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Temporal, Spatial and Chromatic Mechanisms: Their Interrelationship in the Glaucomatous Eye

Jocelyn Faubert

A Thesis

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ABSTRACT

Temporal, Spatial and Chromatic Mechanisms: Their Interrelationship in the Glaucomatous Eye

Jocelyn Faubert

The research reported in this thesis proposes that the X (sustained) and Y (transient) classification of cells relating to the functional responses of the human visual system can be utilized to generate testable predictions concerning changes in central functions as a result of glaucoma. Specifically, it is proposed that Y-cells are damaged early in the glaucomatous eye and that this is be reflected by specific functional deficiencies. In light of the knowledge in the literature about X/Y cells, it was hypothesized that temporal resolution and spatial contrast sensitivity for lower and middle spatial frequencies would be affected along with colour vision.

Thirty eyes of 30 different individuals were used in the study consisting of an early glaucoma, a glaucoma suspect, and a control condition with 9, 10 and 11 observers respectively. Temporal resolution was measured with multi-flash campimetry; spatial contrast sensitivity with the "Anticipated Threshold Technique"; and colour vision with the Farnsworth-Munsell 100-hue (FM-100) test and the American Optical Hardy-Rand-Rittler Pseudoisochromatic (HRR) plates.

A difference between groups was found only for temporal resolution. Multi-flash campimetry scores from the central 10 degrees of the visual field were compared with sensitivity scores obtained for lower and

middle spatial frequencies for the patient populations. The strongest correlation was obtained between the central 10 degrees of multi-flash and the lower and middle spatial frequencies for the glaucoma group ($r = -.65$). When comparing spatial contrast sensitivity scores with the error scores obtained from the FM-100 test, the highest correlation was obtained between the error scores and the sensitivity scores of the higher spatial frequencies in the glaucoma suspects ($r = -.75$). The correlation between these factors in the glaucoma group was $r = -.57$. No errors were made on the HRR plates by any observer. The results suggest that the X/Y classification represents extremes of a continuum and that the Y-cells, assumed to have larger axons, are affected early in the glaucomatous eye.

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Statement of the Problem

The traditional psychophysical approach in visual perception has been to quantify thresholds of sensitivity to a variety of visual stimuli. This method offers the opportunity to observe indirectly how the visual system functions by determining the differential sensitivities to stimuli of different sizes, shapes, hues, saturations, intensities, orientations, and temporal separation. Parallel to and sometimes in conjunction with the study of psychophysics, researchers have made an attempt to elucidate the physiology of the visual system. However, relatively few studies have examined the response of the human visual system to psychophysical testing when the eyes are impaired.

There are several advantages in using an impaired visual system for experimentation. For one, there is no need to artificially eliminate some visual capacities in order to isolate functional roles. Another advantage in using an impaired visual system is that the presence or absence of interactions between different visual mechanisms can be observed. For example, if spatial channels are affected independently of temporal sensitivity loss, it can be assumed that at least two different mechanisms are present. Since the interactions of spatial, temporal and colour mechanisms of the visual system are still poorly understood, the use of impaired visual systems opens an important avenue of approach to the the study of these interactions.

In this study an attempt was made to examine several mechanisms of

the human visual system by using glaucomatous eyes in very early stages of the pathology as well as eyes that were suspected of having chronic simple open angle glaucoma. The physiological deficiencies caused in early stages of glaucoma are generally located in the neural connection stretching from the retinal ganglion (RG) cells to the lateral geniculate nucleus (LGN) neurons of the brain. Recent neurophysiological findings have demonstrated that, for the glaucomatous eye, the majority of axons affected in the ganglio-geniculate connection are large. Further, psychophysical and neurophysiological findings demonstrate that there is a "transient" or Y-cell and a "sustained" or X-cell classification of functional response. Y-cells have large axons and receptive fields while X-cells have small axons and receptive fields. The Y-cells correspond mostly to temporal and lower spatial frequency information while the X-cells respond more to higher spatial frequencies. Evidence also suggests that neural colour codes can be either temporal and spatial in nature. The X/Y functional classification of cells, however, appears not to be the consequence of distinct cell types. Rather, these cell types should be considered components of a continuous system within which the X or smaller cells reside on one end of the continuum and the Y or larger cells on the other.

Assuming that the X/Y classification exists in the human visual system, it was hypothesized that, in chronic open angle glaucoma, the larger or Y-cell types are affected first. Therefore, functional deficits that correspond specifically to Y-cell classification should be obtained when testing eyes with glaucoma. The use of glaucoma suspects

and early confirmed glaucoma patients is necessary in order to obtain the differential responses mentioned because, in later stages of the disease, a more generalized depression of the visual system is observed.

The Neurophysiology and Psychophysics of Spatial and Temporal Mechanisms

Neurophysiological research has demonstrated that, in the mammalian visual system, there are a minimum of two types of neurons with different functional responses (Blake & DiGianfilippo, 1980; Cleland, Dubin & Levick, 1971; Enroth-Cugell & Robson, 1966; Ikeda & Wright 1972). These neurons called X (sustained) and Y (transient) cells, respond differently to temporal and spatial information. In a series of experiments where neuronal responses of retinal ganglion and lateral geniculate cells of cats were recorded, Cleland and his coworkers (1971) demonstrated that the X/Y functional categorization was present at both levels of the visual system. This is consistent with the notion advanced by Hubel and Wiesel (1962) that cells with response criteria similar to those exhibited by the retinal ganglion cells, like the center-surround properties of the cat's retina (Kuffler, 1953), can be found in the lateral geniculate nucleus.

Cleland and his coworkers separated the transient and sustained cells with the use of four tests which define the functional differences of the two categories. The first test presents small targets with "appropriate" contrast, which means that the initial responses to the presentation of the stimuli were similar for X- and Y-cells. The target size for the Y-cells had to be larger than the X- cells to get a similar response (1.5 vs. 0.5 degrees of visual angle). After the initial

response, the sustained cells exhibited a constant level of firing throughout the presentation. However, the transient cells quickly decreased their firing rates to pre-stimulated levels. When the target was covered, the sustained cells decreased firing rate at levels lower than the pre-stimulated levels and slowly recovered.

Secondly, the response to a series of parallel black and white bars (square wave grating) was measured. A massive response to lower spatial frequencies for both X- and Y-cells was recorded when the grating passed through their respective receptive fields. As the gratings became finer, the pattern specific response of the Y cells diminished and those of the X-cells remained above unstimulated levels untill the gratings were too small to elicit any response. The Y-cells exhibited an increase in firing rate to fine gratings only if these were set in motion, demonstrating a non-pattern specific response. In other words, the Y-cells responded more readily to temporal information and lower spatial frequencies.

Thirdly, white and black circular targets of increasing size were moved across the receptive fields. The ganglion cells showed a preferential size, below and above which the response levels decreased. This preference was different for the X- and Y-cells, the X-cells responding more to smaller targets (below 1 degree of visual angle) and the Y-cells to larger targets (larger than 1 degree of visual angle). A preference to speed of presentation showed Y-cells responding at both low and high temporal frequencies and the X-cells mostly to the lower temporal frequencies.

As their fourth measure of X/Y differentiation Cleland and his

coworkers employed the periphery effect where a stimulus, usually large, presented well away from the determined receptive field area of a given cell, elicits a response from this cell. When this was applied to their pool of cells, Cleland and his coworkers found a strong periphery effect in the Y-cells, and only slight or no response in the X-cells. In addition, simultaneous recording of retinal ganglion cells and lateral geniculate neurons showed that fast conducting optic axons were projections of the Y-cells and the slow projecting axons were from the X-cells.

The results of these experiments demonstrate that there is a functional difference between transient and sustained neurons at the ganglionic and geniculate levels of the visual system. It can also be assumed that the ganglio-geniculate connection has fast and slow conducting optic axons reflecting properties of Y- and X-cells. Furthermore, transient cells are less sensitive to pattern stimuli of higher spatial frequencies, are more sensitive to temporal information, and have larger receptive fields than sustained cells.

Ikeda and Wright (1972) extended these findings and showed that the Y-cells had ill-defined center-surround properties as opposed to X-cells. They conclude that the functional role of the Y-cells is to detect moving objects in the periphery because of their responses to both defocused and moving stimuli and because Y-cell receptive fields are distributed mainly in the periphery of the retina. The functional role of the X-cells is thought to be the analysis of spatial contrast and fine detail.

Hochstein (1979) has cautioned against a strict "parallel system"

interpretation of the X/Y functional classification. He points out that X/Y functional differences can be observed in relation to axonal size (conduction time), spatial summation characteristics, receptive field sizes and retinal distribution but that delimitation to one class or another is often arbitrary. Reporting the data obtained from 100 geniculate cells of 16 cats, he mentions that positive correlations do exist between these conditions but that they are generally weak (below +.50). He concludes that the X/Y dichotomy does not exist as a distinct bimodal distribution of cell types, but is a monomodal distribution or at best a distribution with peaks on opposite ends of a continuous spectrum.

Attempts to identify sustained and transient cells in the human visual system by psychophysical means have been reported (Tolhurst, 1973; Kulikowski & Tolhurst, 1973). Using the method of adjustment with flickering gratings, Kulikowski and Tolhurst (1973) determined the threshold for detecting flicker and the threshold for discriminating gratings for the same stimulus. Moreover, differential flicker thresholds for on/off and counterphase flicker were obtained. The on/off pattern was created by alternating a spatial pattern with a uniform field of the same average luminance. The counterphase flicker stimulus is an alternation between the dark and light bars at a set rate. For a stimulus of a given spatial frequency flickering at a set rate, observers were asked to adjust the contrast to determine when flicker was just perceived and at what contrast the spatial pattern was just perceived.

In obtaining these responses, a classification of separate channels

similar to the transient and sustained-type of cells proposed by the physiological data was possible. These channels were termed form-analyzing channels for the sustained responses (X-cells) and movement-analyzing channels for the transient responses (Y-cells) by Kulikowski and Tolhurst (1973). Generally, the transient channels respond better to low and medium spatial frequencies and are twice as effective in detecting stimuli of alternating phases over on/off flicker throughout all spatial frequencies tested. They also prefer temporal rates between 5 to 6 Hz with a sharp reduction of the response at lower temporal frequencies. The form-analysing channels responded better to higher spatial frequencies (above 3 c/d) and respond equally to counterphase and on/off temporal modulations.

Recently, Hess and Plant (1985) reported a study which attempted to identify the specific temporal components involved for lower and middle spatial frequency discriminations. Using spatial frequencies of 2.0 and 0.2 cycles per degree of visual angle (c/d) flickering sinusoidally at temporal frequencies of 0 to 32 Hz, they also demonstrated a peak detection threshold between 4 and 6 Hz. However, their data demonstrate an additional peak sensitivity at 32 Hz for the lower spatial frequency of 0.2 c/d which suggest an additional temporal mechanisms for larger patterns.

Hess and Plant (1983) examined spatial and temporal characteristics of vision in optic neuritis patients. They varied the temporal frequency for sinusoidal gratings of 0.5 and 4.0 cycles per degree of visual angle (c/d). The stimulus was initially presented below threshold and adjusted by the observer until either the temporal or

spatial characteristics were perceived. They report that at 4.0 c/d temporal stimulation has no effect on the decreased sensitivity shown by optic neuritis eyes. At 0.5 c/d however, the effect of decreased sensitivity gradually disappears as the temporal rate of the stimulus is increased. The authors tested normal observers with simulated paracentral scotomas within the central ten degrees of visual angle and they obtained results similar to those patients. They conclude that subtle scotomas within the central ten degrees could explain the results obtained by their patients, but, that for optic pathology of a less patchy nature - caused by ischemia or compression like glaucoma - such a specific effect would not be observed. It cannot be determined from their report whether the patients responded to spatial or temporal stimuli first. The results demonstrate, however, that in the case of optic neuritis, temporal resolution interacts more strongly at lower spatial frequencies.

Neural Colour Codes

Neurophysiological research has found inconsistent results for temporal coding of colour. In the monkey, Gouras (1968) reports colour-coded ganglion cells showing sustained responses to steady stimuli and slow conducting axons. These slow conducting axons were related to small ganglion cells called "tonic" and displayed colour-opponent properties. Other ganglion cells called "phasic" were large and displayed transient responses to any change of light. Other reports show that slow and fast conducting neurons respond differently to different colour stimuli (Lennox, 1958; Motakawa, Oikawa & Tasaki, 1957).

DeValois, Abramov and Jacobs (1966), in their neurophysiological study of the macaque monkey, report that most lateral geniculate nucleus (LGN) cells respond to colour stimuli. The stimuli consisted of various flashes of lights of different wavelengths presented across the visual field, with the response recorded from single LGN cells exhibiting spontaneous activity. Their results show two major classifications of neural response. These are "spectrally opponent" and "nonopponent" cells. The nonopponent cells respond the same way to all wavelengths while the opponent cells are excited by some wavelengths and inhibited by others. Opponent cells with the same response patterns to colours can still differ in the intensity of the neural response. Thus, they may be qualitatively similar and be quantitatively different.

de Monasterio (1978) has reported concentric cell types in the retina of the macaque monkey with X/Y cell properties. The X-cells had centers receiving input from one cone type and the surround from another while the Y-cells recieved input from one cone type for both the center and the surround. The Y-cells responded more to the lower spatial frequencies and the transient response was localized in the surround.

Psychophysically, there is evidence of both temporal and spatial neural codes for colour vision. McCollough (1965) presented an observer with alternating vertical and horizontal bars of different colours. The vertical bars were black and orange and the horizontal bars were black and green-blue. A grating was presented for 5 seconds followed by a 1 second dark period; then the grating of different orientation was presented under the same temporal conditions. This adaptation was done for several minutes, after which, the presentation of a black and white

grating elicited colour aftereffects. A black and white vertical grating appeared green-blue and a horizontal grating appeared yellow. When a grating oriented at 45 degrees was presented no colour aftereffect was reported. Stromeyer and Mansfield (1970) induced similar aftereffects using movement. Upward and downward movements of gratings were used as opposed to orientation changes.

Festinger, Allyn and White (1971) reported that several subjective colour perceptions can be obtained using stationary monochromatic stimuli with different temporal properties. In the first experiment, temporal patterns were generated, mimicking the retinal illuminance produced by a Benham's disk with little success in creating subjective colour. However, when a background light flickering in a square-wave fashion was also present, subjective colours were perceived. New temporal patterns, compensating for the flickering background, were successful only in creating red, blue and green colours. The other temporal patterns estimated from colour mixtures were not efficient in producing the anticipated colours.

The Pathophysiology of Glaucoma

The most common explanation for the loss of visual function in glaucoma is the occurrence of axonal damage at the optic nerve head. This, in turn, is thought to produce the classical visual field defects such as the nasal step or depressed sensitivity in the Bjerrum area (Quigley, Flower, Addicks & McLeod, 1980). Optic disc damage could be either due to ischemia in which the reduction of blood supply causes axonal death, or by a reduction of stoppage of axoplasmic transport

(Cockburn, 1985). Most of the support for an ischemic cause of optic disc atrophy comes from fluorescein angiograms of the nerve head where fluorescien filling defects correspond with visual field defects (Greve & Heijl, 1977; Talusan, Schwarts & Wilcox, 1980). However, Mizokami, Okubo and Isayama (1983), could not reproduce these findings on their glaucoma patients. They conclude that while the collapse of blood vessels does not preclude optic disc damage, it is secondary to it.

