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Duty Cycle and Luminance Considerations in Multi-Flash Campimetry

Mike J. Dixon

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in
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of
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Abstract

Duty Cycle and Luminance Considerations in Multi-flash Campimetry

Mike J. Dixon

Multi-flash campimetry is a clinical psychophysical technique in which the duty cycle of 5 Hz, constant pulse luminance (CPL) flicker is systematically reduced until the flicker is detected. CPL duty cycle reduction, however, may allow observers to base responses on the reduction in Talbot brightness of fused points rather than on flicker. Furthermore, critical fusion frequency (CFF) research reveals that while CPL duty cycle reduction between 100 and 50% causes increases in temporal resolution, further reductions cause decreased temporal resolving power. CFF investigations of time-average luminance (TAL) stimuli suggest these confounds could be avoided, for TAL duty cycle reduction can elicit monotonic increases in temporal resolution, without changing Talbot brightness. To see if variable frequency CFF findings could be extrapolated to 5 Hz multi-flash campimetry, 32 healthy observers were exposed to TAL, and CPL stimuli composed of different duty cycles and presented at retinal locations comparable to those in multi-flash campimetry. Temporal sensitivity was determined by assessing the minimum luminance modulation above and below a mean luminance level required to detect flicker. Within a given eccentricity, sensitivity was found to depend primarily on the amplitude of the fundamental Fourier frequency component of the stimulus. Subsequent experiments indicated that flicker detection

in multi-flash campimetry also depended on this amplitude. Since TAL duty cycle reduction causes monotonic increases in the fundamental amplitude, it should also evoke monotonic increases in temporal sensitivity. Thus using a TAL stimulus both circumvents the brightness-flicker confound in multi-flash campimetry, and causes sensitivity to the flickering point to increase monotonically.

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DUTY CYCLE AND LUMINANCE CONSIDERATIONS IN MULTI-FLASH CAMPIMETRY

Introduction

In many ways the manner in which we perceive the world around us is dependent on how our visual system processes information over time. Because our eyes are constantly moving, the visual input that is received consists of a large number of discrete images, all acquired from slightly different perspectives. What we actually see however, when we focus on a given object, is a single, stable, static image. In order to understand how temporal mechanisms within the eye could contribute to such complex phenomena, researchers first attempted to gain an understanding of how the visual system processed simple stimuli that varied over time. To this end, researchers conducted thousands of investigations using simple time-varying stimuli, namely, flickering lights.

Early investigators generally used rotating sector disks to produce flickering pulse trains. These disks were circular pieces of metal with pie shaped sections cut away at various locations of the disk. When these disks were rotated in front of an illuminating source, the alternation of open and occluding sectors would produce flicker. By increasing the speed of rotation of the disk, the perception of flicker would become more and more difficult, eventually giving rise to the perception of a steady light of uniform brightness. The frequency at this transitional point, where a flickering stimulus becomes fused, is called the critical fusion frequency or CFF. If the visual system is especially adept at detecting certain types of flicker, then very high frequencies will be necessary to cause a flickering stimulus to be seen as steadily on. Conversely, other types of stimuli could be dealt with by the visual system in a less effective manner, resulting in relatively low critical fusion frequencies. In this manner vision researchers could investigate how specific attributes such as luminance, size, and level of light adaptation influenced "temporal resolution" or the ability to detect flicker.

Another related method of assessing the temporal resolving power of the visual system is the two-flash or double-pulse technique. The influence of specific stimulus attributes such as luminance, size, and level of light adaptation, on temporal resolution can be assessed by establishing the minimum separation between two pulses of light necessary for each pulse to be seen as a unique event. Thus, if the eye is particularly adept at processing certain stimuli, for example two high luminance pulses, then relatively short separation intervals will be required to discern both of these pulses. If the temporal mechanisms of the eye are ill suited to dealing with certain other types of stimuli, such as small, eccentrically viewed low luminance pulses, longer intervals will be required.

Up until the middle of this century the most prominent and arguably, the most effective means of psychophysically assessing the temporal resolving power of the eye involved the assessment of the critical fusion frequency. In 1952 H. De Lange proposed that the sensitivity of the visual system could be assessed by determining the minimum extent that luminance had to be modulated above and below a mean luminance level before flicker could be detected. With the advent of De Lange's depth of modulation technique, the functional capability of the visual system could be assessed along an entire range of frequencies rather than only at CFF, the highest resolvable frequency. The seminal work of De Lange heralded the modern era of research concerning the temporal capabilities of the healthy visual system.

While temporal resolution techniques such as the CFF paradigm, the two-flash paradigm, and sensitivity paradigms such as De Lange's depth of modulation technique have been used to gain insight into the functional capabilities of the healthy visual system, recently, such techniques have also been successfully applied to investigations of the diseased visual system. The application of such techniques to the investigation of ocular pathology describes the primary considerations of a relatively new branch of psychology called clinical psychophysics.

Researchers such as Hylkema (1942), Titcombe and Willison (1961), and Daley, Swank and Ellison (1979) used variations of the critical fusion frequency technique to study the visual consequences of demyelination in multiple sclerosis. Tyler (1982) investigated glaucoma and ocular hypertensive patients using De Lange's depth of modulation technique. Galvin, Regan and Heron (1976) used a form of the two-flash paradigm to gather visual field information in patients with retrobulbar neuritis, while Regan, Milner and Heron (1976) used a between eye double-flash procedure which Regan called the perceptual delay technique to obtain similar information.

While all of the techniques mentioned above have proven effective in gathering information relative to ocular pathology, each technique possesses certain inherent drawbacks that serve to limit their clinical efficacy. Multi-flash campimetry is a clinical psychophysical technique that has attempted to circumvent these shortcomings while retaining many of the advantageous characteristics of its clinical psychophysical predecessors. This technique has proven useful in the monitoring of residual vision in patients suffering from degenerative disorders such as multiple sclerosis (Brussell, White, Bross, Mustillo, Borenstein, 1981/1982; Mustillo, Brussell, White, and Anderson, 1985; White, Brussell, Overbury, Mustillo, 1983), amblyopia and macular degeneration (Overbury, Brussell, White, 1984), as well as glaucoma (Brussell, White, Faubert, Dixon, Balazsi, and Overbury, 1986). The primary experimental manipulation involves what can be thought of as a combination of the two-flash paradigm and the CFF paradigm. In the multi-flash technique a point is flickered at 5 Hz and the duration of the interval between each successive pulse is systematically increased until flicker is detected. Stated in another manner, in each successive flicker period the duty cycle of the flicker is reduced by decreasing the duration of the on-period and increasing the duration of the off-period until flicker in the pulse train can be resolved. In this technique, temporal resolution is assumed to vary inversely with the duration of the off-period; that is, the longer the off-period required to detect flicker, the poorer temporal resolution is said to be.

In the current form of multi-flash campimetry the type of luminance employed is of the constant pulse variety in which a spot of light is turned on to a predetermined luminance level and then turned completely off. As the duty cycle of the flicker is systematically decreased, the total luminous energy (luminance X duration) incident on the eye is also reduced. Provided that the point is still seen as fused, reducing the energy of the point by decreasing the duty cycle will cause a reduction in the apparent brightness of the point. Thus it could be argued that observers have the potential to base their responses on this reduction in apparent brightness rather than on the detection of flicker per se. One way to circumvent this problem is to hold the amount of energy incident on the eye constant by increasing the intensity of the on-period of the flicker by amounts proportional to the reduction of its duration. Such a manipulation would effectively hold the time-average luminance of the point constant. By holding the time-average luminance of the entire pulse train constant, the possibility of observers basing their responses on criteria other than flicker would be eliminated. The primary question of theoretical and empirical interest that was addressed concerned the effects of implementing a time-average luminance display in multi-flash campimetry.

The ensuing discussion will describe previous experimental investigations of temporal resolution that relate to the practical and theoretical considerations in multi-flash campimetry. Following the discussion of these experimental investigations, early clinical psychophysical techniques that influenced the development of multi-flash campimetry are reviewed. Finally, the ramifications of implementing a time-average luminance display in multi-flash campimetry will be examined by first, reviewing previous investigations concerning temporal resolution and duty cycle reduction, and then proposing an experimental strategy that would allow an empirical investigation of these two variables.

Experimental Investigations of Temporal Resolution

A flickering light, if presented at a high enough frequency will appear to be a light of uniform brightness. Standard tungsten lights for example, actually alternate between periods of high and low intensity 120 times each second. The fact that we cannot detect the periods of reduced intensity inherent in such flicker when looking at a light bulb indicates that the eye integrates luminance over time.

In 1885, Bloch stated that for short pulses of light below a certain length of time known as the critical duration, the effect on the visual system was dependent on the product of the stimulus intensity and duration. This postulate, known as Bloch's Law, has been verified by a number of researchers including Long (1951) who found that below the critical duration the total energy, and not the waveform of the stimulus determined threshold. In this study Long found that for stimuli whose duration was below a critical duration of 100 ms, changing the temporal characteristics of the stimulus from a rectangular luminance distribution (abruptly turned on, maintained, and abruptly turned off) to a triangular distribution (gradual increases up to a peak, followed by gradual decreases to zero) had no effect on threshold whatsoever. Davy (1952) found that equal amounts of energy were required to detect a stimulus regardless of whether the energy was delivered by presenting one, two, three, four or five pulses.

If the eye is viewed as an mechanism capable of integrating luminous energy over time, a question of theoretical interest concerns the exact magnitude of the critical duration or, in other words, the duration of a single integrating period. Stated in another manner, how close must flashes be temporally, in order for them to be perceived as a single event. Rather than using long flicker trains comprised of many flicker cycles to address this question, some researchers adopted the strategy of using the simplest possible type of flicker, a flicker train comprised of only two cycles. This limiting case of flicker where only two pulses of light are presented is known as the two-flash or double-pulse paradigm.

Two-flash experiments.

The two-flash paradigm is ideally suited for investigating the limits of temporal resolution, for by manipulating the temporal interval between the two flashes, researchers could ascertain the temporal separation necessary for each pulse to be seen as a unique event. This minimum separation necessary to distinguish two light pulses can be used to estimate the critical duration (Davy, 1952; Lewis, 1967). Thus if two pulses are presented in two separate integrating periods, each pulse will be detected as a separate entity. If these pulses are presented within this critical duration, however, their energy will summate, and a single pulse having twice the brightness of the two individual pulses will be seen.

Although the value of the critical duration is often stated as being 100 msec (Kaufman, 1967; Cornsweet, 1963), according to many two-flash experiments, this value depends on the luminance of the flashes, the spatial extent of the flashes and the temporal duration of each flash. Mahneke (1957) investigated the latter effect of flash duration on the two-flash threshold (the minimum temporal separation necessary to detect each pulse of light). In this experiment he found that prolonging the duration of each flash by equal amounts, served to decrease the two-flash threshold. In addition, he also found similar decreases in the two-flash threshold when the duration of either the first or second pulse was increased and the duration of the other corresponding pulse was held constant. These findings led Mahneke to conclude that the visual system's ability to discern the dark interval between two pulses of light could be enhanced by increasing the total quantity of light within the stimulus package. Mahneke concluded that such an increase in temporal resolution could be evoked by elevating the luminance of the pulses or by increasing their duration.

Such a "quantity of light" or energy hypothesis was challenged by Kietzman (1967) who replicated Mahneke's findings concerning pulse duration, but failed to find any systematic change in two-flash threshold when the luminance of the pulses were increased. One possible explanation for Kietzman's failure to find an inverse relationship between the luminance of each pulse and the two-flash threshold is postulated by Lewis (1967). Unlike Kietzman, Lewis found that increasing the luminances of the pulses did serve to significantly lower the two-flash threshold, but only for luminances below those tested by Kietzman. In addition to studying the effects of luminance on the two flash threshold, Lewis also investigated the effect of the spatial extent of the pulse stimuli, or the effect of area on the two-flash threshold. Lewis (1968) concluded that there was an inverse relationship between stimulus area and two-flash threshold, and that this relationship was most prevalent at low luminances.

