

Timberlake GT, Van De Velde FJ and Jalkh AE. Clinical use of scanning laser ophthalmoscope retinal function maps in macular disease. Lasers Light Ophthalmol 1989;2:211-222.

Turano K and Rubin GS. Reading performance with peripheral viewing using rapid serial visual presentation. Optical Society of America Topical Meeting on Noninvasive Assessment of the Visual System 1988; Technical Digest 3:192-195.

Van de Velde FJ, Jalkh AE, Katsumi O, Hirose T, Timberlake GT and Schepens CL. Clinical scanning laser ophthalmoscope applications: An overview. In "Scanning Laser Ophthalmoscopy and Tomography". Eds. Nasemann JE and Burk ROW. Quintessenz, Verlag, 1990, p35-47.

van Nes FL and Jacobs JC. The effect of contrast on letter and word recognition. IPO annuals progress report 1981;16:72-80.

Vinding T, Appleyard M, Nyboe J and Jensen G. Risk factor analysis for atrophic and exudative age-related degeneration. An epidemiological study of 1000 aged individuals. Acta Ophthalmol 1992;70:66-72.

Virsu V, Rovamo J, Laurinen P and Nasanen R. Temporal contrast sensitivity and cortical magnification. Vision Res 1982; 22:1211-1217.

Virtanem P and Laatikainen L. Primary success with low vision aids in age-related macular degeneration. Acta Ophthalmol 1991;69:484-490.

von Noorden GK and Mackensen G. Phenomenology of eccentric fixation. Am J Ophthalmol 1962;53:642-661.

Wall M and Sadun AA. Threshold Amsler grid testing. Arch Ophthalmol 1986;104:520-523.

Walsh PM, Harris MJ, Robins D, Fine SL and Guyton DI. "Full field" visual acuity in patients with impaired fixation. ARVO Abstracts. Invest Ophthalmol Vis Sci 1984;25(suppl):310.

Watson G and Berg RV. Near training techniques. In "Understanding Low Vision". Ed. Jose RT. New York, Am Found Blind, 1983, p317-62.

Weale RA. Senile changes in visual acuity. Trans Ophthalmol Soc UK 1975;95:36-38.

Weale RA. A Biography of the Eye. Lewis, London, 1982, p255-263.

Weale RA. The Senescence of Human Vision. Oxford Univ Press, New York, 1992, p204-220.

Webb RH. An overview of the scanning laser ophthalmoscope. In "Advances in Diagnostic Visual Optics". Eds. Breinin G and Sieigel I. Springer-Verlag, 1983, p138-140.

Webb RH and Delori FC. How we see the retina. In "Laser Technology in Ophthalmology". Ed. Marshall J. Kugler and Ghedini Publications, Amsterdam, 1989, p3-14.

Webb RH and Hughes GW. Scanning laser ophthalmoscope. IEEE Trans Biomed Eng 1981;BME-28:488-492.

Webb RH, Hughes GW and Pomerantzeff O. Flying spot TV ophthalmoscope. Appl Opt 1980;19:2991-2997.

Webb RH, Hughes GW and Pomerantzeff O. Further progress with the scanning laser ophthalmoscope. ARVO Abstracts. Invest Ophthalmol Vis Sci 1982;22(suppl):58.

Webb RH, Hughes GW, Timberlake GT and Mainster MA. Laser Flying Spot: Reduction of effects of ocular media clouding. ARVO Abstracts. Invest Ophthalmol Vis Sci 1981;20(suppl):241.

Weiter JJ, Wing GL, Trempe CL and Mainster MA. Visual acuity related to retinal distance from the fovea in macular disease. Ann Ophthalmol 1984;16:174-176.

Wertheim T.H. Uber die indirekte Sehscharfe, Ztschr f Psychol u Physiol der Sinnesorg 1894;7:172.

Weymouth FW, Hines DC, Acres LH, Raaf JE and Wheeler MC. Visual acuity within the area centralis and its relation to eye movements and fixation. Am J Ophthalmol 1928;11:947-960.

White JM and Bedell HE. Eye movements in patients with macular disease. ARVO Abstracts. Invest Ophthamol Vis Sci 1985;26(suppl):259.

White JM and Bedell HE. The oculomotor reference in humans with bilateral macular disease. Invest Ophthalmol Vis Sci 1990;31:1149-1161.

Whittaker SG, Budd J and Cummings RW. Eccentric fixation with macular scotoma. Invest Ophthamol Vis Sci 1988a;29:268-278.

Whittaker SG, Cummings RW and Watson G. Saccades and fixation following central field loss. Optical Society of America Topical Meeting on Noninvasive Assessment of Visual System 1988b; Technical Digest 3:200-203.

Wild JM and Wolffe M. Residual vision in the low vision patient - some concepts. Am J Optom Physiol Opt 1982;59:686-91.

Wolf S, Koyama T, Meyer-Ebrecht D, Reim M. Scanning laser ophthalmoscopy for the quantification of retinal blood-flow parameters: a new imaging technique. In "Scanning Laser Ophthalmoscopy and Tomography". Eds. Nasemann JE and Burk ROW. Quintessenz, Verlag, 1990, p91-96.

Woon WH, Fitzke FW, Chester GH, Greenwood DG and Marshall J. The scanning laser ophthalmoscope. Basic principles and applications. J Ophthalmol Photo 1990;12:17-23.

Woon WH, Fitzke FW, Bird AC and Marshall J. Confocal imaging of the fundus using a scanning laser ophthalmoscope. Br J Ophthalmol 1992;76:470-474.

Wormald R and Evans J. Registration of blind and partially sighted people. Br J Ophthalmol 1994;78:733-734.

Yarbus AL. Eye movements during fixation on stationary objects. In "Eye Movements and Vision". Plenum Press, New York, 1967.

Young RW. Solar radiation and age-related macular degeneration. Surv Ophthalmol 1988;32:252-269.

Zahn JR. Age-related maculopathy (ARM): The rehabilitative process. J Vision Rehab 1989;3:25-33.