Another possible consequence of elevated pressure is the reduction of axonal flow towards either the LGN or the retinal ganglion cells. Axoplasmic transport of proteins and other intracellular materials is an essential function in both orthograde (towards LGN) and retrograde (towards retinal ganglion cells) transport. Labeling materials introduced into the optic nerve cells of monkeys demonstrate that axonal flow in both directions is reduced as a function of increased intraocular pressure (Minckler, Bunt & Johanson, 1977).

A further effect of glaucomatous damage to the eye is the selective loss of large and medium size fibers of the optic nerve tract. Of importance is the finding by Quigley, Dunkelberger and Sanchez (1986), that larger axons are destroyed first due to elevated intraocular pressure. Their study included 23 normal cynomolgus monkeys and 8 eyes with chronic elevated intraocular pressures. They examined optic-nerve cross sections using automated image analysis. The glaucoma eyes demonstrated a range of fiber loss between 25 and 95%. The average axonal diameter remaining in the glaucoma eyes was significantly smaller than the normal eyes. Furthermore, histograms of fiber diameter revealed a sequential loss of large and medium axons. The small fibers

were the last fibers affected. In a similar study, Minckler and Ogden (1986) also showed that large axons were particularly vulnerable to injury in glaucomatous monkey eyes.

These findings show that whether the destructive source is due to ischemia or to a reduction of axonal flow, damage to the ganglio-geniculate pathway is present in glaucoma. Additionally, this damage appears to be selective, at least in the early stages, by progressively damaging large and medium fibers. If these statements are correct, psychophysically demonstrated loss of visual functions, corresponding to the Y-cells should be observed in glaucoma patients and suspects who may have incurred glaucoma. This would be reflected by a selective loss of sensitivity to lower and middle spatial frequencies and a loss of temporal resolving power in early stages of the pathology.

Spatial Sensitivity and Temporal Resolution Loss in Glaucoma

Atkin, Bodis-Wollner, Wolkstein, Moss and Podos (1979) used electronically generated patterns to test glaucoma suspects and glaucoma patients for spatial resolution. A diffuse target and sinusoidal gratings were presented in a counterphase mode, both flickering at 8 Hz (cycles per second). Eleven glaucoma eyes, 10 glaucoma suspects eyes and 37 control eyes were used in the study. The mean luminance level was 40 foot Lamberts and the test target subtended 4 degrees of visual angle. The spatial frequency gratings subtended 1.2 cycles per degree (c/d) of visual angle. Confirmed glaucoma was determined by abnormal visual fields with the use of the Goldmann perimeter and optic nerve head abnormalities in conjunction with intraocular pressures of 22

millimeters of mercury (mm Hg) or higher for untreated eyes. The criterion for glaucoma suspects was an intraocular pressure of 22 mm Hg or greater. A significant decrease was found in the contrast sensitivity functions on both tests for the glaucomatous eyes compared to the normal eyes. The glaucoma suspect means were not significantly different from the normals but, using a 30 db normality criterion, 50% of the suspects fell below this limit (1.5 $\log_{10}$ sensitivity).

Since the advent of Arden plates for testing spatial contrast sensitivity (Arden, 1978), responses to stationary gratings were shown to be affected in glaucoma and also in glaucoma suspects but with less consistency (Hitchings, Powell, Arden & Carter, 1981; Stamper, Hsu-Winges & Sopher, 1982). Neima, LeBlanc and Regan (1984), used computer generated sine waves presented with a counterphase flicker of 8 Hz to test glaucoma patients and glaucoma suspects. The classification criterion for glaucoma was similar to the one used by Atkin and coworkers (1979). Gratings of 2 and 5 c/d were used in addition to a visual acuity task, and the testing was performed across the visual field. The visual acuity task was to determine the spatial frequency cut-off point or the highest spatial frequency that could be seen at 100% contrast by the observer. The 2 and 5 c/d spatial frequency tasks were often abnormal when compared to a normal range while the visual acuity task was no different for the control, suspects or glaucoma groups.

Wolkenstein, Atkin and Bodis-Wollner (1980), as well have found lower and middle spatial frequency losses when using counterphase flickered gratings but also found cut-off frequency deficits in 18

glaucoma patients with 20/20 vision. However, their results are of less reliability because the authors do not mention how they identified glaucoma patients or what the mean age was for the subjects.

Notwithstanding the spatial contrast sensitivity losses of temporally presented patterns mentioned above (Atkin et al., 1979; Neima et al., 1984; Wolkenstein et al., 1980), loss of temporal resolving power in glaucoma has been demonstrated for quite some time. In 1947, Weekers assessed the critical fusion frequency (CFF) for flicker across different meridians of the visual field of glaucoma patients. At the time, visual field measurements were mostly conducted with tangent screens. This test consists of a black background over which a white target can be moved across the differeht meridians. The target is moved from outside the visual field inwards until the observer perceives the target. Using a static method with an immobile target light and a flickering light of increasing rate, he showed that all defects represented by conventional fields tests (tangent screen) were accentuated and that many abnormalities in the CFF were present where no corresponding field defects were detectable. Later, Miles (1950) and Campbell and Rittler (1959) demonstrated losses of the CFF in glaucoma with similar techniques.

Recently, Tyler (1981) tested flicker sensitivity in glaucoma patients and glaucoma suspects. A 5 degree visual field, with an average luminance of 40 candela per square meter (cd/m^2), was used to present a sinusoidally modulated flicker varying from 5 to 100 Hz in the central visual field and in the Bjerrum area. The task of the observer is to adjust the contrast needed to perceive the flicker. Tyler found

significant losses of flicker sensitivity particularly in the 20 to 40 Hz range prior to any signs of visual field defects.

Glaucoma and Acquired Colour Vision Defects

Colour vision deficits are usually classified as congenital or acquired (Pokorny, Smith, Verriest & Pinckers, 1979). The important distinction is that acquired colour vision defects are secondary effects produced as a consequence of a visual pathology or trauma. Congenital colour defects are present at birth without necessarily implying other major visual problems. Another differentiation between congenital and acquired colour vision defects is that congenital defects usually include only one axis of colour deficit, while the acquired colour defects often vary within different axes. In other words, congenital defects are often reflected by a reduced selective response for one of the three basic colours (red, green and blue) and reduced sensitivity for colour mixtures which include the basic colour in question. Acquired defects are reflected by diminished sensitivity to more than one basic colour. Traditional classifications of acquired colour vision defects are usually based on categories suggested by Verriest in 1963 (Pokorny et al., 1979): Type 1, Type 2, and Type 3 colour vision deficits. Type 1 deficits are usually on the red-green axis and vary from mild to severe. They produce trichromatic to monochromatic results in colour matching assessments. The reduction of visual acuity can vary from moderate to severe, and a frequent outcome of such disorders is achromatopsia (scotopic vision). Type 2 colour vision defects are also along the red-green axis with an accompanying milder blue-yellow

deficit and they vary from mild to severe. Visual acuity loss varies from moderate to severe. Individuals may recover or may experience an increased loss of vision. Evidence of trichromatic to monochromatic colour vision are obtained from colour matching tests. Type 3 deficits demonstrate discrimination deficits of the blue-yellow axis from mild to moderate. Visual acuity losses range from mild to severe. Colour matching tests show trichromatic and dichromatic results with only rare occasions of monochromacy. The outcome varies considerably throughout individuals and pathologies. Early stages of Type 3 defects usually demonstrate confusions in the blue region of the chromaticity diagram (Pokorny et al., 1979).

Two basic types of colour vision defects have been observed in confirmed glaucoma patients. Red-green defects have been found, but these cases are rare and, when present, are associated with late stages of glaucoma (Pokorny et al. 1979). The most frequent defects are Type 3, blue-yellow defects. Francois, Verriest, and De Rouck (1957) demonstrated these defects using plate tests, Farnsworth Panel D-15, and a Nagel anomaloscope. Recently, Drance, Lakowski, Schulzer and Douglas (1981) found both defects. However, the blue-yellow defects were found more frequently and were much better predictors of visual field defects. Using the Farnsworth-Munsell (FM) 100-hue test McNaught, Rennie, McClure and Chrisholm (1974) report that in unilateral acute angle closure glaucoma, 40% of the affected eyes displayed Type 3 blue-yellow defects and only one of the affected eyes revealed Type 2 red-green defects. Francois and Verriest (1968), in a review of this literature, mentioned that in established chronic simple open angle glaucoma, 20% of

individuals show normal colour vision, 40% show moderate Type 3 blue-yellow defects, 32% can be classified as severe Type 3 blue-yellow defects, and 6% are red-green defects.

With glaucoma suspects, Lakowski and Drance (1979) have observed that the FM 100-hue test and the Pickford-Nicolson anomaloscope were the two most efficient techniques for clinical diagnosis. Using these techniques, they showed that, of 250 glaucoma suspects, 20% had colour vision deficiency equivalent to that found in severe glaucoma. Nine of the patients who were followed over a 5-year period developed chronic simple glaucoma and the colour vision tests on these patients, while glaucoma suspects, had shown deficiencies in colour discrimination. Thus, Lakowski and Drance consider large losses in colour discrimination as good predictors of chronic simple glaucoma development. Recently, Flammer and Drance (1984) demonstrated that colour deficiencies, measured by FM 100-hue error scores, correlate well with measures of quantitative perimetry.

Present Study

For the present research, an underlying assumption was that the X/Y cell classification is valid for the human visual system, and that this classification corresponds to cell types of small and large axons respectively. The X/Y classification here does not imply two distinct cell types but rather cells which reside at opposite ends of a continuum. The X-cells are the smaller neuron types with more sustained-like properties and the Y-cells are the larger neurons with larger axons thought to have transient-like properties. It was also

assumed that early glaucomatous damage is reflected by a specific loss of large optic nerve axons.

In view of the current knowledge regarding localized neuronal loss in glaucoma, three tests were chosen to assess selective functional losses of hypothetical mechanisms of vision. The three tests measure spatial resolution, temporal resolution, and colour vision respectively. As stated earlier, a selective cell loss may affect spatial, temporal and colour vision mechanisms in specific ways. A loss of large axons can be hypothesized to affect temporal resolution generally and spatial sensitivity channels specifically; notably, at lower and middle spatial frequencies. This would imply that temporal and spatial mechanisms are independent under certain conditions and not in others. If, on the other hand, only one type of test is affected in glaucoma, it could be shown that the mechanism in question functions independently of others. A similar type of argument can be made for colour; however, evidence suggests that colour mechanisms are related to both spatial and temporal mechanisms.

A decrease in temporal resolving power and sensitivity to lower and middle spatial frequencies as well as colour sensitivity, was expected for the early glaucoma and suspect groups. The temporal resolution decrease was expected to be more pronounced because the test used sampled throughout a 40 degree field while the spatial task stimulated only the central eight degrees.

Because temporal resolving power in this study was tested in 120 points of a 40 degree visual field, a progressive assessment of the loss of sensitivity from the fovea towards the periphery was possible.

Moreover, the selection of the patients was such that the difference between the early confirmed glaucoma and the glaucoma suspect eyes was minimal. This allowed for a continuity in the patient population, making it possible to observe early, gradual, functional losses develop from a presumed selective loss of large axons of the optic nerve. Further, a direct comparison between temporal sensitivity, spatial contrast sensitivity and colour vision using independent techniques was possible.

Experiment 1

The purpose of the first experiment was to examine the temporal resolving power across the visual field using the multi-flash campimetry technique (Brussell, White, Bross, Mustillo & Borenstein, 1981/82). This technique is useful for testing temporal resolution because it samples 120 points across a 40 degree visual field. This enables the experimenter to compare directly the field defects obtained from kinetic and static perimetry with losses of temporal resolution in the visual fields.

Method

Subjects Thirty eyes of 30 different observers were used in this study. The observers were separated into three groups which were the early confirmed glaucoma patients, glaucoma suspects, and control subjects consisting of 9, 10 and 11 individuals respectively. All participants had 20/25 (6/7.5) or better corrected visual acuity. The glaucoma and glaucoma suspect patients were all obtained from the private practice of an ophthalmologist specializing in glaucoma. The glaucoma suspect eyes all had intraocular pressures of 21 mm Hg or greater in the untreated eye. They had no visual field abnormalities as measured by the Armaly-Drance technique on the Goldmann perimeter (Drance, Brais & Fairclough, 1972) and no optic nerve head abnormalities. The normality or abnormality of the visual fields and optic nerve heads were determined by the referring ophthalmologist. All the Goldmann visual fields were plotted by the same technician who was unaware of the particulars of the study. The mean age for the glaucoma,

suspect and control groups were 52, 49 and 49 respectively with a global age range between 24 to 75 years. An attempt was made to maintain the age of the study groups similar by selecting observers in decades. Octopus automated static perimetry was also performed on the suspects and glaucoma patients (program 38 or G1 on the Octopus 500R). All the glaucoma suspects showed normal static fields except for one with slight superior depression. Four patient eyes from the glaucoma group showed localized or generalized defects and the other five had normal static fields.

Apparatus Multi-flash campimetry was implemented on a PDP11/10 computer interfaced with a large screen cathode ray tube (Hewlett Packard 1310A with a P15 phosphor). The luminance was measured with a Spectra Spot Meter.

Procedure Multi-flash campimetry tests temporal resolution in 120 points of a 40 degree visual field. The display is divided into four quadrants and these are presented randomly. Within each quadrant, all the target points are constantly illuminated and one of the points is randomly chosen to assess the off-period necessary to perceive a 5 Hz flicker. The duty cycle is systematically decreased and the off period increased by 1.4 % (2.8 msec changes in the on- and off-periods) until the observer perceives flicker and depresses the response key.

Prior to the testing session, practice trials are presented in the form of two quarter circles with a total of 15 points on the screen. One of these points is located in the blind spot when proper fixation is maintained. This practice session is repeated until the observer is comfortable with the task and does not respond to the point in the blind

spot. The head position is fixed with a head and chin rest at a distance from the screen of 57 cm. The luminance level is measured with a small target containing all the points adjacent to one another with a mean luminace of 3 cd/m^2.

Each point on the screen subtends 6 minutes of visual angle. The display consists of 6 concentric circles each containing 20 points (see Figure 1). The retinal eccentricities of the radii of the circles subtend 0.625, 1.25, 2.5, 5.0, 10.0 and 20.0 degrees respectively. At the end of the testing session, a print-out of the mean off-period for each concentric circle with standard errors is available. Individual data points are also printed, indicating whether any points significantly deviate from the criterion which is set at a response level greater than 7 standard errors for the mean response of a given concentric circle or 21 standard errors greater than the general mean response for the eye. These points are replicated to avoid misinterpretation due to lapses of attention or momentary loss of fixation.