Critical fusion frequency experiments.

While the two-flash technique provided one method of measuring the temporal resolving power of the eye, a more commonly employed means of assessing temporal resolution involved measuring the critical fusion frequency (CFF) of a flickering stimulus. Like the two-flash technique, CFF paradigms are also concerned with the minimum separation between light pulses necessary to see such pulses as discrete events. Unlike the double flash technique, CFF paradigms present a sequential series of pulses to the observer, such that, depending on the temporal characteristics of this pulse train, the observer either sees flicker, or alternatively sees a light of uniform brightness. The minimum temporal separation between pulses is manipulated by increasing or decreasing the frequency (the number of pulses per second) of the pulse train presentation. At high frequencies, the temporal separation between pulses will be too short to distinguish these individual pulses, and the display will appear to be one of uniform brightness. At lower frequencies, however, individual pulses can be distinguished, and the display will be seen as flickering.

When comparing CFF to the two-flash paradigm, a number of inherent adavantages of the former technique can be stated. One such advantage is that by displaying a long sequence of flashes, the eye can be adapted to the mean luminance level of the pulse train, rather than undergoing rapid changes in adaptation upon being presented two brief light pulses. Furthermore, in the two-flash technique, only a single chance for detection is afforded, a chance that may be missed due to inherent noise in the visual system. In the CFF paradigm, the subject is provided a great number of opportunities to detect non-uniformities within a given pulse train, an experimental situation that would tend to partially overcome the influence of noise within the system.

As was previously mentioned a typical CFF paradigm involves presenting a flickering test patch to an observer, and increasing the frequency (the number of flashes per second) until flicker can just no longer be detected. If the visual system is especially adept at detecting certain types of flicker, such as high luminance flicker presented using a large test field, then very high frequencies will be necessary to cause a flickering stimulus to be seen as one of uniform brightness. Conversely, other types of stimuli, such as small points flickered at low luminance levels, are dealt with by the visual system in a less effective manner, resulting in relatively low critical fusion frequencies. Thus the determination of the critical fusion frequency, like the determination of the double flash threshold, provides a viable means of assessing the temporal resoluton of the human visual system to the wide possible range of stimulus attributes that comprise a given time-varying stimulus.

Given the multitude of possible variables that can influence the temporal resolving power of the visual system, it is not suprising that a vast number of CFF studies have been conducted over the course of the last century. Outlined below are a select few of these studies, highlighting findings that will be of particular importance to the theoretical considerations of the multi-flash campimetry technique.

In many of the earliest CFF studies a disk, half white, and half black was illuminated by an external source, and the CFF was determined by manipulating the speed of rotation of this disk. One question of empirical interest concerned the effect on CFF of the intensity of the illumination source. The relationship between CFF and the luminance of the flickering stimulus was first established by Ferry in 1892, and this relationship was re-addressed by Porter in 1902. Porter used standard candles, incandescent lamps and an arc light to assess the effects of low medium and high levels of luminance. Porter found that except for the very lowest luminance levels tested, CFF varied directly with the logarithm of the luminance of the disk. In fact, even at the lowest luminance levels tested, a logarithmic relationship between CFF and luminance was maintained, although the rate of variation in the CFF-luminance function was more rapid at these levels. This relationship between CFF and luminance has come to be known as the Ferry-Porter law. Other assessments of the effect of luminance of the flickering test field on CFF indicate that this relationship between CFF and luminance applies only to a limited range of conditions (Kelly, 1961b) and, as such, should be considered a general formulation rather than a law (Brown, 1965) . For the majority of flicker paradigms however, the Ferry-Porter law describes data quite accurately, and stated in very general terms, one can conclude that increasing the luminance of a test stimulus affords consequent increases in CFF.

Another question of empirical interest addressed by early CFF investigators concerned the effect of the stimulus area on the critical fusion frequency. While previous reports concerning stimulus area and CFF were provided by Charpentier (1890) and Ives (1912), it was not until 1930 that a systematic study of the effect of area on CFF was conducted. This seminal work was conducted by Granit and Harper (1930), and the formulations arrived at through this research provided the foundations for the Granit-Harper law which bears their names.

Unlike Porter's (1902) research which made use of black and white rotating disks, Granit and Harper's study made use of the previously described rotating sector disks. As with the disks used by Porter, the critical fusion frequency was assessed by manipulating the speed of rotation of the sector disk. In order to assess the effect of stimulus area, an adjustable diaphragm was interposed between the rotating sector disk and the observer. Using such an experimental setup, Granit and Harper determined the critical fusion frequency for a number of stimulus areas flickered at a total of eight different intensities. These authors concluded that there was a linear relation between CFF and the logarithm of the stimulus area. This relationship was maintained across a variety of stimulus areas ranging from .35 deg^2 to 6.0 deg^2. Beyond six deg^2, increasing the stimulus area of a flickering test patch had no effect on the critical fusion frequency. Other findings included the fact that the slopes of these lines increased with the intensity of the stimulus, and that this influence of intensity was more prominent in the periphery than in the fovea. Unlike the Ferry-Porter law, the Granit-Harper law has proven to be a robust and often replicated formulation that has been used to describe the effect of area on CFF in a number of different paradigms.

The findings of Granit and Harper indicated that stimulus area and intensity differentially affect foveal and peripheral areas of the retina. Such findings indicated the need for an in-depth assessment of how CFF is influenced by the retinal location of the stimulus presentation. A systematic study addressing these issues was conducted by Hylkema in 1942. Hylkema essentially replicated and extended the findings of Granit and Harper (1930), namely, that CFF was highest in the periphery when large stimulus areas were used, and highest in the fovea when small test stimuli were employed. In addition, Hylkema found that the nasal area of the visual field displayed the greatest temporal resolving power, and that the inferior portion of the visual field afforded higher CFF values than the superior visual field. Hylkema postulates that the reason near peripheral areas in the nasal field are maximally efficient, is to compensate for the innefficiency of the blind spot located in the corresponding area of the other eye. In the far periphery beyond 30 deg. however, the temporal field shows greater resolving power as indicated by higher CFF values.

Thus far, all the CFF experiments that have been discussed have used what can be referred to as 100% modulation flicker. That is, luminance presentations consisted of on-periods where a beam of light was presented to the eye at a predetermined luminance level, and an off-period where this luminance level was reduced to the background luminance level. A study by De Lange (1952), however, involved assessing CFF to sine wave stimuli flickered at depths of modulations that were less than 100%.

De Lange's temporal sensitivity experiments.

The problem De Lange investigated concerned how the visual system responded to different temporal waveforms. In order to address this question De Lange initially assessed the critical fusion frequency to a number of these temporal waveforms flickered at close to a 100% depth of modulation. By varying attributes of the stimulus such as duty cycle (the ratio of white to dark sections of the disk), De Lange was able to obtain critical fusion frequencies ranging between 50 and 9 Hz. Because De Lange was interested in the relationship between critical fusion frequency and what he called the "low-frequency characteristics of the eye" De Lange required stimuli that would yield CFF values lower than this 9

Hz limit. To this end, De Lange presented sine waves at various contrast levels or depths of modulation. For example, a sine wave whose maximum luminance was only slightly above the average luminance, and whose minimum luminance was only slightly below the average luminance would be associated with lower CFF values than a sine wave whose amplitude was considerably larger. Thus by using sine waves of varying amplitudes De Lange obtained CFF values that ranged between 1 and 50 Hz.

The manner in which De Lange analysed the CFF data from both sinusoidal and more complex rectangular wave stimuli, involved Fourier analysis. Fourier analysis is a mathematical theorem that involves breaking a temporal waveform into an infinite number of component sine waves of different frequencies, amplitudes and phase relationships. A schematic representation of how component sine waves can be synthesized to produce an approximation of a square wave is illustrated in Figure 1.

As can be surmised from Figure 1. a square wave can be decomposed into: a sine wave that has the same frequency of the stimulus but a larger amplitude, a sine wave that is three times the frequency of the stimulus and 1/3 the amplitude of the first sine wave, a sine wave that is 5 times the frequency of the square wave and 1/5 the amplitude of the first sine wave etc. etc. Such a decomposition of a complex waveform into component sine waves is called Fourier analysis. The results of such an analysis will always reveal one sine wave having the same frequency as the complex stimulus. This sine wave is called the fundamental frequency. The sine waves of higher frequencies are called harmonics. In the

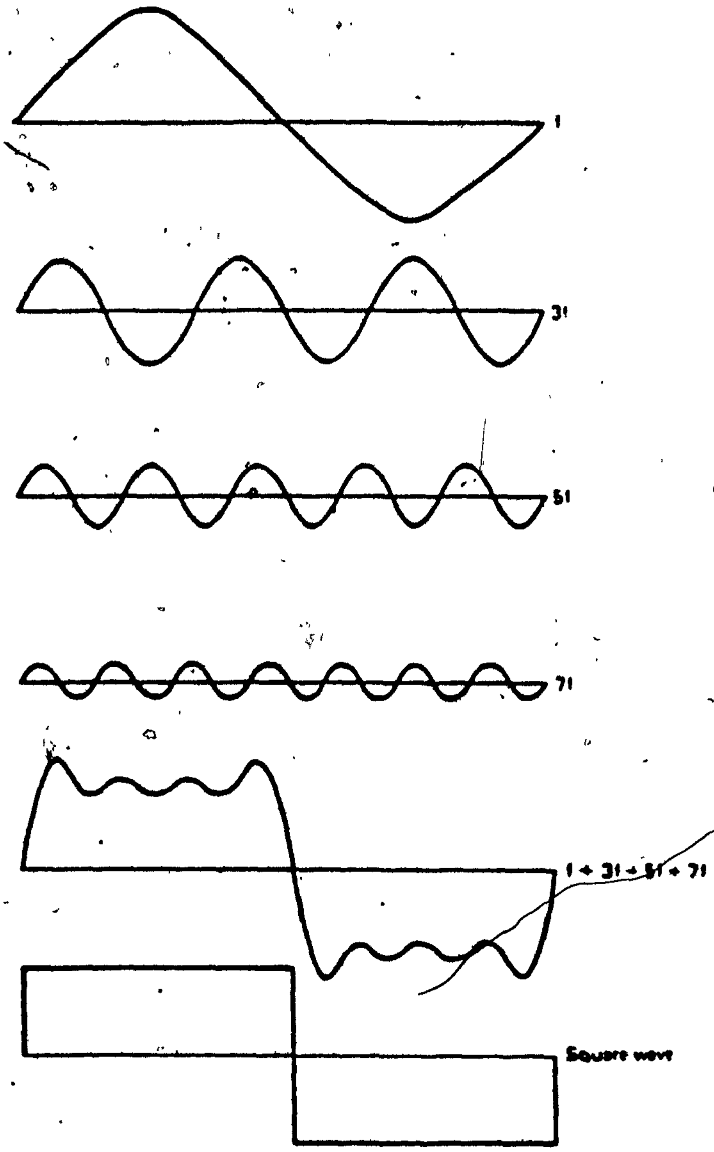

Figure 1. Approximating a square wave using the Fourier frequency components. (Taken from Kaufman, 1974, pp. 105).

language of Fourier analysis therefore, a square wave is comprised of a fundamental frequency (1F in Figure 1.) whose amplitude is 4/3 that of the square wave), and an infinite number of odd harmonics (3F, 5F, 7F etc. in Figure 1).

Although a stimulus can be analyzed into an infinite number of frequency components, De Lange assumed that at threshold, under most conditions, the visual system was primarily responsive to only one of these frequencies; the fundamental frequency. The importance of this fundamental frequency in flicker detection is illustrated by the fact that De lange specified his data in terms of what he called the "ripple ratio". This ratio consisted of the amplitude of the fundamental frequency divided by the average luminance of the stimulus. Essentially De Lange found that regardless of the actual physical characteristics of the stimulus waveform, (maximum and minimum luminances and their durations relative to each other), as long as the ripple ratio was above 2%, CFF depended only on this ripple ratio.