Results

The multi-flash campimetry technique provides a visual field map of the data in the form of a gray scale which demonstrates the temporal sensitivity of the different areas of the visual field. In this study, the mean off-periods necessary to perceive flicker for each concentric circle were used for data analysis. A split-plot factorial design analysis of variance (ANOVA) was used, with the three visual conditions (glaucoma, suspects and controls) as the between measures and the six retinal eccentricities as the within conditions. The individual data

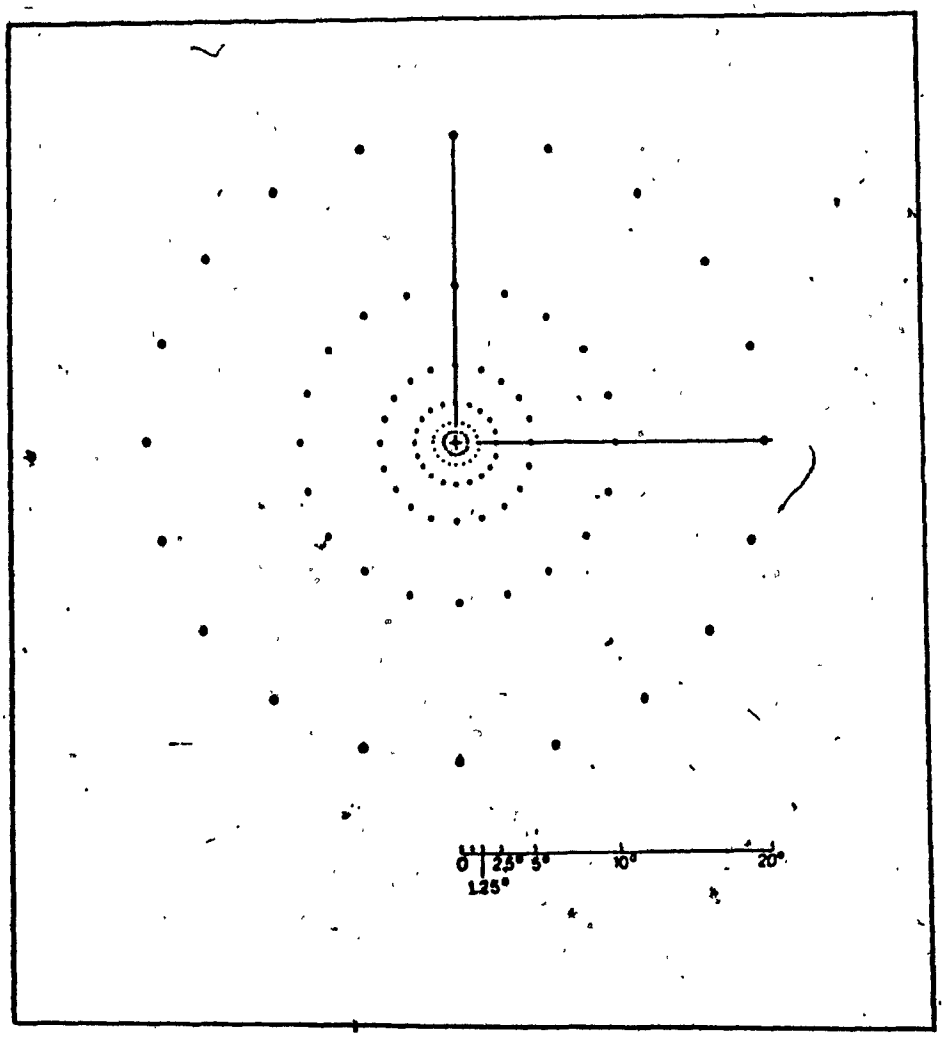

Figure 1. A schematic representation of the stimulus display used in multi-flash campimetry. The lines demonstrate that the display is presented one quadrant at a time.

can be seen in Appendix A. Figure 2 represents the mean and standard error of the off-period necessary to perceive flicker for each group across retinal eccentricity. The group means were significantly different, $F(2,27) = 3.718$, $p<.05$ and the differences across retinal eccentricity were also significant, $F(5,135) = 25.189$, $p<.001$. The interaction between the within conditions (retinal eccentricity) and the between conditions (diagnostic category) was not significant. Post hoc Scheffé tests revealed that the glaucoma and suspect groups are only significantly different at 1.2 and 2.5 degrees away from the fixation point. While both the glaucoma and the suspect group differ from the control at the three most distant eccentricities, the glaucoma group differs from the control at all retinal locations. As seen in Figure 2, the temporal resolving power, measured by multi-flash campimetry, is best centrally and then progressively declines, with the worst sensitivity at five degrees of eccentricity, and then asymptotes for the last two eccentricities. This pattern remains constant regardless of the diagnostic category as evidenced by a lack of significant interaction.

Discussion

The results obtained confirm those reported by Atkin et al (1979), Campbell and Rittler (1959), Miles (1950), Neima et al. (1984), Tyler (1981) and Weekers (1947) that temporal resolving power is attenuated in glaucoma. In addition, multi-flash campimetry demonstrates specifically that the decrease of temporal resolution caused by glaucoma is consistent throughout the 40 degree visual field measured. Figure 2

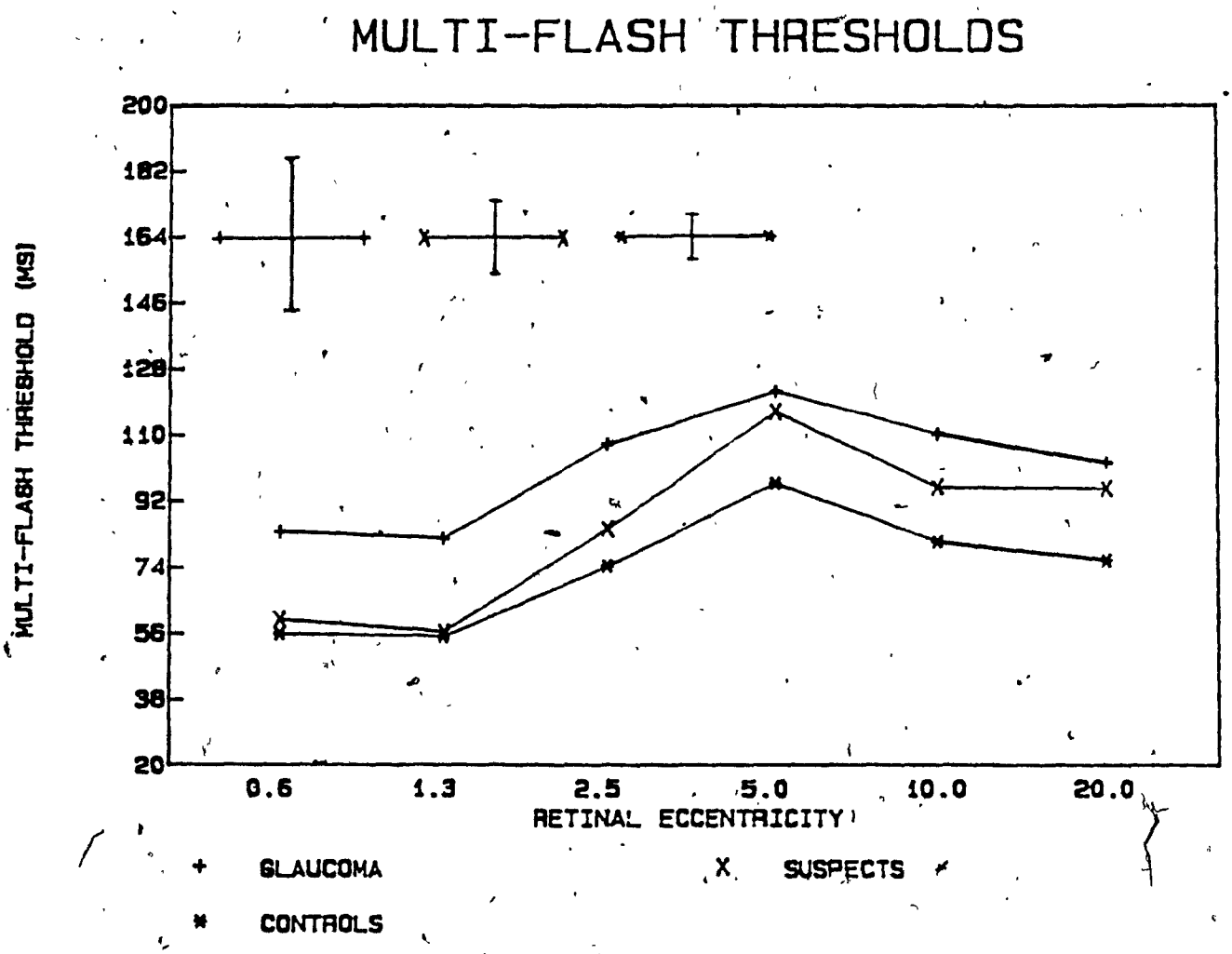

Figure 2. Mean multi-flash thresholds (critical off-period) for the different diagnostic categories as a function of retinal eccentricity. Average standard error bars are shown for the individual conditions.

suggests that the earliest damage occurs in the periphery. The suspect group demonstrates significant differences from the control group at five degrees eccentricity and beyond. This corresponds well with the notion that Y-cells with large axons, which are affected first (Minckler & Ogden, 1986; Quigley et al., 1986), create selective losses in the periphery. The data show a clear pattern where temporal sensitivity declines progressively after 1.3 degrees of retinal eccentricity to reach a maximum at 5 degrees. Further, as glaucoma progresses, the functional impairment generalizes to include the more central areas of the retina as demonstrated by the glaucoma group. The variability of the data also increases progressively from the controls to the glaucoma eyes. This could reflect a cell loss which would decrease the probability of detecting light and as a consequence would increase the variability for detecting flicker.

Experiment 2

As pointed out in the introduction, spatial contrast sensitivity deficits, particularly in lower and middle spatial frequencies presented in a counterphase mode, have been associated with glaucoma. The second experiment was designed to assess spatial contrast sensitivity deficits in the early stages of glaucoma, thus, to provide evidence for a deficit in spatial contrast sensitivity as predicted by the X/Y classification paradigm in the case of glaucoma.

Method

Subjects The same 30 eyes of the 30 observers were used for this experiment.

Apparatus The same computer (PDP11/10) and CRT screen (HP 1310A) were used, interfaced with Wavetek function generators. The latter allowed projection of sine wave gratings within an 8X8 degree of visual angle window on the CRT. The average luminance was measured with a Spectra Spot Meter.

Procedure The viewing distance was one meter with the head supported by a head and chin rest. The anticipated threshold technique developed by Brussell and Cavanagh (1984) was used to generate stationary sinusoidal gratings of six different spatial frequencies. This technique uses previous information obtained from the observer to estimate the threshold point. Each trial operates in two steps. In the first half of the entire estimated threshold time, contrast increases rapidly and in the other half contrast increases slowly. This allows for an increased speed of assessing spatial contrast sensitivity without

compromising detection at threshold. The mean luminance of the screen was set at 5 cd/m^2 and the spatial freqencies tested were 1.00, 1.82, 3.31, 6.03, 10.99 and 20.00 CPDs. Each spatial frequency was tested in blocks of seven trials. The first two are considered practice trials and the average is calculated only for the last five. Catch trials and delayed intervals were introduced randomly to avoid time-based responses. All observers wore their distance correction throughout the test. The presentation sequence of spatial frequencies was randomized.

Results

Individual spatial sensitivity data are presented in Appendix B. The highest spatial frequency used (20 c/d) was excluded from the analysis because the observers were unable to see this grating at the luminance level used. The data show no significant differences between diagnostic categories but show, as expected, a significant difference across spatial frequency $F(4,108) = 114.9$, $p<.001$. The ANOVA also reveals a statistically significant interaction between the diagnostic categories and the spatial frequencies, $F(8,108) = 2.55$, $p<.02$. Figure 3 illustrates that the three group means are similar.

If the proposed hypothesis that Y-cells are primarily affected by early glaucoma damage was true, a relationship between lower and middle spatial frequencies should exist regardless of the fact that mean spatial sensitivities are not significantly different between diagnostic groups. Table 1 summarizes Pearson correlation coeficients obtained from several combinations. The data for spatial contrast sensitivity was grouped into two different categories. The lower and middle spatial frequency data (1.00, 1.82 and 3.31 c/d) were combined to obtain an

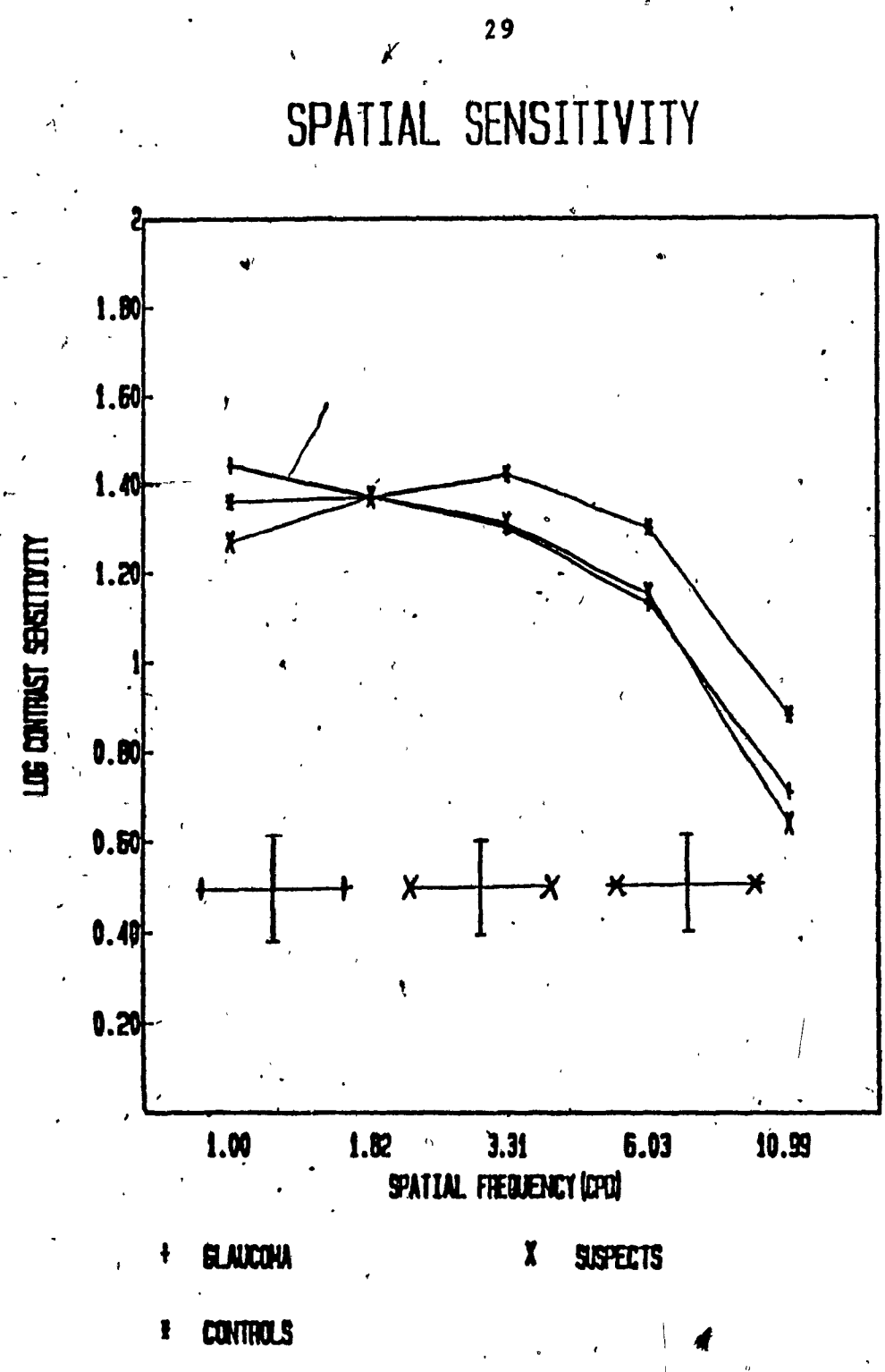

Figure 3. Mean log contrast sensitivity scores for the different diagnostic categories as a function of spatial frequency. Average standard error bars are shown for the individual conditions.

Table 1

Correlations between multi-flash campimetry and spatial contrast sensitivity data

Controls

Spatial Fre.	Central 10 Degrees	Beyond 10 Degrees
lower 3	-.53	-.51
higher	-.45	-.58 $p<.06$

Glaucoma and Suspects

Spatial Fre.	Central 10 Degrees	Beyond 10 Degrees
lower 3	-.47 $p<.05$	-.29
higher 2	-.30	-.04

Glaucoma

Spatial Fre.	Central 10 Degrees	Beyond 10 Degrees
lower 3	-.65 $p<.06$	-.32
higher 2	-.33	+.20

Suspects

Spatial Fre.	Central 10 Degrees	Beyond 10 Degrees
lower 3	-.48	-.33
higher 2	-.37	-.39

average and the same was done for the higher spatial frequencies (6.03 and 10.99 c/d). Further, the multi-flash thresholds were averaged across the central 10 degrees of the visual field which corresponds to the first four concentric circles, and another average was calculated for the rest of the visual field. This separation was performed because the central 10 degree measure corresponded best to the area of the visual field covered by the 8X8 degree window used for the spatial task. If a relationship exists, negative correlations should be expected because loss of sensitivity is reflected by higher multi-flash thresholds and lower spatial contrast sensitivities. The correlation coefficients for the control eyes show homogeneity, varying from -.45 to -.58. The significance levels in Table 1 reflect the dispersion away from a mean of $r = 0$. This homogeneity is disrupted particularly for the glaucoma group. However, the strongest correlation was between the lower three spatial frequencies and the central 10 degrees of the glaucoma group ($r = -.65$), where presumably more damage has occured. The same though weaker pattern is present for the suspect group.

Discussion

The lack of significance between group means is inconsistent with the findings of other researchers (Atkin et al. 1979; Hitchings et al. 1981; Neima et al. 1984; Stamper et al. 1982; Wolkenstein et al. 1980). However, two factors must be taken into account to explain these results. The first factor is that the criterion for glaucoma classification required only disc cup abnormalities or visual field abnormalities and not both conditions as in the other experiments. This

means that some eyes were considered glaucomatous without any visual field defects. The second factor is that stationary gratings rather than temporally modulated gratings were used in this study.

The correlational data are consistent with the proposition that Y-cells with larger axons are affected early in glaucoma. The homogeneity demonstrated by the correlational data of the controls implies that, in the normal visual system, the different visual mechanisms maintain a similar relationship across spatial frequencies, which renders support for a linear model of X/Y classification. The important finding is that while some of the other correlations change with condition in the positive direction, the correlation between the central 10 degrees of multi-flash and the lower and middle spatial frequencies for the glaucoma group are actually strengthened. This supports the notion that there is a tendency for the larger Y-cells to respond more to temporal resolution and larger spatial frequencies than the X-cells.

The fact that the group means for temporal resolution are more affected than those for spatial contrast sensitivity in these results could be due to the inherent characteristics of the techniques used. The spatial task verifies central vision specifically and the temporal technique probes throughout a 30 degree field. Given that Y cells are more common towards the periphery, it would be expected that the the most peripheral sampling points are affected first in glaucoma. This is well represented by the larger multi-flash deficits towards the periphery as can be seen in Figure 2.

Experiment 3

The aim of the third study was to assess whether colour vision as measured by the HRR plates and the FM-100 test would be reduced in early stages of glaucoma. Assuming that neural colour codes can be transmitted by either X- or Y-cell types, reduced colour sensitivity was expected.

Method

Subjects Twenty-six of the 30 eyes used in the previous experiments were used in this study. Four observers could not perform the colour test due to scheduling problems. The glaucoma, glaucoma suspect and the control group contained 9, 8 and 9 observers respectively.

Apparatus A standard FM 100-hue testing kit and a set of American Optical H-R-R Pseudoisochromatic plates (HRR) were used to assess colour vision. Both tests were performed under the illumination of an Easel Lamp (Macbeth Corporation).

Procedure The standard instructions for HRR and FM 100-hue tests were given to the observers with the exception that no time limit was imposed for the completion of the FM 100-hue test. The FM 100-hue test consists of 85 different colour chips separated in four different boxes presented at random to the observer. The task is to place the chips in the correct sequence of hue. For the HRR test, the subjects were required to name the geometrical patterns, formed by coloured dots, and point to their location on the plate.

Results

No errors were made on the HRR plates by any of the observers. This excludes the possibility that colour blindness may interfere with the FM 100-hue results. For the FM 100-hue test, no statistically significant differences were found between the three groups. Figure 4 represents the three group means with their standard errors. The individual data scores and FM-100 maps are in Appendix C.

Correlations between the contrast sensitivity data of the lower spatial frequencies (1.00, 1.82 and 3.31 c/d) and the FM 100-hue error scores, and the higher spatial frequencies (6.03 and 10.99 c/d) and error scores were calculated. The highest correlations were obtained between the higher spatial frequencies and the FM-100 error scores (see Table 2). Negative correlations should be expected between colour and spatial scores because a decrease in sensitivity in the respective tests is reflected in opposite directions while the reverse is true for the temporal and colour scores. The homogeneity of the response from the control eyes reflected in the previous correlations between spatial and temporal sensitivity is again reflected between temporal, spatial and colour scores in Table 2. A marked change in the correlation coefficients occurs between the controls and the glaucoma group of the temporal resolution data while sensitivity to higher spatial frequencies varies with sensitivity to colour and in some cases this association becomes stronger than the controls.

Discussion

FM 100-hue error scores vary enormously across individuals (from 4

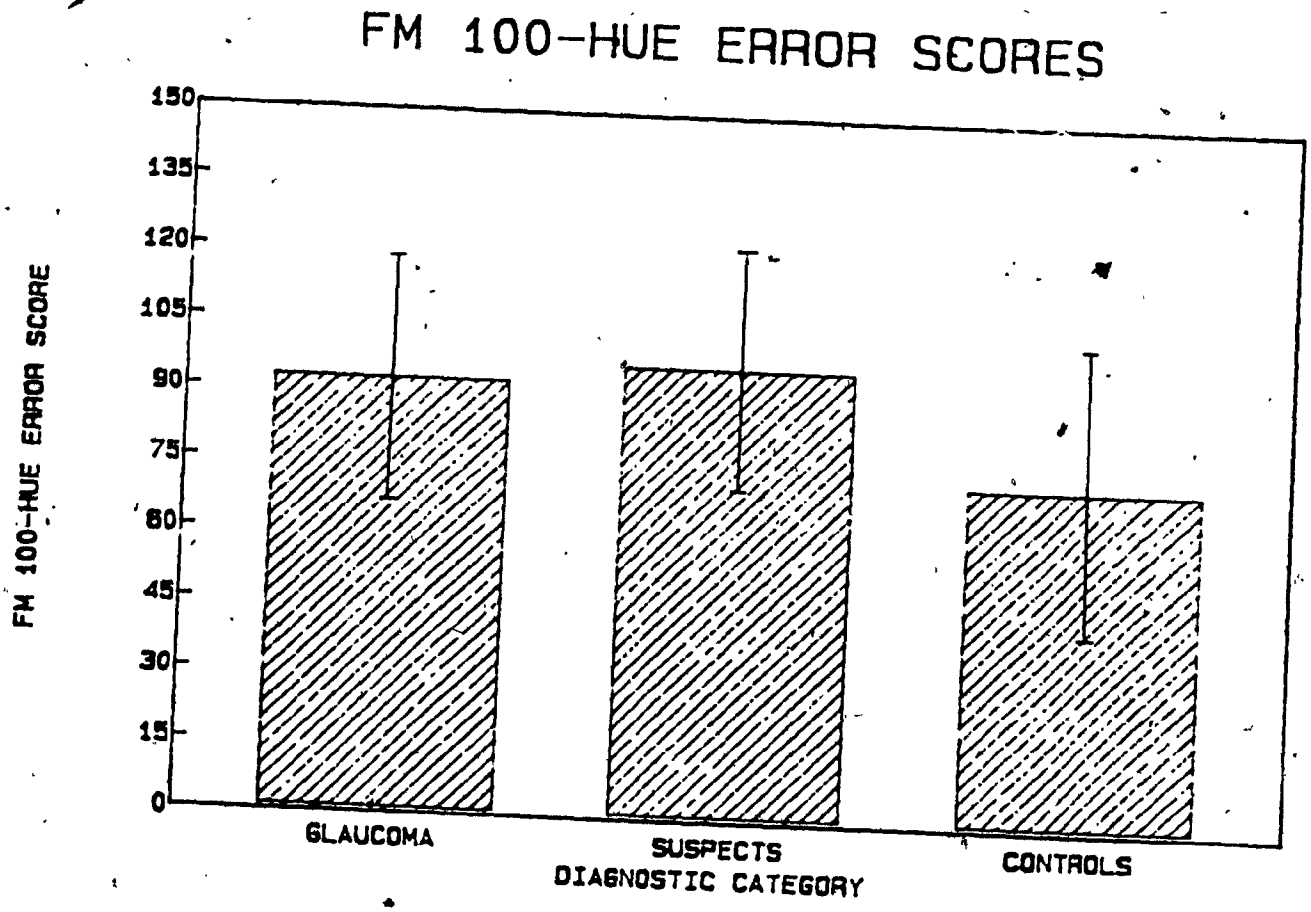

Figure 4. Mean FM 100-hue error scores for the different diagnostic categories. Standard error bars are shown for each condition.

Table 2

Correlations between FM 100-hue error scores and spatial and temporal sensitivity data

FM-100 and Spatial Frequency Data

Error Score	Lower 3 Spatial Fre.	Higher 2 Spatial Fre.
Controls	-.42	-.67 $p<.05$
Glau & Susp	-.26	-.62 $p<.01$
Glaucoma	-.41	-.57
Suspects	-.02	-.75 $p<.05$

FM-100 and Temporal Frequency Data

Error Score	Central 10 Degrees	Beyond 10 Degrees
Controls	+.61	+.54
Glau & Susp	+.05	-.13
Glaucoma	-.01	-.39
Suspects	+.21	+.27

to 184). The lack of significance between the mean error scores of each group is not surprising with such a small sample size. The correlational data implies that the colour information obtained from the FM-100 task was spatial in nature and would possibly involve X-cells. In the type of task required by the FM 100-hue test, high spatial frequency channels in the central area of the visual field are extremely important. Perhaps a temporally modulated chromatic task would reveal functional deficits more consistently related to glaucomatous optic nerve atrophy.

General Discussion

It was proposed in this study that early damage caused by glaucoma affects a specific type of nerve cell, as suggested by physiological studies (Minckler & Ogdon, 1986; Quigly et al., 1986). These cells, frequently referred to as Y-cells, are believed to have selective functional properties (Blake & DiGianfilippo, 1980; Cleland et al., 1971; Enroth-Cugell & Robson, 1966; Ikeda & Wright, 1972). The use of early confirmed glaucoma or glaucoma suspects as observers allows for a clearer assessment of whether the first cell types affected are Y-cells. Temporal resolution loss, as measured by multi-flash campimetry, was expected to be present, along with spatial contrast sensitivity loss of the lower spatial frequencies and colour vision loss.

As found by other researchers (Atkin et al., 1979; Campbell & Rittler, 1959; Miles, 1950; Neima et al., 1984; Tyler, 1981; Weekers, 1947), a loss of temporal resolving power was observed. The differences in mean scores of contrast sensitivity for lower and middle spatial frequencies were not significant. This is probably not surprising if one attends more closely to the diagnostic criteria, and the actual implementations of the tasks. The studies that were clear in their diagnostic criteria, considered an eye to be glaucomatous when both classical visual field defects and optic disc abnormalities were present in addition to elevated pressures. In the present study, either one of the former conditions, in conjunction with elevated pressure, was enough for an eye to be considered glaucomatous. Furthermore, the temporal resolution task samples 120 points in a 40 degree visual field while the spatial contrast sensitivity task samples centrally. The quantity of Y-

cells increases towards the periphery thus temporal resolution was sampled for a larger number of Y-cells.

The correlation coefficients obtained for the controls were homogeneous across all the conditions. This supports the notion that X/Y cells are components of a continuum (Hochstein, 1979). If the X/Y classification depended on distinct cell types, then temporal resolution and the lower spatial frequencies should have a stronger relationship than temporal resolution and higher spatial frequencies, which was not the case. However, a selective loss of large axons by glaucomatous damage, which decreases temporal sensitivity significantly, does not affect the relationship between temporal resolving power and lower spatial frequencies but does affect the relationship between temporal resolving power and higher spatial frequencies. Therefore, as Enroth-Cugell and Robson (1966) and Hochstein (1979) have argued for neurophysiological data, it should be said that the Y-cells have a "tendency" to respond more to temporal information and lower spatial frequencies.

The results obtained from Experiment I support strongly the assumption that large axons are injured first in early glaucomatous damage. The progressive loss of sensitivity as a function of eccentricity for the glaucoma suspects, demonstrates that the larger cells in the periphery are affected first. The damage then generalizes in later stages of glaucoma to include loss of temporal resolving power in the central area.

Scores from the FM 100-hue test show no significant differences between groups at these early stages of glaucomatous development. It

was argued that colour neural codes can be spatial in nature (deMonasterio, 1978; McCollough, 1965) or temporal (deMonasterio, 1978; Festinger et al., 1971). The colour data obtained from this study are not surprising given the assumption that Y-cells are primarily affected early in glaucoma. The use of the FM 100-hue test biases high spatial frequency channels because of the physical properties of the colour chips. That is, acuity channels or channels used to perceive fine detail centrally are essential to perform well on the FM-100. Thus, the error scores should be affected very little by an early Y-cell loss. Figure 2 demonstrates that only the glaucoma group shows significant deficits in temporal resolution. The suspect group shows no deficit centrally but does peripherally. Thus, as the disease progresses, the functional deficits generalize to the central area where a colour deficit would be expected. If a colour deficit was observed using a central task, prior to other functional deficits, this could mean that the damage is already generalized and, as such, represents later stages of the pathology. Individual differences in light sensitivity can account for a lack of field defects in these patients. A similar argument can be made for spatial contrast sensitivity functions which measures central vision.

Further, Lennie (1984) argues that there may be two sepparate mechanisms in the retino-geniculate projections of the monkey visual system. One of the mechanisms corresponds to the projections that go from the retinal ganglion cells to the parvocellular cells of the dorsal LGN which have slow conduction velocities, smaller receptive fields, and are responsible for colour information. The other mechanism is the

result of fibers reaching from the retinal ganglion cells to the the magnocellular cells of the ventral LGN which have fast conduction velocities, larger receptive fields, and are responsible for achromatic information. This would argue that a loss of colour perception as a result of selective loss of large and medium fibers in early glaucoma should not be expected.

Several suggestions can be made for future research. First, along with the use of separate techniques for assessing temporal, spatial and colour information, a more direct comparison between these mechanisms would be beneficial. Neima and coworkers (1984) have compared spatial and temporal thresholds within the same test by changing task requirements, in different areas of the visual field. Colour tests modulated both temporally and spatially would be interesting when testing glaucomatous eyes. There exists a possibility that Y-cells in the human system are important in colour perception. This sensitivity could be examined with the use of temporally modulated colours. If Y-cells are indeed affected first in early glaucoma, a reduction of sensitivity to temporally modulated chromatic stimuli would be more severe than for spatially modulated stimuli.

Finally, both the vision researchers and the medical community would profit from further research in this area. As neurophysiological evidence increases in favor of specific types of cell losses in glaucoma, more direct and controlled studies of different visual mechanisms are possible. If this research can localize defects of different cell types, more efficient diagnostic and monitoring methods can be developed.