De Lange viewed the visual system as being essentially analogous to a linear network of electrical circuitry that served to act as a low pass filter. The results of his CFF experiments, therefore, can be explained in terms of such a filter model by considering the frequency relationships among the various Fourier components that make up a 100% modulated square wave stimulus. If the visual system is viewed as a low pass filter, then oscillations in low frequency Fourier components would remain unchanged; but these oscillations in high frequency components would be attentuated by the filtering action of the visual system. Since the square wave in Figure 1 is comprised of a fundamental frequency (equal to the frequency of the presented stimuli), and an infinite number of higher frequency components, as the frequency of the presented stimulus is increased, more and more of the high frequency components would effectively be filtered out. As such there should be a certain frequency at which only the fundamental frequency would be below this attenuation threshold. A further increase in frequency would push the fundamental above the highest frequency that can be resolved, causing the presented waveform to be percieved as a light of uniform luminance. This frequency, according to De Lange represents the CFF value.

Both the methodology of De Lange´s study, and his electrical analogue approach to viewing the visual system, stimulated a new direction in vision research. As an isolated example, Kelly (1961b) found that the visual system was far less sensitive to low frequencies when a test stimulus with a blurred border was used compared to low frequency sensitivity for De Lange´s small test field against a uniform background. The importance of De Lange´s electrical analogy, however, is attested to by the fact that Kelly postulates that the visual system acts as a band pass, rather than a low pass filter.

Experimental investigations of temporal resolution indicate that if short pulses of light are presented within a critical interval the effect on the visual system will not depend on the stimulus characteristics of the waveform, but rather on the energy (intensity X duration) of the stimulus (Long, 1951). One method of estimating the duration of the critical duration is to establish the minimum interval required to detect two distinct pulses of light, or the two-flash threshold (Davy, 1952; Lewis, 1967). Increases in either the pulse duration (Mahneke, 1957), or the pulse luminance (Lewis, 1967), serve to decrease this two-flash threshold. A second means of measuring temporal resolution involves determining the critical fusion frequency of a flickering stimulus. Increases in either the luminance of the test field (Porter, 1902), or the spatial extent of the test field (Granit and Harper, 1930) have been shown to result in elevations of the critical fusion frequency. For fixed levels of stimulus area, and luminance, the critical fusion frequency has been shown to depend on the amplitude of the fundamental Fourier frequency component of the presented stimulus (De Lange, 1953).

De Lange recognized that his methodology and resultant sensitivity curves were important not only for investigations of the healthy visual system, but also could provide essential information about the diseased visual system (De Lange 1957 as cited in Tyler, 1981). The use of psychophysical techniques to assess the functional capabilities of the diseased visual system comprises a relatively new area of psychology called clinical psychophysics. In order to fully understand the benefits of multi-flash campimetry as a clinical psychophysical technique it is necessary to see how previous psychophysical techniques have been applied to the investigation of the diseased visual system.

Clinical Investigations of Temporal Resolution

In the 1940's the methods that were contemporarily used by ophthalmologists to acquire visual field information typically involved the ability to distinguish between different hues in the peripheral visual field, or the minimum area of a test spot required for that spot to be detected using peripheral vision (Hylkema, 1942). When used as indicators of the global functional capabilities of the visual field, each of these methods contained certain inherent drawbacks. For example, the collection of visual field information based on the patients ability to distinguish differences in hue were often found to be unreliable (Hylkema, 1942). Furthermore visual field information acquired in this manner can be confounded by disturbances in colour mechanisms causing normal visual fields (in every respect other than colour discrimination) to appear to be functionally impaired. Other methods such as determining the minimum spatial extent of a spot of light required for visual detection, are problematic in that they may be confounded by factors such as differential acuity across the visual field. In order to circumvent these problems Hylkema (1942) suggested using a critical fusion frequency paradigm to obtain information about visual fields. These methods, according to Hylkema, would be effective for they are not influenced by optical blur, and do not require the use of the colour mechanisms within the visual system.

While use of CFF paradigms may be particularly useful for practical reasons such as those outlined by Hylkema, the nature of the task is of great medical interest as well. Demyelination has been shown to either slow or completely block conduction along neuronal fibres (Halliday & McDonald 1977). Even prior to these neurophysiological experiments, Titcombe and Willison (1961) postulated that in demyelinating diseases such as multiple sclerosis (MS), reductions in the critical fusion frequency might be due to lesions anywhere along the visual pathway. As such, they surmised that this technique would be of great diagnostic value in evaluating patients suspected of having multiple sclerosis.

In order to assess the clinical efficacy of such a paradigm Titcombe and Willison (1961) measured the critical fusion frequency for 60 MS patients and 28 controls. The critical fusion frequencies required by controls was significantly higher than the CFF values obtained by patients. Other analyses indicated ~~that~~ CFF and visual acuity tests were related, but there was not a strong link between these two measures of visual functioning. In addition, a strong inverse relationship was obtained between CFF and the degree of pallor associated with the optic disk. This finding suggested that the depression in CFF may be linked to the presence of retrobulbar neuritis. In support of this postulate these authors cited cases in which CFF was dramatically reduced during acute episodes of this disorder, and restored in remission phases of the disease.

Another study concerning CFF and multiple sclerosis was conducted by Daley, Swank, and Ellison (1979). In this series of experiments, CFF values were shown to be abnormal in 48% of a sample of 122 MS patients. When these same subjects were tested in a CFF paradigm where the test patch was encircled by a flickering surround, 78% of the MS patients illustrated impaired CFF values. The impetus for using the flickering surround was based on the finding that impaired but not destroyed demyelinated fibres have been show to fatigue (Raminsky and Sears 1972, as cited in Daley et al., 1979). Based on this assumption it was hypothesized that the flickering surround served to fatigue damaged neurons through repetitive activation, and in so doing evoked a reduction in CFF in patients with less severe demyelination. The fact that the control group did not show significant changes in CFF when tested with the flickering surround lends credence to the arguments of Daley et al., for only pathways with some degree of neuronal damage, would become fatigued under these conditions.

While CFF research has proven to be effective in distinguishing patients from normals, it must be noted that such techniques measure only the upper limits of the visual system's temporal sensitivity function. Recognising this fact, Tyler (1981) used De Lange's methodology to assess the temporal sensitivity loss of glaucoma and ocular hypertension patients, across an entire range of frequencies. Tyler used a 5 deg flickering test field to obtain sensitivity curves for both foveal and peripheral areas of the retina. The lowest frequency tested by Tyler was 5 Hz, while the upper limit was the highest resolvable frequency of the observer being tested.

Tyler found that this De Lange type paradigm illustrated temporal sensitivity impairment in 100% of the glaucoma patients tested, and in 90% of the ocular hypertensive patients who were administered this test. Of special importance was the finding that the greatest sensitivity losses occured in middle frequencies, rather than at the highest resolveable frequency. The fact that Tyler found nine cases in which patients displayed normal CFF values, at 100% modulation, but abnormal mid-frequency sensitivity values indicates that the De Lange type paradigm is a more sensitive indicator of temporal impairment than traditional CFF tests.

Another interesting finding that emerged from Tyler's study was the detection of <u>central</u> visual field losses in 77% of the patients tested. While standard perimetric assessment leads one to expect peripheral field losses in glaucoma, rarely do these assessments reveal central field loss. Furthermore, Tyler's use of the De Lange type paradigm in the assessment of ophthalmalogical disorders is especially effective for this technique reveals field loss even prior to any losses in the overall light sensitivity used by standard perimetric techniques.

The clinical psychophysical techniques discussed so far have proven effective in distinguishing members of a patient population from normal healthy individuals. Such tests, however, cannot identify specific areas of dysfunction within the visual field because such techniques intentionally make use of large flickering test fields. The rationale for using large fields such as the 5 deg field employed by Tyler, is specifically to avoid decreases in CFF due to the inadvertent placement of the test patch over scotomas within the visual field. Researchers adopting this strategy were attempting to acquire a general measure of visual functioning, and therefore, hoped to avoid reductions in CFF due to localized defects. Thus by using large test patches, it was thought that CFF values would only be affected by very large, sharp edged scotomas

(Titcombe & Willison 1961).

The perceptual delay technique.

A different approach was adopted by Regan and his co-workers in their studies of visual fields in patients with demyelinating diseases (Regan, Milner, and Heron, 1976). By using small test stimuli and presenting these stimuli at numerous locations throughout the visual field, these researchers were able to detect small areas of reduced temporal resolution or, using Regan's terminology, "islands of dysfunction". In order to elicit this information these researchers made use of previously mentioned fact that conduction along demyelinated pathways is often slowed or blocked altogether. Thus the detection of a single luminance pulse will be relatively delayed when viewed with an eye suffering from retrobulbar neuritis, compared to the detection of a similar pulse when viewed by a normal eye (Regan, Milner and Heron, 1976). The absolute value of this perceptual delay can be estimated by determining the minimum stimulus onset asynchrony (SOA) between each pulse required for the observer to say that the two pulses were presented simultaneously.

The reason for variations in the dependent variable of the perceptual delay technique can be illustrated by giving an example. In a healthy observer, there is no delay in conduction along the optic nerve in either eye. Thus in order for two pulses of light to appear simultaneously, each pulse must actually be presented to each eye at approximately the same time (zero SOA). If, however, two simultaneous pulses were presented to a patient with unilateral optic neuritis, the inordinate amount of processing time required by the damaged eye will cause the two pulses to appear sequentially. Thus in order for the two pulses to appear to be presented simultaneously, the onset of the pulse presented to the undamaged eye must follow the onset of the pulse presented to the damaged eye by some specifiable amount. The magnitude of the stimulus onset asynchrony between pulses will therefore be determined by the amount of "perceptual delay" inherent in the damaged eye.

Using this strategy these researchers were also able to assess the perceptual delay to abrupt <u>decreases</u> in luminance, by determining the minimum SOA between two interuptions of a steady luminance presentations, required for the subject to indicate that these interuptions occured at the same time (Regan, Milner, and Heron 1976). Interestingly, the measurements of visual delay for rapid increases, and rapid decreases in luminance often yielded different perceptual delay values. According to Regan et al., such a finding indicated that there are two distinct channels for detecting increasing and decreasing luminance steps, and that these channels are differentially effected by demyelinating pathologies such as retrobulbar neuritis.

In addition to providing general information concerning the functional capability of a given eye, the perceptual delay technique allows visual field information to be obtained. In order to test various locations throughout the visual field the first pulse presentation was located in the fovea and provided a reference for variable retinal locations of the second pulse. Visual field information could, therefore, be obtained by looking at the distribution of obtained perceptual delay values for various locations across the entire visual field. Such a procedure could be implemented to test perceptual delay between eyes (Regan, Milner, and Heron, 1976), or within the same eye (Galvin, Regan, and Heron, 1976).

By associating functional areas of the visual field with low perceptual delay values, and areas of dysfunction with high perceptual delay values, this technique enabled researchers to detect small "islands of dysfunction" within the visual field. It must be noted however, that the perceptual delay latencies for different areas of the visual field are measurements that are relative to the foveal reference point rather than absolute quantifications of functioning. As such, the perceptual delay strategy runs the risk of committing a type II statistical error. If for instance the perceptual delay was measured for an impaired location in the periphery using a foveal reference point that also happened to be impaired, the equal amount of delay encountered during the processing of each point would cause simultaneous presentations to actually appear at the same time, affording an SOA value approximately equal to zero. Such a small perceptual delay value would not be distinguishable from the SOA value obtained from fully functional, undelayed test and reference locations.

Double flash campimetry.