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Appendix A

Multi-flash Campimetry Data

Concentric circle mean off-period for the glaucoma group across retinal eccentricities

Glaucoma patients

Obser.#	Eye	age	.625	1.25	2.50	5.00	10.00	20.00
1	R	24	63.42	79.60	138.30	117.30	79.60	67.30
2	L	27	89.60	77.70	118.70	180.70	189.90	179.00
3	R	40	37.60	45.90	66.00	88.20	70.70	67.00
4	L	49	39.50	47.00	72.10	78.40	62.40	66.00
5	L	55	53.88	53.30	90.58	132.40	103.38	80.30
6	R	62	65.60	82.00	161.40	114.50	144.20	131.60
7	R	66	177.20	142.60	71.60	67.00	70.50	82.30
8	L	69	60.40	56.42	82.80	135.50	126.68	117.40
9	L	75	166.10	151.60	166.40	182.90	144.90	130.60
Means		52	83.70	81.79	107.54	121.87	110.25	102.38

Multi-flash Campimetry Data

Concentric circle mean off-periods for the suspect group across retinal eccentricity

Glaucoma Suspects

Obser.#	Eye	Age	.625	1.25	2.5	5.0	10.0	20.0
10	L	24	47.10	56.45	81.90	145.80	95.70	91.10
11	R	34	62.40	63.40	91.10	102.60	100.80	90.80
12	R	34	49.80	53.20	75.30	88.30	83.90	78.55
13	L	35	43.75	41.95	63.40	80.20	72.10	76.00
14	R	43	53.20	64.50	99.60	108.70	81.00	79.50
15	R	57	33.98	34.84	49.66	80.36	61.72	75.30
16	L	61	51.72	40.10	54.10	117.48	70.78	68.66
17	R	63	73.09	56.26	118.30	128.30	146.70	140.80
18	L	64	104.00	69.00	86.00	166.80	140.70	153.40
19	L	72	78.68	84.12	125.50	145.12	104.18	101.58
Means		49	59.77	56.38	84.48	116.36	95.75	95.56

Multi-flash Campimetry Data

Concentric circle mean off-period for the control condition across retinal eccentricity

			Control Condition					
Obser.#	Eye	Age	.625	1.25	2.5	5.0	10.00	20.00
20	R	27	41.00	51.86	76.14	86.97	57.90	52.64
21	L	28	42.50	46.90	64.00	79.40	54.88	54.00
22	R	31	37.62	42.52	66.50	91.10	77.90	66.34
23	L	42	45.70	44.90	52.50	84.70	94.00	83.80
24	L	54	72.30	64.10	88.90	113.90	74.60	76.70
25	L	54	76.10	72.10	86.80	104.50	86.90	79.30
26	R	56	58.06	58.04	91.10	129.14	89.32	81.40
27	R	57	60.70	56.50	65.66	93.20	92.88	89.80
28	L	58	37.10	40.60	51.60	64.50	61.30	52.70
29	R	63	59.90	57.90	81.30	103.00	98.50	103.30
30	R	65	84.10	71.10	93.10	115.70	101.90	95.00
Means		49	55.91	55.13	74.32	96.91	80.91	75.90

Appendix B

Spatial Contrast Sensitivity Data

Log contrast sensitivity means for the glaucoma condition across the different spatial frequencies

Glaucoma Patients

Obser.#	1.00	1.82	3.31	6.03	10.99
1	1.57	1.70	1.54	1.51	.98
2	1.25	1.30	1.20	1.42	1.09
3	1.71	1.50	1.44	1.26	.75
4	1.41	1.41	1.37	.92	.62
5	1.40	1.30	1.35	1.06	.68
6	1.65	1.45	1.55	1.34	1.04
7	1.32	1.17	.94	.84	.53
8	1.50	1.42	1.44	1.18	.55
9	1.23	1.15	.91	.67	.18
Means	1.44	1.37	1.30	1.13	.71

Spatial Contrast Sensitivity Data

Log contrast sensitivity means for the suspect condition across the different spatial frequencies

	Glaucoma Suspects				
Obser.#	1.00	1.82	3.31	6.03	10.99
10	1.27	1.39	1.24	1.27	.99
11	.94	1.06	1.06	.75	0.00
12	1.25	1.46	1.39	1.22	.76
13	1.30	1.24	1.31	1.20	.43
14	1.28	1.34	1.28	1.29	1.12
15	1.53	1.70	1.52	1.36	1.03
16	1.48	1.53	1.45	.94	.72
17	1.24	1.32	1.35	1.29	.49
18	1.31	1.43	1.22	1.02	.37
19	1.16	1.24	1.34	1.19	.49
Means	1.27	1.37	1.31	1.15	.64

Spatial Contrast Sensitivity Data

Log contrast sensitivity means for the control condition across the different spatial frequencies

	Control Condition				
Obser.#	1.00	1.82	3.31	6.03	10.99
20	1.66	1.67	1.80	1.63	1.46
21	1.61	1.57	1.52	1.30	.93
22	1.60	1.64	1.68	1.43	.74
23	1.45	1.36	1.42	1.24	1.04
24	1.21	1.20	1.28	1.17	.76
25	1.23	1.17	1.24	1.11	.58
26	1.14	1.11	1.11	1.06	.95
27	.84	1.17	1.12	1.11	.70
28	1.43	1.34	1.54	1.55	1.04
29	1.41	1.58	1.53	1.31	.58
30	1.41	1.26	1.44	1.41	1.00
Means	1.36	1.37	1.42	1.30	.88

Appendix C

Farnsworth-Munsell 100-hue Error Scores

Error scores of the Farnsworth-Munsell 100-hue test for the different diagnostic categories

Observer.#	Glaucoma	Obser.#	Suspects	Obser.#	Controls
1	44	10	60	20	4
2	32	12	112	21	72
3	80	14	80	22	8
4	84	15	40	23	28
5	144	16	164	24	96
6	88	17	84	25	152
7	184	18	168	26	44
8	100	19	72	29	160
9	88			30	100
Means	93.77		97.50		73.77

```
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*    FM-100 DATA FILE    *
*                        *
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```

NAME : OBSERVER #1
AGE : 24
EYE TESTED : R
DATE TESTED : 17-SEP-85
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : GLAUCOMA
FILE NAME : #1

TOTAL ERROR SCORE: 44
SQUARE ROOT: 6.6

85 TO 21:

85	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21	20
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

22 TO 42:

22	23	24	25	26	27	28	29	30	31	33	32	34	35	36	37	38	39	40	41	42
1	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	3

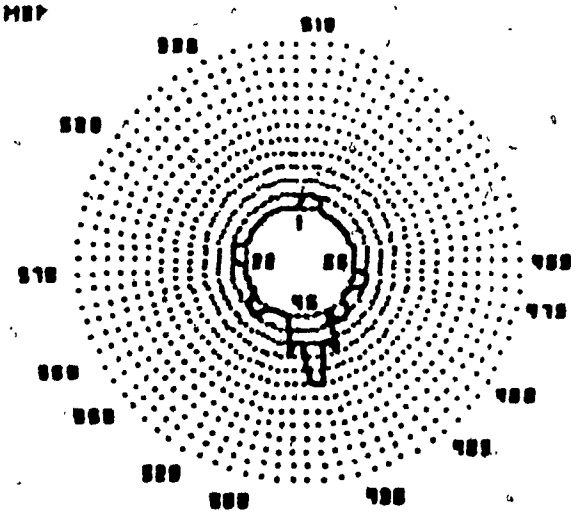
43 TO 63:

46	43	44	47	48	45	49	50	51	53	52	54	55	56	57	58	59	60	62	61	63
5	2	2	2	2	5	3	0	1	1	1	1	0	0	0	0	0	1	1	1	1

64 TO 84:

64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	84	83
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

FM-100 MAP



FM-100 DATA FILE

NAME : OBSERVER #2
AGE : 27
EYE TESTED : L.
DATE TESTED : 03-DEC-85
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : GLAUCOMA
FILE NAME : #2

TOTAL ERROR SCORE: 32
SQUARE ROOT: 5.6

---

85 TO 21:

85	1	2	3	4	5	6	7	8	10	9	11	12	13	14	15	16	17	18	19	20	21
0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0

22 TO 42:

22	23	24	25	26	27	28	29	30	31	33	32	34	35	36	37	38	39	40	41	42
0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0

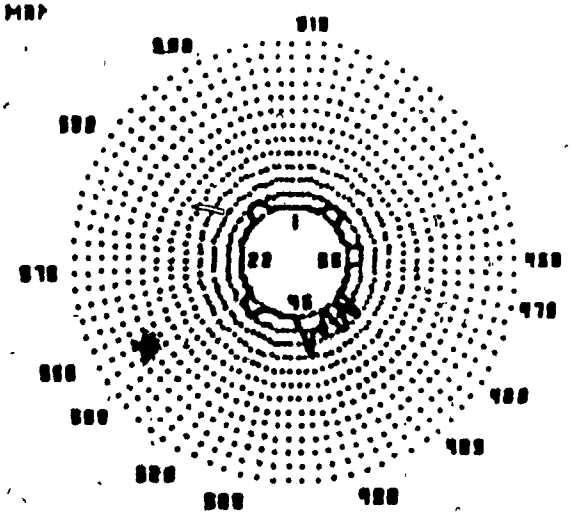
43 TO 63:

43	44	45	47	48	46	49	50	51	52	55	54	53	56	57	58	59	60	61	62	63
0	0	1	1	1	3	2	0	0	2	2	0	2	2	0	0	0	0	0	0	0

64 TO 84:

64	65	67	66	68	69	70	71	72	73	74	75	77	76	78	79	80	81	82	83	84
0	1	1	1	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0

FM-100 MAP



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*    FM-100 DATA FILE    *
*                        *
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```
     NAME : OBSERVER #3
      AGE : 40
 EYE TESTED : R
DATE TESTED : 14-MAR-86
   EXAMINER : J.F.
   REFERRAL : DR. BALAZSI
    COMMENT : GLAUCOMA
  FILE NAME : #3

TOTAL ERROR SCORE: 80
      SQUARE ROOT: 8.9
```

```
85 TO 21:
85  1  2  3  4  5  6  7  9  8 11 10 12 14 13 15 16 17 18 19 20 21
 0  0  0  0  0  0  0  1  1  2  2  1  2  1  1  1  0  0  0  0  0  1


22 TO 42:
23 22 24 25 26 27 28 29 31 30 33 32 34 35 36 37 39 40 42 41 38
 1  1  1  0  0  0  0  1  1  2  2  1  1  0  0  1  1  1  1  2  6


43 TO 63:
43 45 44 48 47 46 49 50 51 52 53 54 55 57 56 58 59 60 61 63 62
 5  1  3  3  0  2  2  0  0  0  0  0  1  1  1  1  0  0  1  1  2


64 TO 84:
65 64 66 67 68 70 69 71 72 73 74 76 75 78 77 79 80 82 81 83 84
 2  1  1  0  1  1  1  1  0  0  1  1  2  2  1  1  1  1  1  1  0
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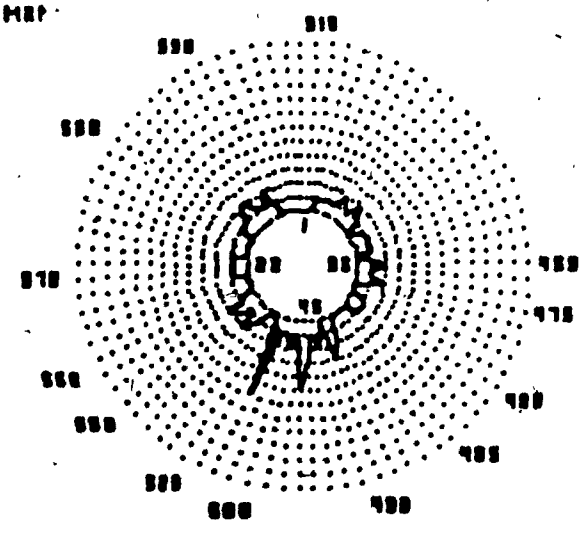


FM-100 DATA FILE

NAME : OBSERVER #4
AGE : 49
EYE TESTED : L
DATE TESTED : 25-SEP-85
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : GLAUCOMA
FILE NAME : #4

TOTAL ERROR SCORE: 84
SQUARE ROOT: 9.1

85 TO 21:

1	85	2	3	4	5	6	8	9	7	10	11	12	13	14	15	16	17	18	19	20	21
1	1	1	0	0	0	1	1	1	3	2	0	0	0	0	0	0	0	0	0	0	0

22 TO 42:

22	23	24	25	26	28	27	29	31	32	34	33	30	35	36	38	37	40	39	41	42
0	0	0	0	1	1	1	2	1	1	1	2	6	4	1	1	2	2	1	1	4

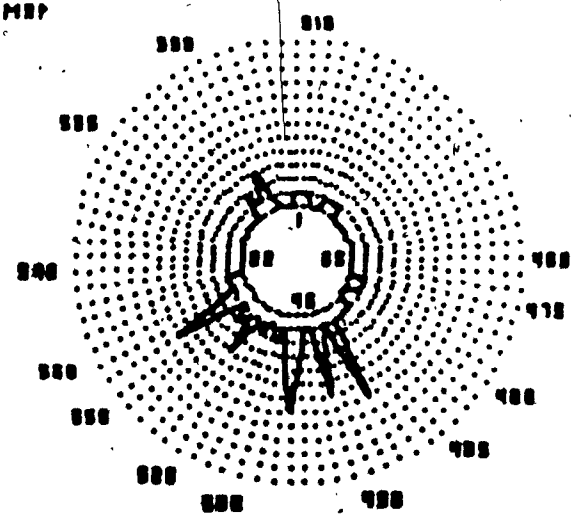
43 TO 63:

47	44	46	45	43	50	48	49	51	52	54	53	55	56	57	58	60	59	61	62	63
6	3	1	1	7	7	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0

64 TO 84:

64	65	66	67	68	69	70	71	72	73	74	75	76	77	79	78	80	81	82	83	84
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1

FM-100 MAP



FM-100 DATA FILE

NAME : OBSERVER #5
AGE : 55
EYE TESTED : L
DATE TESTED : 10-JAN-86
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : GLAUCOMA
FILE NAME : #5

TOTAL ERROR SCORE: 144
SQUARE ROOT: 12

85 TO 21:

1	2	85	3	4	5	6	9	8	7	10	12	11	13	14	15	17	16	18	20	19	21
4	1	3	2	0	0	2	2	0	2	3	1	1	1	0	1	1	1	2	1	1	1

22 TO 42:

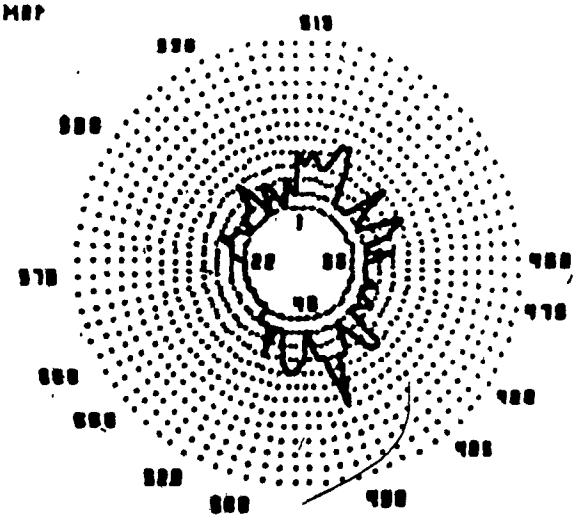
22	23	24	25	26	27	28	29	30	31	32	33	34	35	37	36	38	41	39	40	42
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	3	3	1	1	4

43 TO 63:

46	47	43	45	44	48	53	52	49	51	50	54	56	55	57	59	58	61	60	62	63
3	3	4	1	3	7	4	2	3	1	3	4	1	1	2	1	2	2	1	1	1

64 TO 84:

65	64	66	69	67	68	70	74	72	71	73	75	76	78	77	79	82	84	80	83	81
1	1	3	3	1	1	4	4	1	1	2	1	1	1	1	3	3	4	5	3	5



FM-100 DATA FILE

NAME : OBSERVER # 6
AGE : 62
EYE TESTED : R
DATE TESTED : 16-AUG-85
EXAMINER : J.F.
REFERRAL : BALAZSI
COMMENT : GLAUCOMA
FILE NAME : # 6

TOTAL ERROR SCORE: 88
SQUARE ROOT: 9.3

85 TO 21:

85	1	2	4	3	5	6	7	8	9	10	11	12	13	14	15	16	17	18	21	20	19
0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	2

22 TO 42:

22	23	24	25	26	27	28	29	30	31	32	33	35	34	36	37	38	42	40	41	39
2	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	3	4	1	1	4

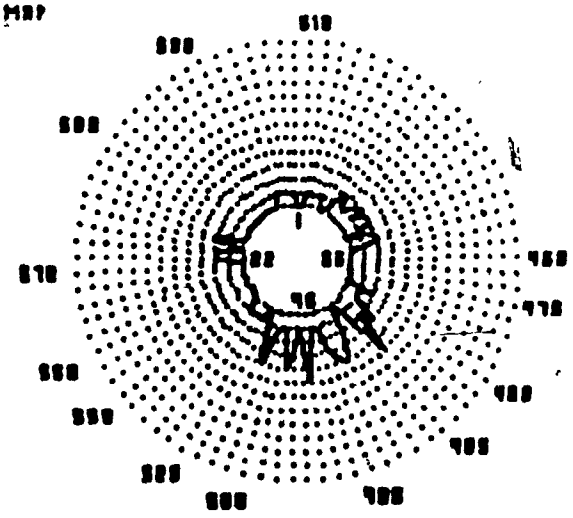
43 TO 63:

43	44	46	47	49	45	48	50	54	51	52	53	55	57	58	56	59	60	61	62	63
3	1	1	1	4	5	3	4	5	2	0	1	2	1	1	3	2	0	0	0	0

64 TO 84:

64	65	66	67	68	71	70	69	72	73	75	74	77	76	78	79	80	81	83	82	84
0	0	0	0	2	2	0	2	2	1	1	2	2	1	1	0	0	1	1	1	1

FM-100 MAP



FM-100 DATA FILE

NAME : OBSERVER #7
AGE : 66
EYE TESTED : R
DATE TESTED : 28-SEP-85
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : GLAUCOMA
FILE NAME : #7

TOTAL ERROR SCORE: 184
SQUARE ROOT: 13.5

85 TO 21:

4	5	85	2	1	3	6	8	7	9	10	11	13	12	15	14	16	17	18	21	19	20
5	4	5	1	1	3	3	1	1	1	0	1	1	2	2	1	1	0	2	3	1	1

22 TO 42:

22	24	23	25	27	26	28	29	31	30	32	33	35	34	36	37	38	41	42	40	39
2	1	1	2	1	1	1	1	1	1	1	1	1	1	1	0	2	2	1	1	3

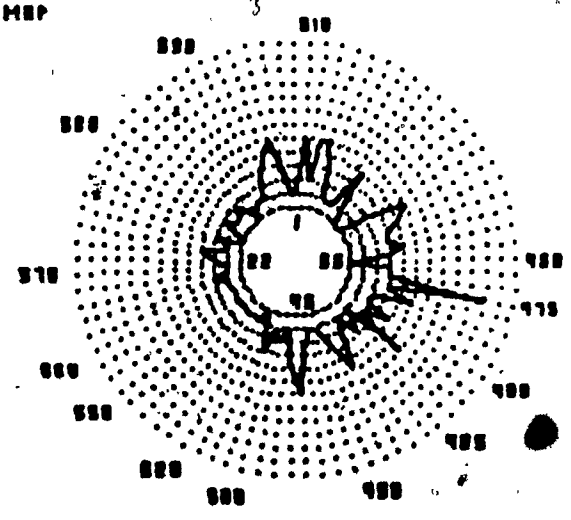
43 TO 63:

43	45	47	46	44	50	51	48	49	53	52	54	55	62	57	56	59	58	61	63	60
4	2	1	1	6	5	2	2	3	3	1	1	6	10	4	2	2	2	3	3	5

64 TO 84:

64	65	66	70	68	71	67	69	72	73	74	75	76	78	77	82	80	79	81	84	83
3	0	3	4	3	5	4	3	2	0	0	0	1	1	4	5	1	1	3	2	5

FM-100 MAP



FM-100 DATA FILE

NAME : OBSERVER #8
AGE : 69
EYE TESTED : L
DATE TESTED : 10-JAN-86
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : GLAUCOMA
FILE NAME : #8

TOTAL ERROR SCORE: 100
SQUARE ROOT: 10

85 TO 21:

85	1	2	3	4	5	6	8	7	10	9	11	12	13	14	15	16	18	17	19	20	21
1	0	0	0	0	0	1	1	2	2	1	1	0	0	0	0	1	1	1	1	0	0

22 TO 42:

22	23	24	26	25	27	28	30	29	31	32	33	34	36	35	38	37	40	42	39	41
0	0	1	1	1	1	1	1	1	1	0	0	1	1	2	2	2	3	3	3	3

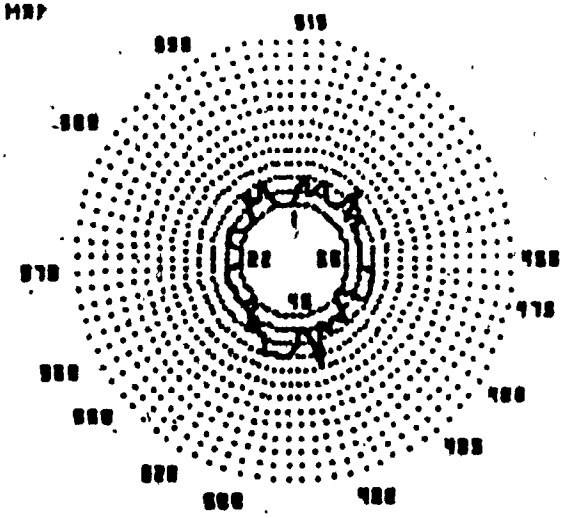
43 TO 63:

44	43	47	45	46	48	49	51	50	53	52	54	55	56	57	58	61	62	59	60	63
2	3	4	1	1	1	1	1	2	2	1	1	0	0	0	2	2	2	2	2	2

64 TO 84:

64	66	65	67	68	70	69	71	72	75	73	74	76	77	79	78	80	82	81	84	83
1	1	1	1	1	1	1	1	2	3	1	1	1	1	1	1	2	1	2	2	1

FM-100 MAP



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*    FM-100 DATA FILE    *
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NAME : OBSERVER #9
AGE : 76
EYE TESTED : L
DATE TESTED : 12-SEP-85
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : GLAUCOMA
FILE NAME : #9

TOTAL ERROR SCORE: 88
SQUARE ROOT: 9.3

---

85 TO 21:

85	2	1	4	3	5	6	7	8	9	10	11	12	13	14	15	16	17	18	20	19	21
4	1	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

22 TO 42:

22	23	24	25	27	26	28	29	31	30	33	32	34	35	37	36	40	39	38	41	42
0	0	0	1	1	1	1	1	1	2	2	1	1	1	1	3	3	0	2	2	0

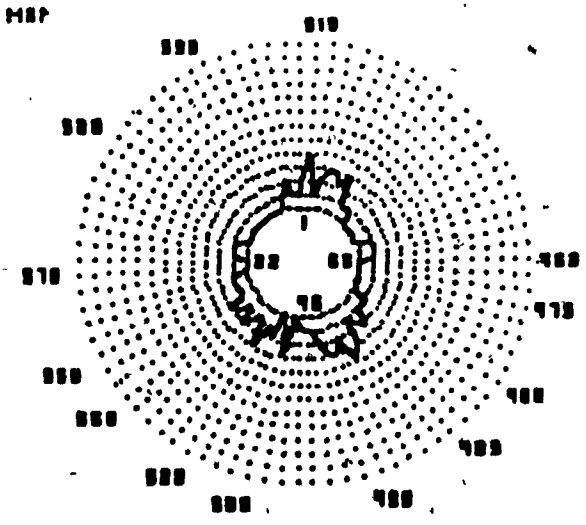
43 TO 63:

43	45	44	46	48	51	49	47	50	53	52	54	56	55	57	58	59	60	61	62	63
1	1	1	2	3	3	2	3	4	2	1	2	1	1	1	0	0	0	0	0	0

64 TO 84:

64	65	66	68	67	69	70	71	72	73	74	75	76	78	77	79	82	84	83	80	81
0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	3	3	1	2	2	3

FM-100 MAP



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*    FM-100 DATA FILE    *
*                        *
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```
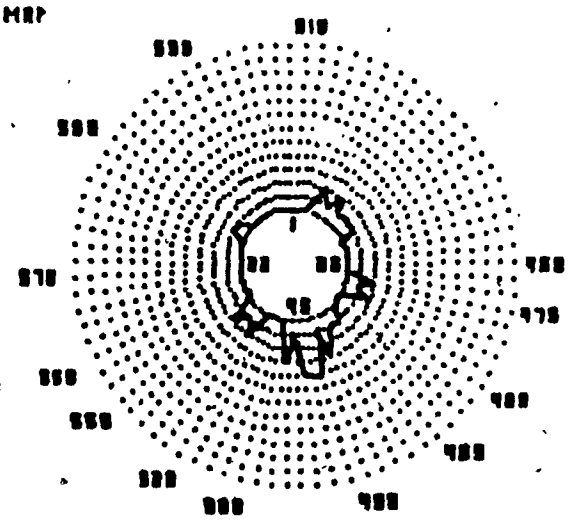