A second strategy for acquiring visual field information that circumvents this problem of relative rather than absolute specifications of visual field functioning involves using a double-flash paradigm. This technique was previously discussed in connection with the assessment of temporal resolution in the healthy visual system (Mahneke, 1957; Lewis, 1967, Kietzman, 1967). The first clinical application of the two flash technique was conducted by Galvin et al. (1976) in an investigation concerning patients with retrobulbar neuritis. Galvin's version of the double-flash paradigm made use of the method of ascending and descending limits to assess the minimum ISI required to see each of the two pulses. The ISI between two identical pulses of light was systematically increased from a very small duration in which these pulses were not distinguishable, to a duration that allowed the two pulses to be seen as discrete events. Next, the ISI was systematically decreased from a value in which the two pulses were consistently seen as separate events, until only a single pulse was detected. The ISI's corresponding to response reversals (single to double) for two ascending passes and two descending passes (double to single) were averaged and this value was taken to be the minimum flash separation required to see the double pulse.

The principal difference between this double-flash technique and the perceptual delay task is that in the former technique the second pulse appears at the same retinal location as the first pulse. Thus the obtained double-flash thresholds describe temporal resolving capability within distinct areas of the visual field rather than referencing specific locations against temporal resolving power in another area of the visual field. In addition to providing visual field information that requires fewer assumptions to be made, the double-flash technique was found to be more sensitive than the perceptual delay paradigm for certain types of optic neuropathy (Regan 1979). Because the double-flash technique can detect small "islands of demyelination" (Regan 1979), it was deemed to be clinically superior to the use of visual evoked potentials (monitoring electroencephalographic responses to visually presented stimuli), in acquiring visual field information. It was also found to be superior to the Pulfrich pendulum test in which a pendulum swinging back and forth on a fixed plane appears to be moving in an elipse if visual delay is present (Rushton, 1975). Another measure which was found to be inferior to the double-flash technique was contrast sensitivity, where the minimum amount of contrast required to detect the presence of a sine wave grating is determined to assess the degree of impairment within the visual system. When comparing these tests, the overall efficiency and relative inexpensiveness of the double-flash technique led Regan (1979) to conclude that if a single test was to be chosen from a battery of tests including, double-flash, CFF, visual evoked potentials, contrast sensitivity, and the Pulfrich pendulum test, the best choice would be the double-flash technique.

When any psychophysical test is being considered for use in a clinical setting, the duration of the test becomes of paramount importance. Since many ophthalmalogical disorders such as macular degeneration and glaucoma are most prevalent among the elderly, psychophysical tests that are unduly long will be considered innappropriate by the physician, irrespective of their experimental validity and ability to provide information about a given pathology. Thus, despite the efficacy of the double-flash technique in providing high quality visual field information, using the method of ascending and descending limits in acquiring this information may render the technique clinically inefficient.

In reviewing some of the clinical psychophysical techniques that use temporal resolution to investigate ophthalmalogical pathologies it is clear that each individual technique has specific advantages over other paradigms, as well as specific shortcomings. While CFF provides a relatively rapid means of assessing visual field information, potentially informative mid-frequency losses may go undetected because this range of frequencies are not sampled in such paradigms. Tyler's depth of modulation technique, may detect these losses, but the size of the test stimulus precludes the acquisition of information concerning specific "islands of demyelination". The perceptual delay paradigm allows these small areas of visual field dysfunction to be assessed, but affords relative rather than absolute temporal resolution data. The double-flash threshold allows islands to be detected and quantifies the visual field using a psychophysically sophisticated measure, but is probably not clinically effective due to the duration of the test.

Multi-flash campimetry.

Multi-flash campimetry is a clinical psychophysical technique that attempts to incorporate the advantageous components of previously described techniques, while at the same time circumventing any shortcomings inherent in these paradigms. In its present form a stimulus display comprised of 120 6 min points is presented to the observer. A schematic representation of this stimulus display is given in Figure 2. On any given trial, a computer randomly selects one of these points and begins to flicker it at 5 Hz. The duty cycle (the proportion of the flicker period that is lit) starts off at 100% and is progressively reduced by increasing the duration of the dark interval and decreasing the length of the lit interval by 2.8 ms each successive 200 ms cycle. This reduction of duty cycle continues either until the observer indicates with a paddle press that flicker has been detected, or the dark interval reaches a value of 200 msec. In either case another point in the visual field is randomly selected (without replacement) and the procedure just described is repeated. By determining the minimum duty cycle required to detect flicker the multi-flash technique allows the temporal resolution of 120 points in each visual field to be sampled in about a half hour.

The multi-flash paradigm is similar to the CFF assessment of visual fields in it's rapidity of administration. Rather than using a time consuming psychophysical method, flicker starts at duty cycles well above fusion and is systematically reduced until flicker is detected. The quality of data collected in this potentially noisy fashion is controlled by replicating any statistically aberrant points. Unlike CFF measurements, a constant frequency is maintained, and duty cycle is manipulated in a fashion that is analogous to Regan's double-flash method. The multi-flash

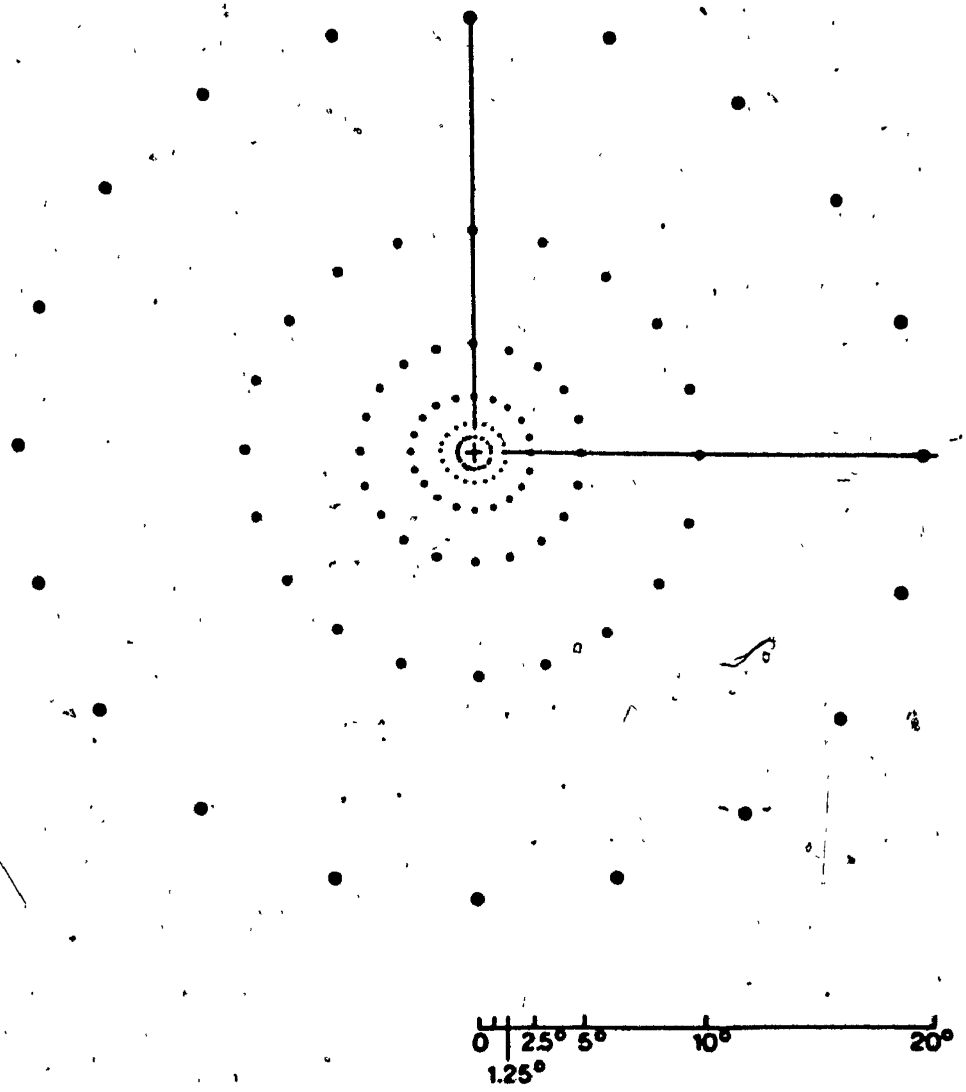

Figure 2. The stimulus display in multi-flash campimetry. Each of the 120 Points subtends six min of arc.

thresholds therefore, can be thought of as the minimum dark interval between a series of pulses required for the subject to first detect flicker.

The decision to use very small stimuli in multi-flash campimetry was influenced by the double-pulse paradigm (Galvin et al, 1976), which acquired double-pulse thresholds for a large number of small points located throughout the visual field. Like Galvin's technique, the utilization of six min points in multi-flash campimetry, allows specific "islands of dysfunction" to be detected. The presence of such "islands", as well as any visual field defects can be illustrated by presenting the data in terms of 2-dimensional visual field plots such as those depicted in Figure 3.

Each numerical value presented in Figure 3. corresponds to the off-period required for flicker to be detected at that corresponding location in the visual field. While the multi-flash paradigm is similar to Galvin's double flash technique in it's ability to detect "islands of dysfunction" such as those portrayed in this multiple sclerosis patient, unlike the double-flash technique, this information can be obtained in a relatively short period of time.

While multi-flash campimetry circumvents many of the problems inherent in other clinical psychophysical techniques, it is not entirely free from potential criticism. The grounds for this criticism involve the progressive reduction of the duty cycle of a constant pulse luminance 5 Hz flicker train. Inherent in this procedure is the systematic reduction of the Talbot brightness of the flickering point as the duty cycle of the flicker in this point decreases.

Figure 3. Two-dimensional visual field maps for the left and right eyes of an Multiple Sclerosis patient.

Because the eye integrates luminance over time, a flickering point, if presented at a high enough frequency, will appear to be a non-flickering point of uniform brightness. The off-periods, or dark intervals of such a flicker train, although not detected, still influence the visual system, however, for such a point will appear less bright than a point of the same luminance that is not flickering. The degree of difference in brightness between two such presentations depends on the duty cycle of the flickering stimulus. The manner in which the brightness of a fused stimulus can be quantified is by stating the Talbot brightness of this stimulus. This Talbot brightness takes into account the effect of duty cycle on perceived brightness and is calculated by multiplying the luminance of the point by the duty cycle of the flicker when this duty cycle is expressed as a proportion. Thus decreasing the duty cycle of a point affords decreases in the Talbot brightness, and consequently the apparent brightness of this point. In the multi-flash paradigm, therefore, as the duty cycle of the flicker is systematically reduced, the Talbot brightness of the flickering point will decrease.

Because of the systematic reduction of the apparent brightness of one point in the multi-flash display compared to all the others, observers could potentially base their responses upon this brightness reduction cue rather than on the detection of flicker. Such a situation would result in an underestimation of the degree of temporal resolution impairment within an observer's visual field. The degree of impairment would be underestimated because a brightness reduction can only be observed in a fused point;

responses based on this brightness reduction would therefore, by definition occur prior to the detection of flicker. Although experimentally undesirable, the confounding of duty cycle reduction and apparent brightness is not a fatal flaw in the multi-flash technique for its only possible ramification is the commission of a type II statistical error, potentially causing deficient fields to appear normal. Given the detrimental side effects of pharmacological treatments of ocular pathologies such as glaucoma, if errors are to be made, it is preferable to make type II errors rather than erroneously conclude that healthy observers are in need of such treatment.

Fortunately, this whole problem can be circumvented by holding the time-average luminance of the flickering point constant. Since the time-average luminance of flicker can be considered a measure of luminous energy, it is dependent on both the duration, and the intensity of the on-periods within each cycle of a flickering stimulus. As a simplified example, suppose one wanted to equate the time-average luminance of 75% duty cycle flicker with 25% duty cycle flicker. Since the duration of the on-periods in the 25% duty cycle stimulus is 3 times less than that of the 75% duty cycle stimulus, the intensity of the on-periods of the former would have to be increased by a factor of 3. Thus, 75% duty cycle flicker having a maximum luminance of 4 cd/m^2, has the same time-average luminance as 25% duty cycle flicker, with a pulse luminance of 12 cd/m^2. When the total luminance of each presentation is averaged over time, therefore, the total "energy" value, or time-average luminance, will be the same regardless of duty cycle. According to the

Talbot-Plateau law, if each of these flicker trains were presented at frequencies high enough to obviate the perception of flicker, their appearance would be identical.

In multi-flash campimetry, the time-average luminance and consequently the Talbot brightness of the entire pulse train can be maintained at a constant level by increasing the intensity of the on-periods within each flicker period by amounts proportional to the decrease in the duration of these on-periods as the duty cycle is of the flicker is reduced. The luminance characteristics of multi-flash pulse trains which maintain either a constant pulse luminance, or a constant time-average luminance are presented in Figure 4. Such a manipulation would serve to equate the Talbot brightness of the pulse trains used in multi-flash campimetry, and eliminate the possibility of observers basing responses on changes in the apparent brightness of the point.

While the implementation of a time-average luminance display in the multi-flash procedure seemed to be advantageous for the reasons previously discussed, a question that remained to be addressed concerned the effects that such a luminance presentation would have on temporal resolution. In order to address this question, previous studies concerning time-average or constant pulse luminance and duty cycle reduction will be reviewed below.

CFF Investigations of Time-average and Constant Pulse Luminance

Classical studies concerning the effect of duty cycle reduction on CFF have yielded different results depending on whether they held

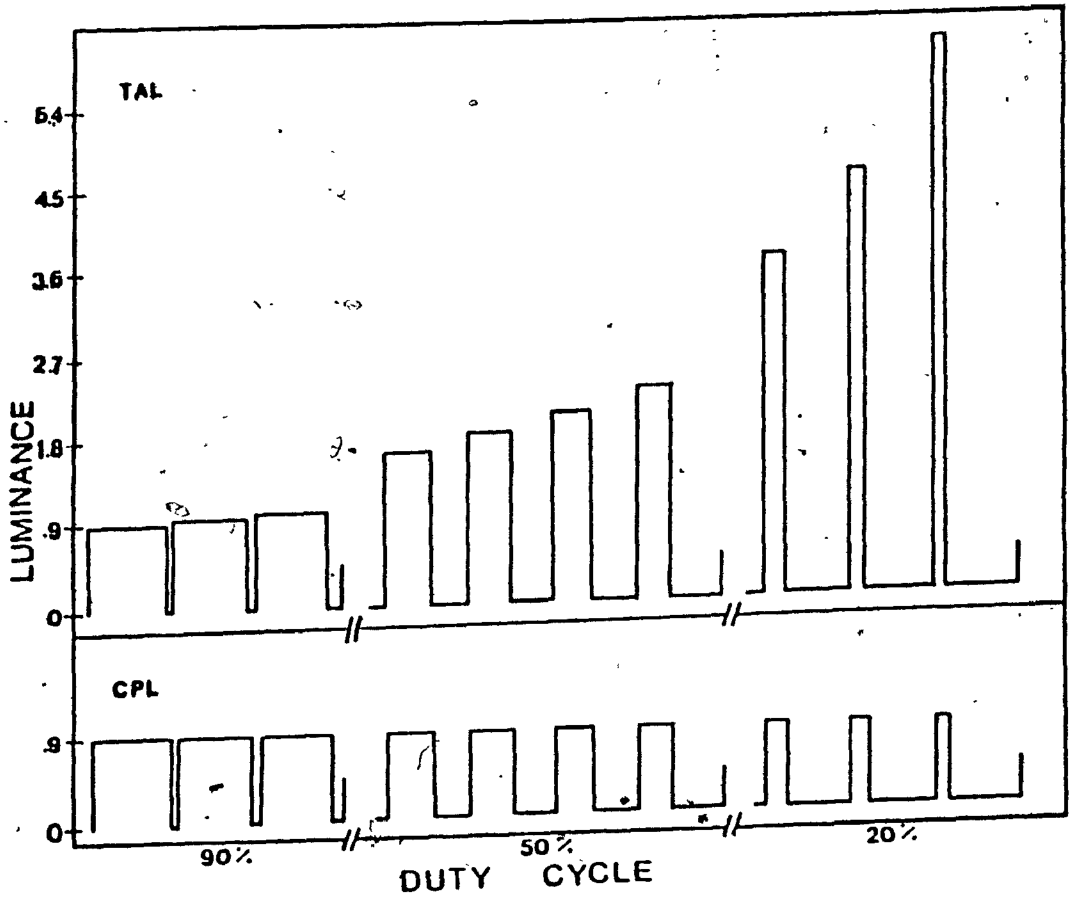

Figure 4. Time-average luminance (TAL) and constant pulse luminance (CPL) trains used in multi-flash campimetry. Duty cycle is systematically reduced by 2.8 ms each 200 ms cycle. Luminance is calibrated in foot lamberts.

the time-average luminance or the pulse luminance of the flicker constant. The majority of studies that utilized a constant time-average luminance have found that as duty cycle decreases CFF increases. For example, by using rotating sector disks of various shapes, and neutral density filters to compensate for changes in apparent brightness, Ives (1922a) compared flicker trains comprised of different duty cycles. As was previously mentioned, rotating sector disks have pie shaped sections removed in order to allow light to pass through to the observer. When a light source was placed behind one side of these rotating disks, the alternation of open and occluding sections of the disk would cause flicker to be produced. Duty cycle was manipulated by varying the proprortion of the open sectors of the disk to total disk area. Using such a procedure Ives found that CFF values were highest for those disks that had the smallest total open area, or what he called the smallest light to dark ratio. In general, Ives found that decreasing the light to dark ratio, or in modern terminology, decreasing the duty cycle of the flicker, evoked increases in critical fusion frequency.

Over a decade later P. W. Cobb (1934), readdressed the relationship between duty cycle and CFF. Rather than using neutral density filters to maintain a constant time-average luminance, Cobb equated the Talbot brightness of flicker comprised of different duty cycles by increasing the actual intensity of the light source to compensate for decreases in the duration of the on-period due to the reduction of duty cycle. By maintaining a constant time-average luminance across all duty cycles in this fashion, Cobb obtained results that were consistent with the findings of Ives: a general inverse relationship between duty cycle and CFF.

Ross (1938) illustrated that the findings of Ives and Cobb held for different levels of illumination, and that the relationship between CFF and log retinal illumination was independent of the relationship beween CFF and the duty cycle of the flicker. Essentially, Ross found that increasing the illumination of a flickering test patch served to elevate the CFF - duty cycle curve, but the inverse relationship between duty cycle and CFF was maintained for all brightness levels tested.

Further support for the aforementioned relationship between CFF and duty cycle comes from Winchell and Simonson (1951). These authors noted that many of the studies cited above were characterized by data collected from a small number of subjects. Using a larger sample of 23 subjects, however, only served to confirm the general relationship previously established by the earlier researchers.

While studies using a constant time-average luminance for flicker comprised of different duty cycles indicate that as duty cycle decreases CFF increases, investigations using a constant pulse luminance have been somewhat less consistent in their findings. Ives (1922b) found that CFF increases as duty cycle decreases reaching a maximum at 50% duty cycle. Unlike time-average luminance curves, however, further decreases in duty cycle below 50% lead to concommittent <u>decreases</u> in CFF. Thus Ives' CFF data can best be described by a roughly symmetrical inverted U with maximum CFF values at a 50% duty cycle, and decreasing values as one moves away from this peak in either direction. This finding replicated an earlier finding of Porter (1902), also showing a maximum fusion frequency at a 50% duty cycle, and curves that are symmetrical about this point.

Ross (1943), however, found results that were inconsistent with those of Ives and Porter. Ross found that the shape of his obtained functions depended on two factors, the luminance of the test flash and the retinal location of the test patch presentation. For foveal presentations at low luminance levels he obtained curves that were basically in accordance with the results obtained by Ives (1922). For these low luminance foveal presentations he found increases in CFF as duty cycle was reduced from 90% to 50% and decreases in CFF between 50% and 10% duty cycles. For higher illuminance presentations, however, the maximum fusion frequency was a function of the flash brightness. As the flash brightness increased peak CFF moved away from 50% towards the lower duty cycles. When flash presentations were made to parafoveal areas, however, Ross found that increases in flash intensity caused the peak CFF to shift from lower duty cycles towards a 50% duty cycle. Thus in general, over a wide range of luminances, Ross found curves that differed from the monotonically increasing time-average luminance curves, but unlike the findings of Ives, found these curves to be assymetrical about 50% with higher duty cycles always affording lower CFF values, and peak CFF values dependent on pulse intensity and the location of the presentation.

The effect of constant pulse luminance presentations on temporal resolution to flicker using various duty cycles is further complicated by factors such as the area of the flickering test patch. Landis (1954) found that using a 10.4 deg test patch elicited maximum fusion frequencies at duty cycles between 40% and 50% duty cycles, while a smaller 1.6 deg field evoked maximum CFF values at a 25% duty cycle. As noted by Ross (1943), however, it is difficult to differentiate between the effects of stimulus area per se and retinal location.

Summarizing the critical fusion frequency literature it seems that maintaining a constant time-average luminance elicits a consistent monotonic increase in CFF as the duty cycle of the presented stimulus is decreased. The findings from critical fusion frequency investigations concerning the effect of maintaining a constant pulse luminance are not as consistent, for they depend on characteristics such as the area of the flickering test patch, the retinal location of its presentation, and especially the luminance of the pulses used. Based on studies that utilize luminance levels similar to those used in multi-flash however, certain general characteristics concerning CFF and constant pulse luminance displays can be stated. Relevant findings within this luminance range suggest that CFF curves for this type of luminance increase from 100% up to a peak frequency between 50% and 30% duty cycle. Further decreases in duty cycle below this peak invoke reductions in the critical fusion frequency.

Initially, it may seem somewhat surprising to find that temporal resolution is better for a 50% duty cycle pulse train than for a 20% duty cycle pulse train, for the latter display contains longer intervals between successive pulses. Such a finding is however, consistent with the results obtained in two-flash experiments in which pulse duration was manipulated. Previously mentioned studies such as those by Manheke (1957), and Lewis (1967), indicated that as the energy of the pulse was elevated by increasing the pulse duration, temporal resolution also increased. Conversely, if the energy of the pulse was decreased by reducing the pulse duration, temporal resolution decreased. Lowering the duty cycle of constant pulse luminance flicker, should theoretically have an effect analagous to decreasing the pulse duration in a two-flash experiment, thereby eliciting reduced temporal resolving power for low duty cycle flicker. At higher duty cycles, the effect of increasing the total energy of the pulse on temporal resolution is overshadowed by the small dark interval duration separating successive pulses.

In addition to adequately describing the temporal resolution of constant pulse luminance flicker, this "energy hypothesis" is also in accordance with the CFF experiments that maintained a constant time-average luminance across duty cycle. By maintaing a constant amount of energy for all duty cycles, temporal resolution would be dependent solely on the duration of the off-period or the dark interval. Thus as duty cycle is reduced, this dark interval becomes greater, resulting in a higher probability of detecting flicker.

Because the multi-flash technique represents an amalgamation of the CFF paradigm, and the two-flash paradigm, it is both similar and at the same time dissimilar to either technique when considered in isolation. The multi-flash campimetry technique, unlike CFF paradigms, assesses temporal resolution by determining the duty cycle necessary to detect flicker in a point of light flickering at a constant frequency of 5 Hz. CFF paradigms, on the other hand, assess temporal resolution by increasing the frequency of the presented stimuli until flicker can just no longer be detected. While both the two-flash paradigm, and multi-flash campimetry assess temporal resolution by establishing the minimum separation required for all pulses to be seen, the latter technique presents a sequential series of pulses rather than just two. Thus, while the CFF and two-flash literature is informative, because of the inherent differences between multi-flash campimetry and either of these paradigms, it remained to be seen whether one could predict how subjects would perform in a time-average luminance version of multi-flash campimetry, based on the results of CFF and two-flash studies concerning time-average, and constant pulse luminance.