```
       NAME : OBSERVER #10
        AGE : 24
 EYE TESTED : L
DATE TESTED : 28-SEP-85
   EXAMINER : J.F.
   REFERRAL : DR. BALAZSI
    COMMENT : SUSPECT
  FILE NAME : #10

TOTAL ERROR SCORE: 60
      SQUARE ROOT: 7.7
```

```
85 TO 21:
85 1  2  3  4  5  6  7  8  9  10 11 12 13 15 14 16 17 18 19 20 21
0  0  0  0  0  0  0  0  0  0  0  0  0  1  1  1  1  0  0  0  0  0


22 TO 42:
22 23 24 25 26 27 28 29 30 31 33 32 35 34 36 37 38 39 40 41 42
0  0  0  0  0  0  0  0  0  1  1  2  2  1  1  0  0  0  0  0  3


43 TO 63:
46 44 43 47 45 49 48 50 52 51 53 54 55 56 57 58 60 59 62 61 63
4  1  3  4  4  3  1  2  1  1  1  0  0  0  0  1  1  2  2  1  1


64 TO 84:
64 65 66 67 68 69 70 71 72 74 73 75 76 78 77 80 79 81 82 83 84
0  0  0  0  0  0  0  0  1  1  1  1  1  1  2  2  1  1  0  0  0
```



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*   FM-100 DATA FILE     *
*                        *
**************************
```

NAME : OBSERVER #12
AGE : 34
EYE TESTED : R
DATE TESTED : 05-NOV-85
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : SUSPECT
FILE NAME : #12

TOTAL ERROR SCORE: 112
SQUARE ROOT: 10.5

85 TO 21:

85	1	2	3	4	5	6	8	7	9	10	11	12	13	14	15	16	17	19	18	21	20
0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	1	2	2	3

22 TO 42:

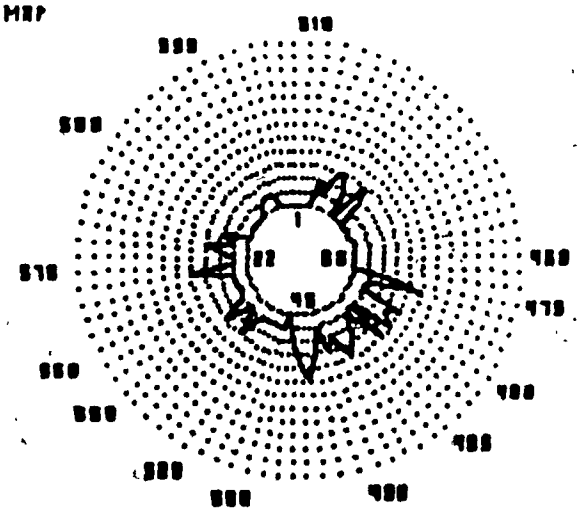
24	22	23	25	26	28	27	29	30	32	33	31	34	36	35	37	38	40	39	41	42
4	1	1	1	1	1	1	1	1	1	1	3	3	1	1	1	1	1	1	1	0

43 TO 63:

43	46	44	48	47	45	50	49	52	53	51	54	57	55	56	61	59	60	58	62	63
2	3	4	3	1	5	4	2	2	1	3	4	3	1	4	5	1	1	4	3	0

64 TO 84:

64	65	66	67	68	69	70	71	72	73	74	75	78	77	76	80	81	79	82	83	84
0	0	0	0	0	0	0	0	0	0	0	2	2	0	3	3	1	3	2	0	0



```
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*                        *
*    FM-100 DATA FILE    *
*                        *
**************************
```

```
       NAME : OBSERVER #14
        AGE : 43
  EYE TESTED : R
DATE TESTED : 21-FEB-86
   EXAMINER : J.F.
   REFERRAL : DR. BALAZSI
    COMMENT : SUSPECT
  FILE NAME : #14

TOTAL ERROR SCORE: 88
      SQUARE ROOT: 8.9
```

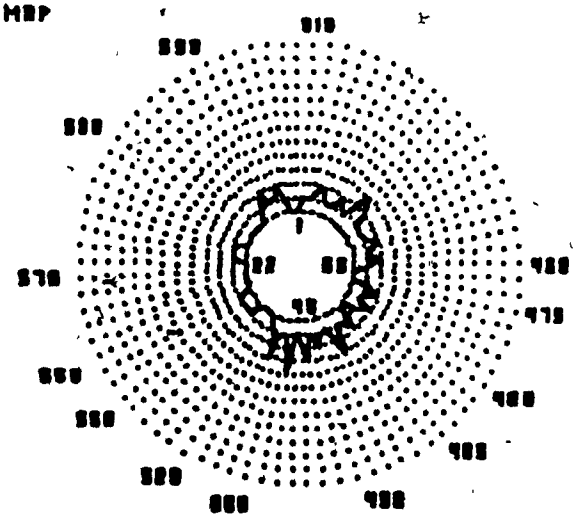
```
85 TO 21:
85  1  2  3  4  6  5  8  7  9 10 11 12 13 14 15 16 17 18 20 19 21
 1  0  0  0  1  1  2  2  1  1  0  0  0  0  0  0  0  0  1  1  1  1


22 TO 42:
22 23 24 25 26 27 28 29 31 30 32 33 34 35 36 37 38 40 41 39 42
 0  0  0  0  0  0  0  1  1  1  1  0  0  0  0  0  1  1  1  3  4


43 TO 63:
45 43 44 47 46 48 49 51 52 50 53 54 55 56 58 57 60 59 61 62 63
 3  1  2  2  1  1  1  1  1  3  2  0  0  1  1  2  2  1  1  0  0


64 TO 84:
64 65 67 66 69 68 70 71 73 72 74 76 77 75 78 79 81 80 82 84 83
 0  1  1  2  2  1  1  1  1  1  2  1  1  3  2  1  1  1  2  1  1
```