Initially it would seem that the most parsimonious method of determining the effects of a time-average luminance display in multi-flash campimetry would involve comparing the performance of subjects tested using a time-average luminance version of multi-flash campimetry, to their performance on the existing constant pulse luminance version. The problem with such a strategy is that healthy observers usually respond to the detection of flicker at duty cycles between 80% and 70%. Such a situation would preclude the exploration of the entire range of duty cycles, limiting the ability to make generalizations concerning how duty cycle affects temporal resolution. In addition, it is known from the CFF literature that the time-average luminance and constant pulse luminance curves tend to differ only at duty cycles below 50%.

Thus if one could extrapolate CFF findings to multi-flash campimetry, comparing subject's performance on a time-average multi-flash display, to their performance on a constant pulse multi-flash display would be of little value. What is required, therefore, is a methodology which would enable the researcher to make a complete investigation of the effects of time average and constant pulse luminance on temporal resolution across a broad range of duty cycles.

One method of ascertaining whether the visual system is differentially sensitive to constant time-average or constant pulse luminances is to find the minimum depth of modulation required for flicker to be detected for both types of luminance presentations. This procedure entails modulating luminance values above and below a fixed mean luminance value in order to determine the minimum depth of modulation (the ratio of maximum to minimum luminances) required to detect flicker. The smaller the ratio of maximum to minimum luminance, (the smaller the depth of modulation) required to detect flicker, the more sensitive the observer is said to be. Using this method allows comparisons between time-average luminance flicker and constant pulse flicker to be made. Furthermore this method allows flicker to be presented at a fixed frequency, using a variety of different duty cycles.

Because the purpose of this depth of modulation experiment was to see how the implementation of a time-average luminance display would affect the performance of observers in the multi-flash procedure, wherever it was possible attempts were made to equate the two paradigms in terms of both procedure and stimulus attributes. A decision had to be made, therefore, concerning the choice of the mean luminance around which maximum and minimum luminances were to be modulated. Two considerations entered into this decision: the steady state luminance of multi-flash points, and the average luminance of these points when they were flickering. In the multi-flash procedure, each of the displayed points has a steady state luminance of 3 cd/m^2. Thus when these points are flickering, their average luminance value (on-period + off-period/2) is 1.5 cd/m^2. Initially therefore, it seemed that the modulation amplitude should have been assessed using a mean luminance value of 1.5 cd^2 Thus when the modulation amplitude was 100% in the sensitivity experiment, the luminance would have been exactly equal to that used in the multi-flash paradigm. Procedurally however, using 1.5 cd/m^2 as a mean luminance level for the flickering point, would have made the two techniques radically different.

In the multi-flash paradigm 36 points are displayed on the screen at any given time with each of these points having a steady state luminance of 3 cd/m^2. If instead of systematically decreasing the duty cycle of a selected point, the depth of modulation required to detect flicker in this point was assessed using a mean luminance of 1.5 cd/m^2, the luminance of this point at a 0% modulation amplitude would be half that of any of the other points within the display. Such a brightness cue would make the two techniques radically different and most likely affect subjects performance by causing discrepancies between the two paradigms in terms of a brightness artifact. In the multi-flash paradigm the stimulus uncertainty was relatively high, for the subject was required to pick one flickering point out of a 36 point display, while in the sensitivity experiment the subject would soon realize that the one point that was dimmer than all the rest was the point that would begin to flicker.

In order to circumvent this problem, maximum and minimum luminances were modulated around a mean luminance of 3 cd/m^2. Thus at a 0% depth of modulation, the luminance of the point which was to be flickered was equivalent to the steady state luminance of the points in the multi-flash procedure. At 100% modulation, however, the maximum luminance of a constant pulse luminance flickering point in the sensitivity paradigm was 6 cd/m^2, twice the luminance of the on-period of flicker in the multi-flash procedure.

Because of this unavoidable luminance discrepancy between the two techniques, in addition to assessing the sensitivity to constant pulse luminance stimuli and time-average luminance stimuli, sensitivity to a third type of waveform was proposed. Unlike standard rectangular waveforms in which maximum and minimum luminances are modulated around a mean luminance level, this third type of waveform involved maintaining a constant maximum luminance of 3 cd/m^2 and altering only the minimum luminance. Thus for this third type of luminance display, assessing the depth of modulation involved assessing the minimum difference between a fixed maximum luminance and a variable minimum luminance. At 100% modulation this third type of luminance would have the same stimulus attributes as a flickering point in the multi-flash technique. Initially it was hoped that this third type of luminance display would illustrate any differences in subjects performance due to discrepancies in the average luminances between the two different paradigms. In the time-average luminance condition, and in the constant pulse luminance condition the time-average luminance and the mean luminance were 3 cd/m^2 respectively. In the third condition, however, as the depth of modulation was increased, the average luminance would decrease proportionally. It was soon realized however, that this third waveform would, therefore, be subject to the problem of observers basing their responses on the reduction of apparent brightness, rather than on flicker detection per se. This would render data collected from this condition uninterpretable, and, for these reasons, this condition will not be considered in the ensuing sections of this thesis.

Based on the review of relevant CFF and two-flash research, certain predictions could be made concerning the time-average luminance and the constant pulse luminance displays in the sensitivity experiment. If, as the CFF literature suggests, the visual system is differentially sensitive to time-average luminance and constant pulse luminance stimuli, then one would expect similar depth of modulation thresholds for duty cycles above 50% but at duty cycles below 50% one would expect that greater depths of modulation would be required to detect constant pulse luminance flicker, compared to the thresholds required to detect time-average luminance flicker. Thus if sensitivity were plotted over duty cycle, a monotonically decreasing function would be expected for a time-average luminance stimulus, while an inverted U-shaped function would be expected for the constant pulse stimuli.

Method

Stimuli and Apparatus

The stimulus display consisted of six lit points and a fixation cross presented against a dark background. The six points were presented along one of the eight separately presented radii depicted in Figure 5. These radii consisted of the temporal and nasal horizontal radii, the superior and inferior vertical radii and the four diagonal radii falling between these axes. For all radii the points were spaced in octave steps such that the first point was .625 deg of visual angle away from the fixation cross and subsequent points were placed at 1.25, 2.5, 5, 10, and 20 degrees of visual angle away from the fixation cross when viewed from a distance of 57 cm. Each individual point subtended a visual angle of about 6 minutes of arc when viewed from this distance. In order to determine temporal sensitivity to duty cycle, 7 representative duty cycle values were tested. These values were 20, 30, 40, 50, 60, 70 and 80%. In addition, points were flickered using either a mean constant pulse luminance, or alternatively, maintaining a constant time-average luminance.

The entire display was generated on a 19 in diagonal cathode

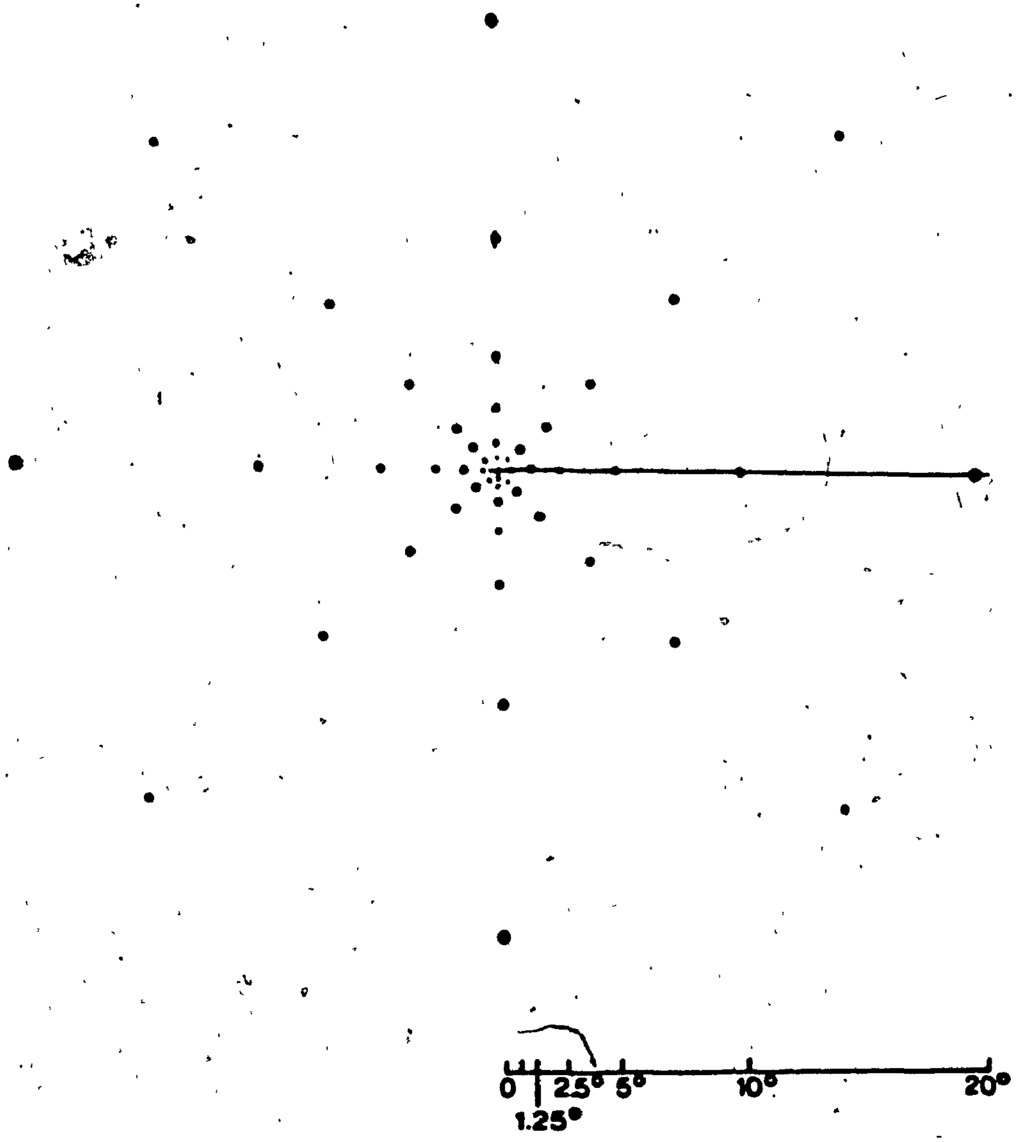

Figure 5. Stimulus display used in depth of modulation study. Six points are presented along one of eight meridians. Individual points subtend six min of arc.

ray tube (model 1310a, Hewlett Packard Company, Palo Alto, California) by a PDP 11/10 computer (Digital Equipment Corporation, Marlboro, Masssachusetts). The CRT was interfaced with the computer via digital to analog (D/A) converters. These D/A converters controlled the location of points within the stimulus display by specifying the X-Y coordinates on the CRT, and values input to the Z D/A specified the luminance of the points displayed on the monitor. All luminance measurements were made with a Spectra Spot Meter (Photo research Division, Kollmorgen Corporation, Burbank, Calif.)

Subjects

Eleven male subjects and 21 female subjects participated in the experiment. The ages of these subjects ranged from 20 to 35 years of age with a mean age of 24 years. Subjects' far point acuities were assessed using the Keystone Visual Skills Test. Based on this evaluation the eye with the best acuity was used throughout the experimental procedures, and the other eye was occluded by an eye patch. If the subject's acuities were equal, the eye that was tested was chosen so that equal numbers of left and right eyes were associated with each radius group. Corrected acuities for the unoccluded eyes ranged from Snellen equivalents of 20/15 to 20/25.

Calibration Procedures

The calibration procedures used in this present research were based in part on the procedures used in multi-flash campimetry. The spot photometer, such as the one used for both multi-flash campimetry and the sensitivity technique, bases its measurements on the amount of luminous energy incident upon a circular area which is 3 mm in diameter. This spot is analogous to a visual spatial summating area, and as such will allow the luminance of individual points to be specified, providing that these luminances are estimated using a calibration display that is larger than this spatial summating area, and presented at the same refresh rate as the display in question. In fullfilment of the latter of these requirements, the multi-flash campimetry technique uses a 9 pixel by 5 pixel rectangle to cover the spatial summating area used by the photometer. This rectangle is displayed on a the CRT and the luminous intensity of this rectangle is measured photometrically. By adjusting the intensity dial on the CRT, the luminance of the rectangle can be set at the same mesopic level each day, ensuring that each subject will be tested under the same luminance conditions.

In order to ensure that the present study was comparable to the multi-flash procedure in terms of luminance attributes, the multi-flash display was calibrated according to the procedure described above, and the sensitivity display was psychophysically brightness matched with the multi-flash display. This psychophysical matching was informally carried out by asking three observers to equate any single point in the sensitivity experiment with any single point in the multi-flash display. After the three observers reached a general consensus concerning the luminance level which best equated the points in each paradigm, a new calibration rectangle was displayed on the screen at this agreed upon intensity, and this rectangle was photometrically measured.

This new calibration rectangle differed from the rectangle used for calibration in the multi-flash technique in that it used the exact refresh rate determined by the computer program that produced the sensitivity display. Thus the photometric reading of 3 cd/m^2 obtained from the sensitivity calibration rectangle equals the steady state luminance of each point in the sensitivity display. Because the brightness of this display was based on a psychophysical brightness match between the sensitivity experiment points and multi-flash campimetry points, 3 cd/m^2 also approximates the luminance value of any single point in the multi-flash display.

Luminance presentations

Determining the maximum and minimum luminance values for time-average luminance (TAL) and mean constant pulse luminances (MCPL) in the present research involved the use of the Michelson contrast ratio to estimate what these maximum and minimum luminances would be for any given depth of modulation. The mathematical formulations involved in estimating these luminance values are presented in Appendix A.

In the time-average luminance condition, the time-average luminance was always equal to 3 cd/m^2, regardless of the depth of modulation, while in the MCPL condition the time-average luminance varied according to the duty cycle, but the average luminance (unweighted by time) was always equal to 3 cd/m^2 regardless of the depth of modulation.

Procedure

Temporal resolving power to small 6 min points was assessed for 32 healthy observers. These points were flickered along one of the eight radii depicted in Figure 2. Also depicted in Figure 5 are the six retinal eccentricities at which flicker could be presented. Temporal resolution was also assessed for the seven previously mentioned duty cycles. In addition, flicker could be presented maintaining either a constant time-average luminance across duty cycle (the TAL condition), or, alternatively, maintaining a mean constant pulse luminance, for all duty cycles (the MCPL) condition.

A split-plot factorial design was employed in this sensitivity study with radius being the between subjects factor and duty cycle, light type, and eccentricity the within subject factors. Since there were eight radii to be tested, subjects were pseudo-randomly assigned into eight groups such that two right eye subjects and two left eye subjects were in each group.

Because it was not possible to test all the possible combinations of the within subjects factors (light type, eccentricity, and duty cycle) in a single testing session, only one type of luminance presentation was displayed on a given day.

For a single test session the minimum depth of modulation threshold was assessed for each different within subject treatment combinations (6 eccentricities, and 7 duty cycles) using 42 separate staircases (Cornsweet, 1962). The staircase procedure entailed presenting the flickering stimulus at a given depth of modulation and recording whether or not flicker was detected. The subject's task was to push a "flicker" paddle if flicker was detected, and a "no flicker" paddle if no flicker was percieved. An example of one such staircase is depicted in Figure 6. In this staircase the subject having failed to see flicker at 6, 7, 8, 9, 10 and 11%, finally detects flicker at 12% causing the staircase to reverse direction and the next presentation of flicker to be presented at an 11% depth of modulation. Because the subject was again able to detect flicker at a 11% depth of modulation, this depth of modulation was decreased to a value of 10%. A no flicker response at a 10% depth of modulation represents the second reversal, causing the depth of modulation to increase to 11%. The staircase procedure continued in this fashion until the staircase reversed direction four times, yielding four estimates of the threshold depth of modulation required to detect flicker for this stimulus combination. As can be seen in Figure 6. the 3rd and 4th reversals are recorded at 12 and 11% respectively. As was previously mentioned a complete testing session involved collecting data from 42 such staircases, one for each of seven different duty cycles, presented at six different retinal eccentricities.

Prior to the actual testing session, the subject was administered a practice session. The purpose of these practice sessions was to: a) familiarize the subject with the procedure, b) adapt the subject to the mesopic luminance level used in the actual test session, and c) to reduce the duration of the test administration by estimating the threshold depths of modulation for

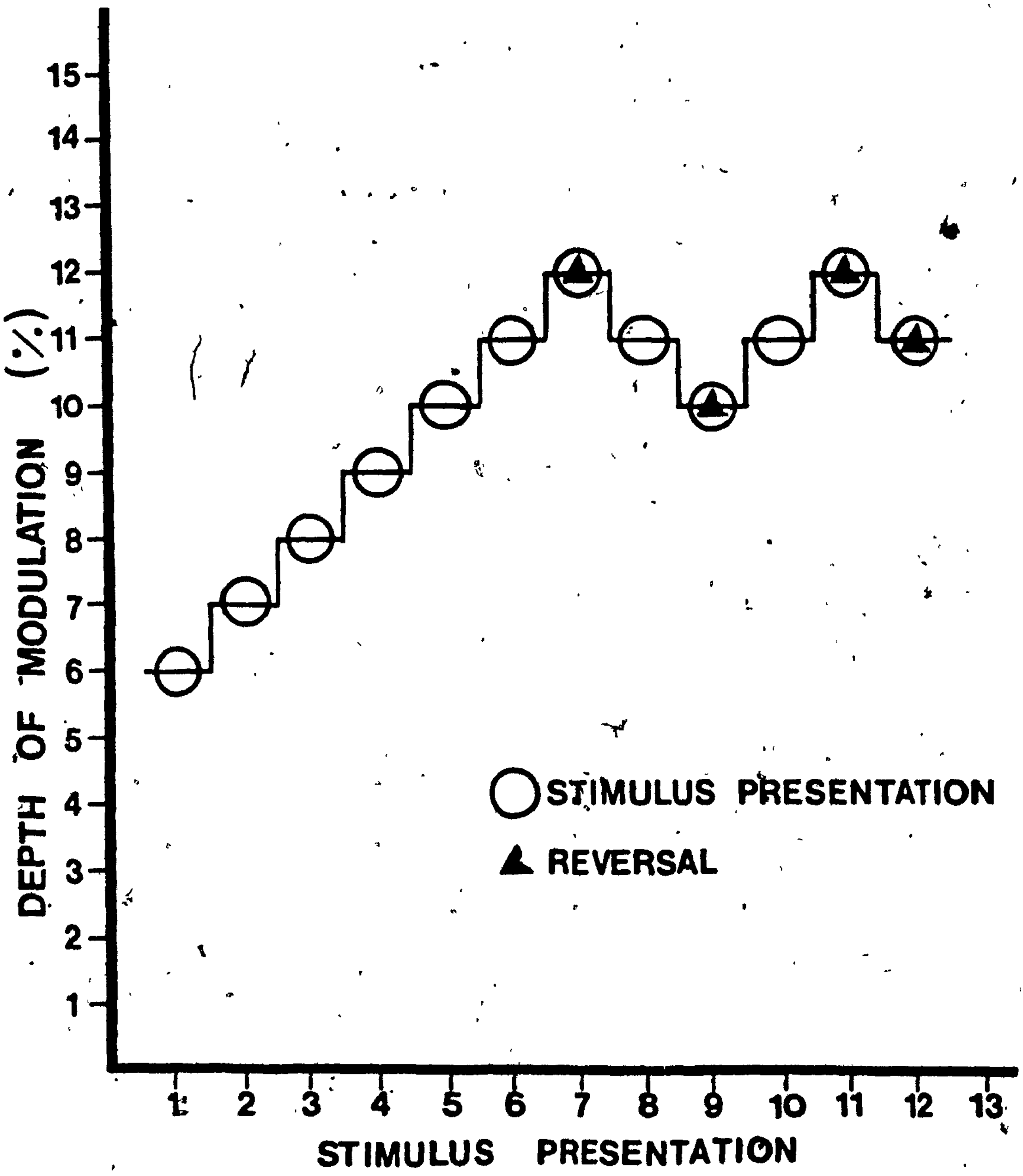

Figure 6. A single example of the four reversal staircase procedure used in the depth of modulation study.

each point. If the staircases were initiated at depths of modulations near the threshold value testing time would be markedly reduced, compared to a situation which requires the subject to make 30 no flicker responses before achieving the first reversal. In order to estimate the threshold values for each of the 42 stimulus combinations, a limited subset of these combinations were presented in the practice session. Nine stimulus combinations were presented to the subject (eccentricities .625, 2.5, 20 deg, and duty cycles of 20, 40 and 50%) and a stopping criterion of 2 reversals was employed for each of the nine practice staircases.

At the beginning of the practice session, the subject would enter the testing room, put an eye patch over their best eye and place their chin in a chin rest. The testing room, in which all experimentation took place was completely dark, except for the light emitting from the display on the CRT. A paddle press would prompt a display consisting of 6 test points oriented along the radius for which that particular subject had been previously assigned. The subject was instructed to focus on the central fixation cross during each individual trial. The intitiation of each trial was cued by a mid-frequency tone of short duration. Following the presentation of the tone, flicker was presented using one of the 9 stimulus combinations. In order to make the task relatively easy to understand, subjects were initially presented with pulse trains flickered using relatively high depths of modulation. Presenting the stimulus at initial depth of modulation values that were well above the flicker threshold, and systematically decreasing these depths of modulation using the previously described staircase procedure, enabled subjects to become familiar with the appearance of various degrees of flicker in this display. Subjects were asked to indicate whether or not they saw flicker by pressing either a "flicker" or "no flicker" paddle. Pressing either paddle would cause another stimulus combination to be presented and the above procedure to be repeated. If a subject failed to respond after 5 seconds, a long tone would sound, flicker would cease, and the computer would wait indefinitely for a response to be made. Thus subjects were able to take breaks at any time merely by remembering, but not making a response until they felt ready to continue the task. In the practice session the depth of modulation staircases were incremented or decremented in steps of 2% in order to obtain initial reversals more quickly. Upon obtaining two reversals for each of the nine staircases the subject was required to repeat the practice session a second time in order to both ensure that the subject was familiar with the task, and to re-estimate threshold values in the subject's increasingly dark adapted eye.

After completing this second practice session, the computer used the estimated depth of modulation thresholds to calculate the starting staircase values for the actual experiment. Two percent was subtracted from each of the estimated depth of modulation values in order to ensure that subjects started each staircase below threshold. These new values served as starting staircase values for all stimulus combinations regardless of whether they were tested in the practice procedure or not. For the unpracticed duty cycles, 30%, 70%, and 80% took on the same starting value as the practice tested 20% duty cycle, and the untested 60% duty cycle had the same starting value as the practice tested 40% duty cycle. In terms of retinal eccentricities, the untested 1.25 deg starting value was equal to that determined for the practice tested .625 deg value, the tested 2.5 deg value served for both the 5.0 and 10.0 deg value. Unlike the practice session, the actual testing session employed a stopping criterion of 4 reversals rather than two, and incremented or decremented the staircases by values of only 1% in order to obtain a more accurate measure of threshold.

Normally, staircase procedures such as the one outlined above would have half the staircases began at high depths of modulation and the other half at subthreshold depths of modulation. This procedure was deviated from for two reasons. Firstly, it can be postulated that the visual system may adapt to flicker in much the same way as it does to other stimulus configurations such as gratings. Secondly, by starting all the staircases at minimum contrast levels, the subject is afforded the opportunity to adapt to the luminance level of a perceptually uniform display. For such reasons it was decided to initiate all staircases at least 2% below their estimated thresholds.

After completing the first test session, subjects were asked to return on subsequent days to complete each of the two remaining test sessions. After the completion of all three test sessions subjects were debriefed as to the purposes of the experiment, and paid for their participation.