FM-100 MAP



```
**************************
*                        *
*    FM-100 DATA FILE    *
*                        *
**************************
```

NAME : OBSERVER #15
AGE : 57
EYE TESTED : R
DATE TESTED : 16-AUG-85
EXAMINER : J.F.
REFERRAL : BALAZSI
COMMENT : SUSPECT
FILE NAME : #15

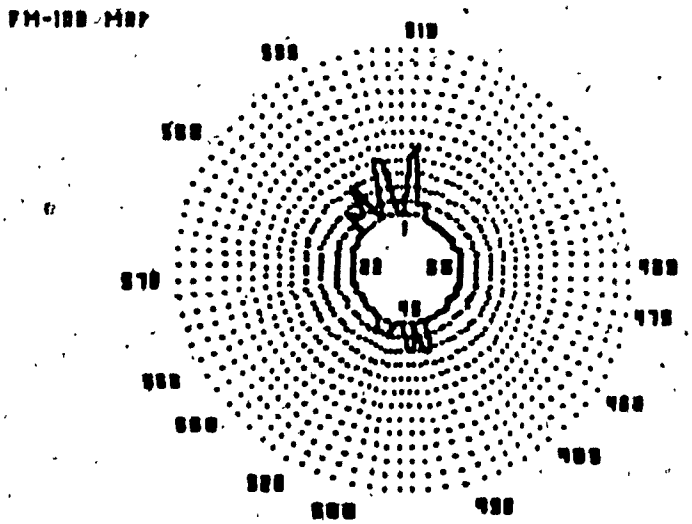
TOTAL ERROR SCORE: 40
SQUARE ROOT: 6.3

1 TO 21:																				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
4	0	0	0	4	4	0	0	1	1	1	3	2	0	0	0	0	0	0	0	0

22 TO 42:																				
22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	39	38	40	41	42
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0

43 TO 63:																				
43	44	47	46	45	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
0	2	2	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

64 TO 84:																				
64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	83	82	84
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	5



```
##########################
#                        #
#    FM-100 DATA FILE    #
#                        #
##########################
```

NAME : OBSERVER #16
AGE : 61
EYE TESTED : L
DATE TESTED : 12-SEP-85
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : SUSPECT
FILE NAME : #16

TOTAL ERROR SCORE: 164
SQUARE ROOT: 12.8

---

85 TO 21:

1	85	2	3	4	5	7	6	9	8	10	11	12	13	15	14	16	17	19	20	18	21
4	1	1	0	0	1	1	2	2	1	1	0	0	1	1	1	1	1	1	1	3	2

22 TO 42:

22	23	24	25	27	26	28	29	31	30	33	32	34	37	35	36	38	41	39	42	40
0	0	0	1	1	1	1	1	1	2	2	1	3	3	1	1	3	3	3	3	6

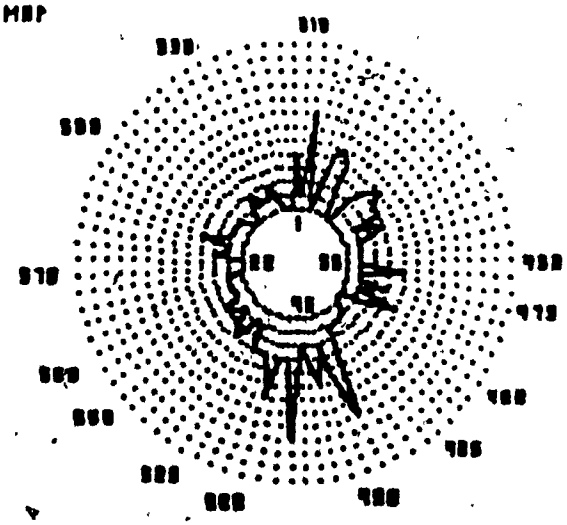
43 TO 63:

46	47	44	45	49	43	48	50	51	53	52	54	55	56	57	58	61	63	62	60	59
9	2	2	3	0	9	5	1	1	1	1	1	0	0	0	2	3	1	1	1	4

64 TO 84:

64	65	67	66	68	69	71	70	74	72	75	73	76	77	78	79	84	80	83	82	81
4	1	1	1	1	1	1	3	4	3	3	3	2	0	0	4	7	5	2	0	4

FM-100 MAP



FM-100 DATA FILE

NAME : OBSERVER #17
AGE : 63
EYE TESTED : R
DATE TESTED : 30-AUG-85
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : SUSPECT
FILE NAME : #17

TOTAL ERROR SCORE: 84
SQUARE ROOT: 9.1

---

85 TO 21:

85	1	2	4	3	5	7	6	8	9	10	11	12	13	14	16	15	17	18	19	20	21
1	0	1	1	1	2	1	1	1	0	0	0	0	0	1	1	1	1	0	0	0	0

22 TO 42:

22	23	24	25	26	27	28	29	30	31	32	33	34	35	37	36	38	39	40	41	42
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0

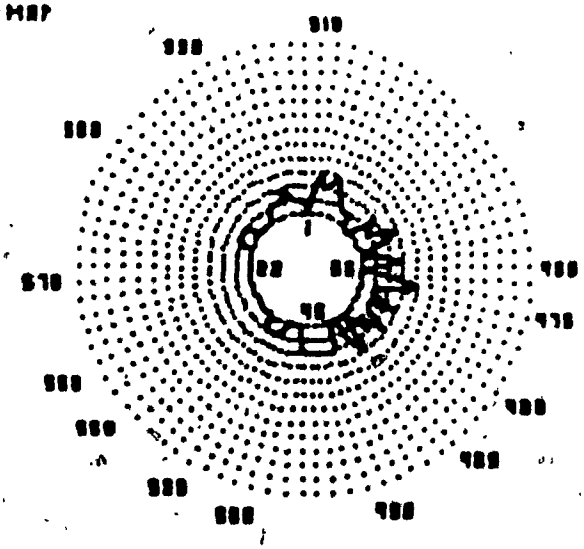
43 TO 63:

43	46	47	44	45	48	49	50	51	54	53	52	56	55	57	58	60	59	63	61	62
2	2	2	2	2	2	0	0	2	2	0	3	3	1	1	1	1	3	4	1	3

64 TO 84:

66	65	64	67	68	69	71	72	70	73	74	75	76	77	79	78	80	82	84	81	83
3	0	2	2	0	1	1	1	3	2	0	0	0	1	1	1	2	2	3	3	2

FM-100 MAP



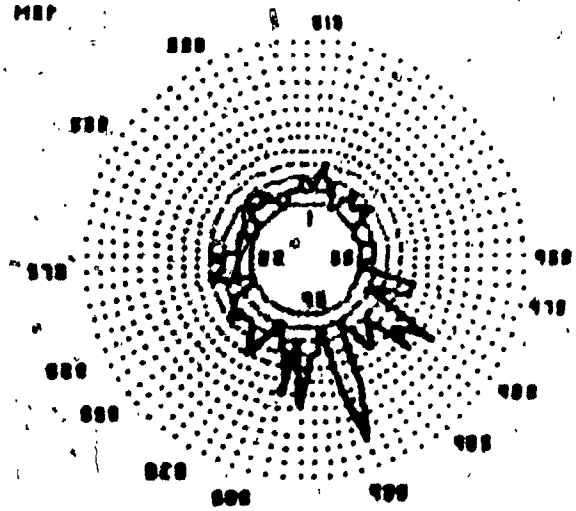
FM-100 DATA FILE

NAME : OBSERVER #18
AGE : 64
EYE TESTED : L
DATE TESTED : 10-JAN-86
EXAMINER : J.F.
REFERRAL : DR. BALAZSI
COMMENT : SUSPECT
FILE NAME : #18

TOTAL ERROR SCORE: 168
SQUARE ROOT: 12.9

85 TO 21:																				
1	85	2	4	3	5	6	7	8	10	9	12	11	13	14	15	16	17	19	18	20	21
2	1	2	1	1	1	0	0	1	1	2	2	1	1	0	0	0	1	1	1	1	1
22 TO 42:																					
23	25	22	24	26	27	28	29	32	33	30	31	35	34	37	38	36	40	39	42	41	
2	3	3	2	1	0	0	2	2	2	2	3	3	2	2	1	4	3	2	2	6	
43 TO 63:																					
48	43	47	44	46	45	49	53	54	51	50	52	56	58	55	60	59	61	57	62	63	
10	7	5	3	1	3	6	3	2	2	1	4	4	3	6	4	1	4	7	4	0	
64 TO 84:																					
64	65	67	66	68	69	70	71	72	73	75	74	77	76	78	79	80	81	84	82	83	
0	1	1	1	1	0	0	0	0	1	1	2	2	1	1	0	0	2	3	1	2	

FM-100 MAP



FM-100 DATA FILE

NAME : OBSERVER #19
AGE : 72
EYE TESTED : L
DATE TESTED : AUG-15-85
EXAMINER : J.F.
REFERRAL : BALAZSI
COMMENT : SUSPECT.
FILE NAME : #19

TOTAL ERROR SCORE: 72
SQUARE ROOT: 8.4

85 TO 21:

85	2	1	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21	20
1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

22 TO 42:

22	23	24	25	27	26	28	29	30	31	32	34	33	35	36	37	38	40	39	41	42
1	0	0	1	1	1	1	0	0	0	1	1	1	1	0	0	1	1	1	1	1

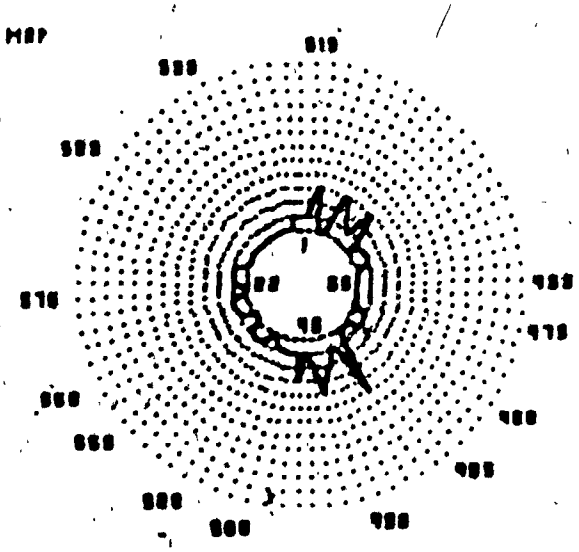
43 TO 63:

44	43	47	48	45	46	51	49	50	52	53	54	55	56	58	57	59	60	61	62	63
1	3	3	2	2	4	3	1	1	1	0	0	0	1	1	1	1	0	0	0	0

64 TO 84:

64	65	66	67	68	69	71	70	72	73	74	76	77	75	78	79	83	82	81	80	84
0	0	0	0	0	1	1	1	1	0	1	1	1	3	2	3	3	0	0	3	3

FM-100 MAP



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*    FM-100 DATA FILE   *
*                       *
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```
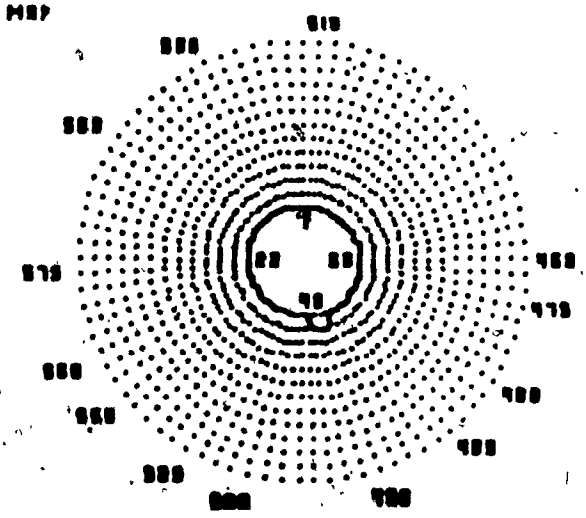

```
       NAME : OBSERVER #20
        AGE : 27
  EYE TESTED : R
 DATE TESTED : 18-AUG-86
    EXAMINER : J.F.
    REFERRAL :
     COMMENT : NORMAL
   FILE NAME : #20

TOTAL ERROR SCORE: 4
      SQUARE ROOT: 2
```

```
01 TO 21:
01  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21
 0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0


22 TO 42:
22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42
 0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0


43 TO 63:
43 44 45 47 46 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63
 0  0  1  1  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0


64 TO 84:
64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84
 0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

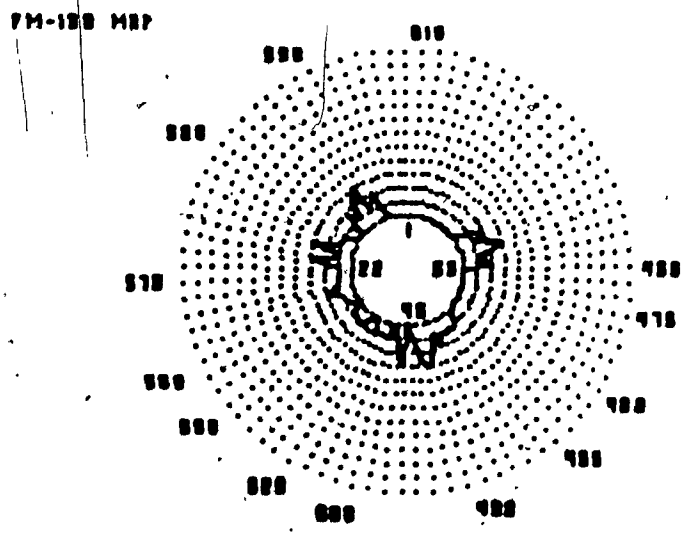


FM-100 DATA FILE

NAME : OBSERVER #21
AGE : 28
EYE TESTED : L
DATE TESTED : 18-OCT-85
EXAMINER : J.F.
REFERRAL : BALAZSI
COMMENT : NORMAL
FILE NAME : #21

TOTAL ERROR SCORE: 72
SQUARE ROOT: 8.4

85 TO 21:																				
85	1	2	3	4	5	6	8	7	10	11	9	12	13	14	15	17	16	18	21	19	20
0	0	0	0	0	0	1	1	2	2	1	3	2	0	0	1	1	1	3	3	1	1
22 TO 42:																				
22	23	25	24	26	28	27	29	30	31	33	32	34	35	36	37	39	38	40	41	42	
1	1	1	1	2	1	1	1	0	1	1	1	1	0	0	1	1	1	1	0	2	
43 TO 63:																				
45	44	43	47	48	46	49	50	52	51	53	54	55	56	57	58	59	60	61	62	63	
2	0	3	3	1	3	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	
64 TO 84:																				
64	65	66	69	67	68	71	70	72	73	74	75	76	77	78	79	80	81	82	83	84	
0	0	2	3	1	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	

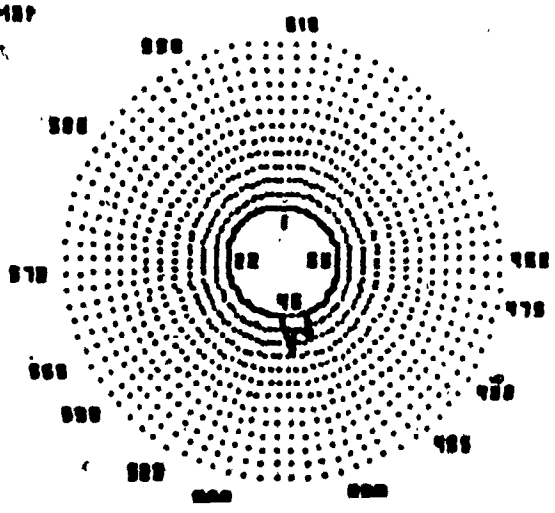


```
**************************
*                        *
*    FM-100 DATA FILE    *
*                        *
**************************
```

```
       NAME : OBSERVER #22
        AGE : 31
 EYE TESTED : R
DATE TESTED : 18-AUG-86
   EXAMINER : J.F.
   REFERRAL :
    COMMENT : NORMAL
  FILE NAME : #22

TOTAL ERROR SCORE: 8
     SQUARE ROOT: 2.8
```

```
01 TO 21:
01 1  2  3  4  5  6  7  8  9  10 11 12 13 14 15 16 17 18 19 20 21
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0


22 TO 42:
22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0


43 TO 63:
43 44 46 47 45 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63
0  1  1  1  3  2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0


64 TO 84:
64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84
0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
```

FM-100 MAP



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*************************
*                       *
*    FM-100 DATA FILE   *
*                       *
*************************
```

NAME : OBSERVER N23
AGE : 42
EYE TESTED : L
DATE TESTED : 19-AUG-86
EXAMINER : J.F.
REFERRAL :
COMMENT : NORMAL
FILE NAME : N23

TOTAL ERROR SCORE: 28
SQUARE ROOT: 5.2

85 TO 21:

85	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	19	18	20	21
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0

22 TO 42:

22	23	24	25	26	27	28	29	30	31	32	33	34	35	37	36	38	39	40	41	42
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1

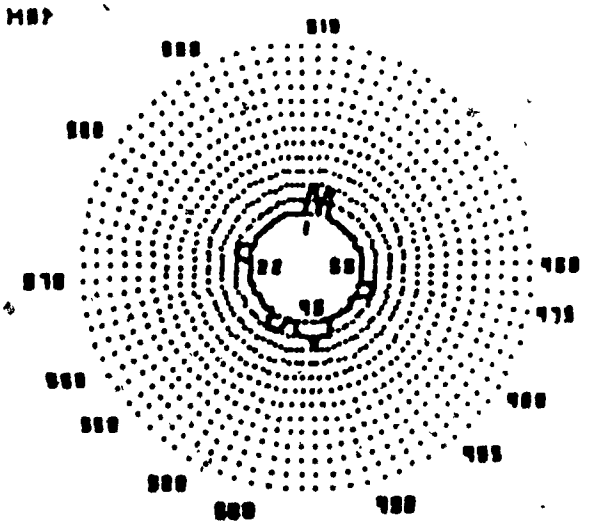
43 TO 63:

44	43	45	47	46	48	49	50	51	52	53	54	55	56	57	58	60	59	61	62	63
1	1	2	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0

64 TO 84:

64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	84	83	82
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	2

FM-100 MAP



```
**************************
*                        *
*    FM-100 DATA FILE    *
*                        *
**************************
```

```
       NAME : OBSERVER #24
        AGE : 54
  EYE TESTED : L
DATE TESTED : 11-JUL-86
   EXAMINER : J.F.
   REFERRAL :
    COMMENT : NORMAL
  FILE NAME : #24

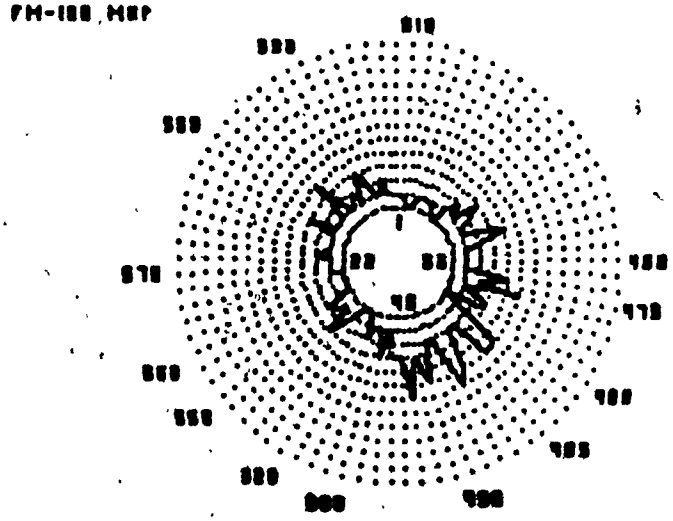
TOTAL ERROR SCORE: 148
      SQUARE ROOT: 12.1
```

```
85 TO 21:
85  2  1  3  4  7  5  6  9  8 10 11 13 14 12 16 15 17 18 20 19 21
 1  1  1  1  2  3  1  2  2  1  1  1  1  1  4  3  1  1  1  1  1  2


22 TO 42:
23 22 24 25 26 27 28 29 30 33 31 32 34 35 36 37 38 41 39 40 42
 1  1  1  0  0  0  0  0  2  3  1  1  1  0  0  0  2  3  1  1  1


43 TO 63:
43 47 44 46 49 48 45 50 53 52 55 51 54 50 57 56 61 63 59 60 62
 3  5  3  3  2  2  6  6  2  2  5  5  5  3  0  4  5  4  3  1  2


64 TO 84:
64 65 67 66 68 70 71 69 73 72 75 74 76 77 78 79 81 80 82 83 84
 1  1  1  1  2  1  1  4  3  2  2  1  1  0  0  1  1  1  1  0  0
```



FM-100 DATA FILE

NAME : OBSERVER #25
AGE : 54
EYE TESTED : L
DATE TESTED : 11-JUL-86
EXAMINER : J.F.
REFERRAL :
COMMENT : NORMAL
FILE NAME : #25

TOTAL ERROR SCORE: 152
SQUARE ROOT: 12.3

---

85 TO 21:

85	1	7	9	8	11	10	12	13	15	14	16	17	21	19	18	20
4	6	3	2	5												
7	3	2	2	6	4	5	6	1	2	2	1	1	1	1	1	1	3	4	1	1	2

22 TO 42:

22	23	24	26	25	28	27	30	29	31	33	32	34	35	37	36	38	41	39	42	40
1	0	1	1	2	2	2	2	1	2	1	1	1	1	1	1	3	3	3	3	3

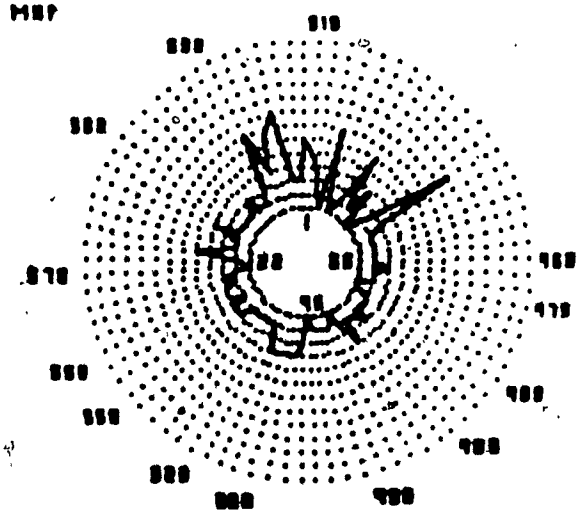
43 TO 63:

43	44	45	47	46	48	49	50	52	53	51	54	55	57	56	58	59	60	61	63	62
2	0	1	1	1	1	0	1	1	1	3	2	1	1	1	1	0	0	1	1	1

64 TO 84:

64	66	65	67	68	70	69	71	73	74	75	76	72	78	77	79	80	81	84	83	82
2	1	1	1	1	1	1	2	1	0	0	3	0	5	1	1	0	2	2	0	6

FM-100 MAP



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**************************
*                        *
*    FM-100 DATA FILE    *
*                        *
**************************
```

NAME : OBSERVER #26
AGE : 56
EYE TESTED : R
DATE TESTED : 18-OCT-85
EXAMINER : J.F.
REFERRAL : BALAZSI
COMMENT : NORMAL
FILE NAME : #26

TOTAL ERROR SCORE: 44
SQUARE ROOT: 6.6

05 TO 21:

05	1	2	3	4	5	6	7	8	10	9	11	12	13	14	16	15	17	18	19	20	21
0	0	0	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	0	0	0	0

22 TO 42:

22	23	24	25	26	27	28	29	30	33	31	32	35	34	36	37	39	38	40	41	42
0	0	0	0	0	0	0	0	2	3	1	2	2	1	1	1	1	1	1	0	1

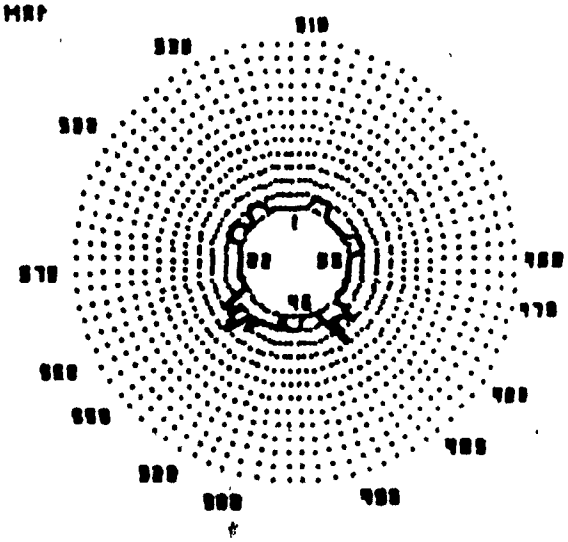
43 TO 63:

44	43	45	46	47	48	49	50	52	53	51	54	55	56	57	58	59	60	61	62	63
1	1	1	0	0	0	0	1	1	1	3	2	0	0	0	0	0	0	0	0	0

64 TO 84:

64	65	66	67	69	68	70	71	72	73	74	75	76	77	78	80	79	81	82	83	84
0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0

FM-100 MAP



```
**************************
*                        *
*   FM-100 DATA FILE     *
*                        *
**************************
```

```
      NAME : OBSERVER #29
       AGE : 63
 EYE TESTED : R
DATE TESTED : 19-AUG-86
   EXAMINER : J.F.
   REFERRAL :
    COMMENT : NORMAL
  FILE NAME : #29

TOTAL ERROR SCORE: 168
      SQUARE ROOT: 12.6
```

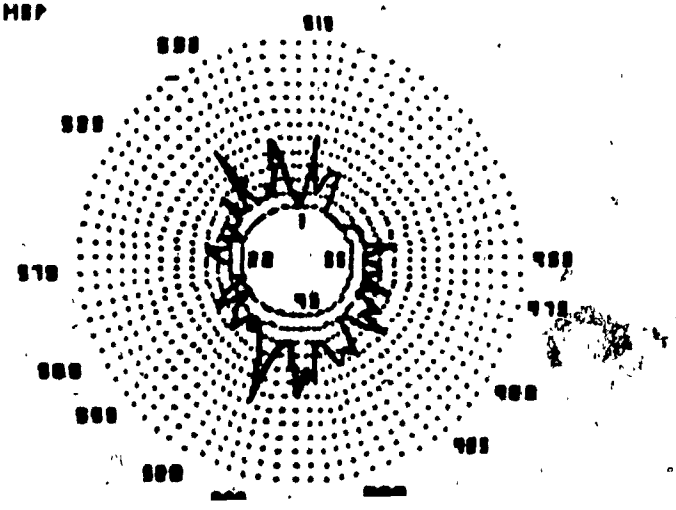
```
85 TO 21:
85  1  2  3  6  7  5  4 10  8  9 11 12 14 15 13 16 17 18 21 19 20
 2  0  0  2  2  1  1  5  6  1  1  1  1  1  1  3  2  0  2  3  1  1


22 TO 42:
22 24 23 25 26 27 28 31 30 29 33 32 35 34 36 37 40 38 41 42 39
 2  1  1  1  0  0  2  2  0  3  3  2  2  1  1  2  3  3  2  2  7


43 TO 63:
45 44 49 48 43 46 47 50 52 53 51 55 57 54 56 58 59 61 62 60 63
 5  4  4  4  6  2  2  3  1  1  4  4  3  3  2  1  1  1  1  3  2


64 TO 84:
64 67 65 66 68 69 71 70 72 73 74 75 76 77 78 79 80 84 81 83 82
 2  3  1  1  1  1  1  1  1  0  0  0  0  0  0  0  3  5  3  1  2
```

FM-100 MAP



FM-100 DATA FILE

NAME : OBSERVER #30
AGE : 65
EYE TESTED : R
DATE TESTED : 19-AUG-86
EXAMINER : J.F.
REFERRAL :
COMMENT : NORMAL
FILE NAME : #30

TOTAL ERROR SCORE: 100
SQUARE ROOT: 10

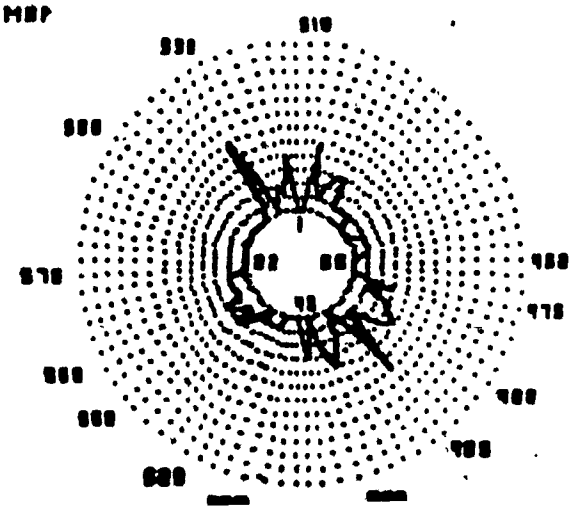
85 TO 21:																				
85	1	2	4	3	8	5	6	7	9	10	11	12	13	14	15	16	17	18	19	20	21
0	0	1	1	4	6	2	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0

22 TO 42:																				
22	23	24	25	27	26	28	29	31	30	33	32	34	35	36	38	37	39	40	41	42
0	0	0	1	1	1	1	1	1	2	2	1	1	0	1	1	1	1	0	0	0

43 TO 63:																				
43	44	47	46	45	49	48	53	50	51	52	54	55	58	56	59	57	61	60	62	63
0	2	2	0	3	3	4	6	2	0	1	1	2	3	3	3	4	3	1	1	0

64 TO 84:																				
64	65	66	67	69	68	70	71	72	73	74	75	77	76	78	79	83	80	82	81	84
0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	3	5	3	1	2	2

FM-100 MAP



Appendix D

Multi-flash Thresholds

SOURCE	SS	DF	MS	F	P
BETWEEN BLOCKS					
DIAGNOSIS	23729.95	2	11864.98	3.72	.036
ERROR	86153.36	27	3190.87		
WITHIN BLOCKS					
ECCENTRICITY	48751.95	5	9750.39	25.19	<.001
DIAGN/ECCEN	2465.77	10	246.58	.64	
ERROR	52256.50	135	387.09		

Contrast Sensitivity Scores

SOURCE	SS	DF	MS	F	P
BETWEEN BLOCKS					
DIAGNOSIS	.36	2	.18	.99	
ERROR	4.86	27	.18		
WITHIN BLOCKS					
SPATIAL FRE	8.43	4	2.11	114.90	<.001
DIAGN/SPATI	.37	8	.05	2.55	.013
ERROR	1.98	108	.02		

Farnsworth-Munsell 100-hue error scores

SOURCE	SS	DF	MS	F	p
DIAGNOSIS	2812.60	2	1406.30	.54	
ERROR	59717.11	23	2596.40		