Results

Data Analysis Procedures

In the experiment described above the primary question of empirical interest concerned subjects' sensitivity to stimuli comprised of various combinations of duty cycle, retinal eccentricity, light type and radius. Sensitivity values are equivalent to the reciprocal of the obtained Michelson Contrast ratios required to detect flicker at each reversal. When using sensitivity data, the conventional manner in which threshold sensitivity is determined is by calculating the geometric mean of the reversal sensitivity values. The reason geometric means rather than arithmetic means were used for this purpose is because conventionally sensitivity values are plotted on a logarithmic scale to ensure reasonably sized axes. In order to ensure that the statistics used were consistent with the type of scale employed, geometric means were adopted as the appropriate measure. For each subject, therefore, 84 threshold sensitivity values were calculated (the geometric mean of 5 replications for 6 eccentricities, 7 duty cycles, and 2 light types). The source table of an analysis of variance using these threshold sensitivity values is presented in Table 1.

Looking at Table 1 it is evident that the radius factor had neither a main effect, nor was involved in any lower order interactions (highest F ratio = $F(42,144) = 1.30$, $p > .05$). This

Table 1

Analysis of Variance for the Sensitivity scores
Split Plot Factorial design SPF 8.267

Source	SS	df	MS	F	Omega^2
1. Between blocks	18.683	31	.603		
2. Radii	3.315	7	.474	.734	
3. Blocks w. radii	15.368	24	.640		
4. Within Blocks	79.125	2656	.029		
5. Light	.043	1	.043	.149	
6. Light x radii	1.647	7	.235	.815	
7. Light x blocks within radii	6.924	24	.289		
8. Eccentricity	25.071	5	5.014	76.320*	.25
9 Radii x Eccen.	2.412	35	.069		
10. Eccen x blocks within radii	7.884	120	.066		
11. Duty	15.048	6	2.508	70.822*	.15
12. Merid x duty	1.115	42	.026	.749	
13. Duty x blocks within radii	5.099	144	.035		
14. Light x eccen.	.057	5	.011	1.013	
15. Merid x light eccen	.408	35	.011	1.042	
16. Light x eccen. x blocks within radii	1.344	120	.011		
17. Light x Duty	.256	6	.042	1.795	
18 Merid x Light x Duty	1.301	42	.031	1.302	
19. Light x duty x blocks w. radii	3.425	144	.024		
20. Eccen. x duty.	.397	30	.013	3.666**	.003
21. Merid x eccen duty	.902	210	.004	1.190	
22. Eccen x duty x blocks w. radii	2.598	720	.003		
23. Light x eccen x duty	.186	30	.006	1.9535**	.0009
24. Merid x light x Eccen x duty	.711	210	.003	1.065	
25. Light x eccen x duty blocks within merid	2.289	720	.003		
26. Total	97.807	2687			

* $p < .05$
** $p < .01$

finding indicates that subject's sensitivities were not influenced by the orientation of the six point presentation. In order to visually display the effects of duty cycle, eccentricity and light type, the data acquired from each of these eight radii was pooled and the resulting values were graphed in Figure 7.

Looking first at the highest order significant interaction, the analysis of variance reveals a significant three way interaction ($F(30,270) = 1.95$, $p < .01$) for the light type, duty cycle and eccentricity variables. Such an interaction indicates that the effect of light type was not uniform for each combination of duty cycle and eccentricity. The meaningfulness of this relationship must be questioned however, given the minute omega squared value of .0009 for this three-way interaction. The omega squared statistic expresses the proportion of the variance of the dependent variable attributable to the effect or interaction reported by the F ratio (Kirk, 1982). This information becomes especially important in evaluating the relevance of significant F statistics in experiments like the present study, for trivial associations between dependent and independent variables may achieve statistical significance when there are many degrees of freedom associated with either of these variables. Thus, the small omega squared value associated with the light type by duty cycle by eccentricity interaction, this interaction cannot be viewed as meaningful.

A similar interpretation must be made for the significant interaction betwwen eccentricity and duty cycle ($F(30,720) = 3.66$, $p<.01$), for the proportion of variance accounted for by this interaction is .003.

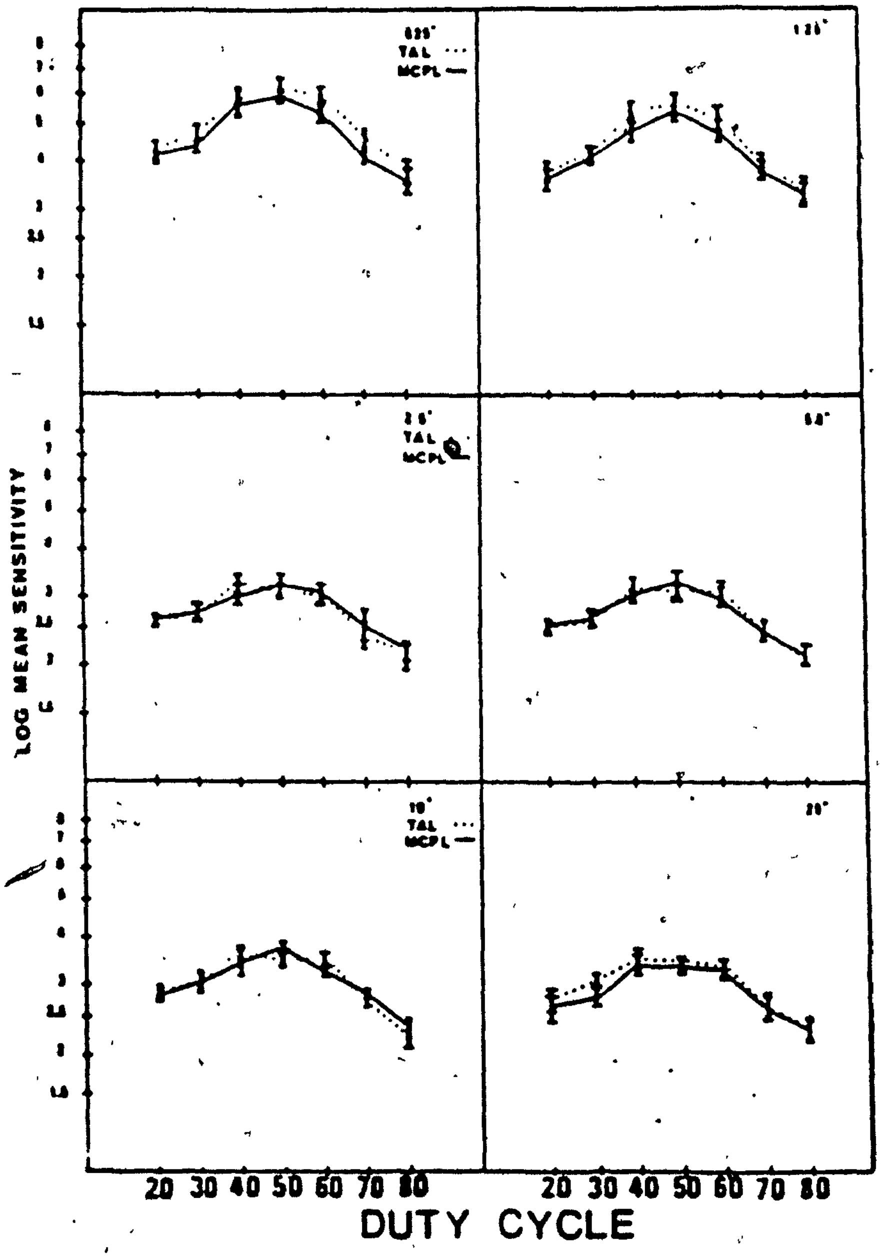

Figure 7. Sensitivity to time-average luminance (TAL) and mean constant pulse luminance (MCPL) for 7 duty cycles presented at 6 retinal eccentricities. Values represent means for 32 subjects.

Unlike either of the significant higher order interactions, the two obtained significant main effects account for a relatively large amount of the variance inherent in the dependent variable. The main effect of eccentricity is significant (F(5,120) = 76.32 p<.01) and accounts for the greatest proportion of dependent variable variance, having an omega squared value of .25. This eccentricity effect is graphically represented by the elevations above the abscissa in each panel of Figure 7. Sensitivity is relatively high for the points closest to the fovea, and tends to decrease with increases in retinal eccentricity.

The duty cycle variable was associated with a significant F ratio (F(6,144) = 70.82, p<.01) and an omega squared value of .1516. Graphically, this main effect of duty cycle, is attributable to the inverted U-shaped functions of both the time-average, and mean constant pulse luminance functions in each of the six panels in Figure 7. The lack of a significant main effect of light type, or any meaningful interactions involving this variable (largest omega squared = .003) indicates that subjects are equally sensitive to both the mean constant pulse luminance stimuli, and the time-average luminance stimuli, for both functions can be adequately described by these inverted U-shaped functions.

In accordance with the data analysis procedures suggested by De Lange (1952), the depth of modulation values obtained in this sensitivity study were analysed in terms of the fundamental Fourier frequency component. Specifically, the amplitude of the fundamental frequency component was calculated for each depth of modulation, or Michelson contrast value, at which a staircase reversal occured.

The means of the four reversal amplitudes were then calculated for every duty cycle, radius, light type and eccentricity combination. The source table of an analysis of variance using these mean amplitudes of the fundamental is presented in Table 2.

An inspection of this table reveals that the radius factor failed to have any systematic relationship with the amplitude of the fundamental. Thus, a pooling procedure similar to that used for the sensitivity data was conducted, where the amplitude data for each of these eight radii was combined to provide data for the graph presented in Figure 8.

The highest order interaction to achieve significance (F(30,720) = 3.66, p<.01) involved the light, eccentricity and duty cycle variables. The omega squared value associated with this interaction was .003, thereby rendering this interaction inconsequential. The same interpretation can be drawn for the other two significant interactions for the eccentricity by duty cycle interaction (F(30,720) = 5.83, p<.01), with an omega squared value of .007, while the omega squared value associated with the significant light by duty cycle interaction (F(6,144) = 9.72 p<.01) was .02.

Of the two significant main effects, only eccentricity can be said to be meaningful. The small omega squared value of .03 associated with the significant main effect of duty cycle (F(6,144) = 12.13, p<.01) indicates that the relationship between duty cycle and the amplitude of the fundamental is trivial. The significant main effect of eccentricity (F(5,120) = 58.075 p<.01, omega squared of .23 however, accounts for 23% of the variance among the

Table 2

Analysis of Variance for the Amplitudes of the Fundamental

Split Plot Factorial design SPF 8.267

Source	SS	df	MS	F	Omega^2
1. Between blocks	9.175	31	.296		
2. Radii	1.689	7	.241	.773	
3. Blocks w. Radii	7.486	24	.312		
4. Within Blocks	35.422	2656	.013		
5. Light	.041	1	.041	.278	
6. Light x radii	.870	7	.124	.844	
7. Light x blocks within radii	3.532	24	.147		
8. Eccentricity	10.226	5	2.045	58.875**	.23
9 Merid. x Eccen.	1.373	35	.039		
10. Eccen x blocks within radii	4.225	120	.035		
11. Duty	1.606	6	.267	12.129*	.03
12. Merid x duty	.934	42	.022	1.008	
13. Duty x blocks within radii	3.178	144	.022		
14. Light x eccen.	.013	5	.003	.406	
15. Merid x light eccen	.272	35	.008	1.191	
16. Light x eccen. x blocks within radii	.782	120	.007		
17. Light x Duty	1.001	6	.167	9.7296*	.02
18 Merid x Light x Duty	.894	42	.021	1.242	
19. Light x duty x blocks w. radii	2.469	144	.017		
20. Eccen. x duty.	.353	30	.012	5.840*	.007
21. Merid x eccen duty	.416	210	.002	.983	
22. Eccen x duty x blocks w. radii	1.453	720	.002		
23. Light x eccen x duty	.1875	30	.006	3.669*	.003
24. Merid x light x Eccen x duty	.3684	210	.002	1.030	
25. Light x eccen x duty blocks within radii	1.227	720	.002		
26. Total	44.597	2687			

* $p < .05$

** $p < .01$

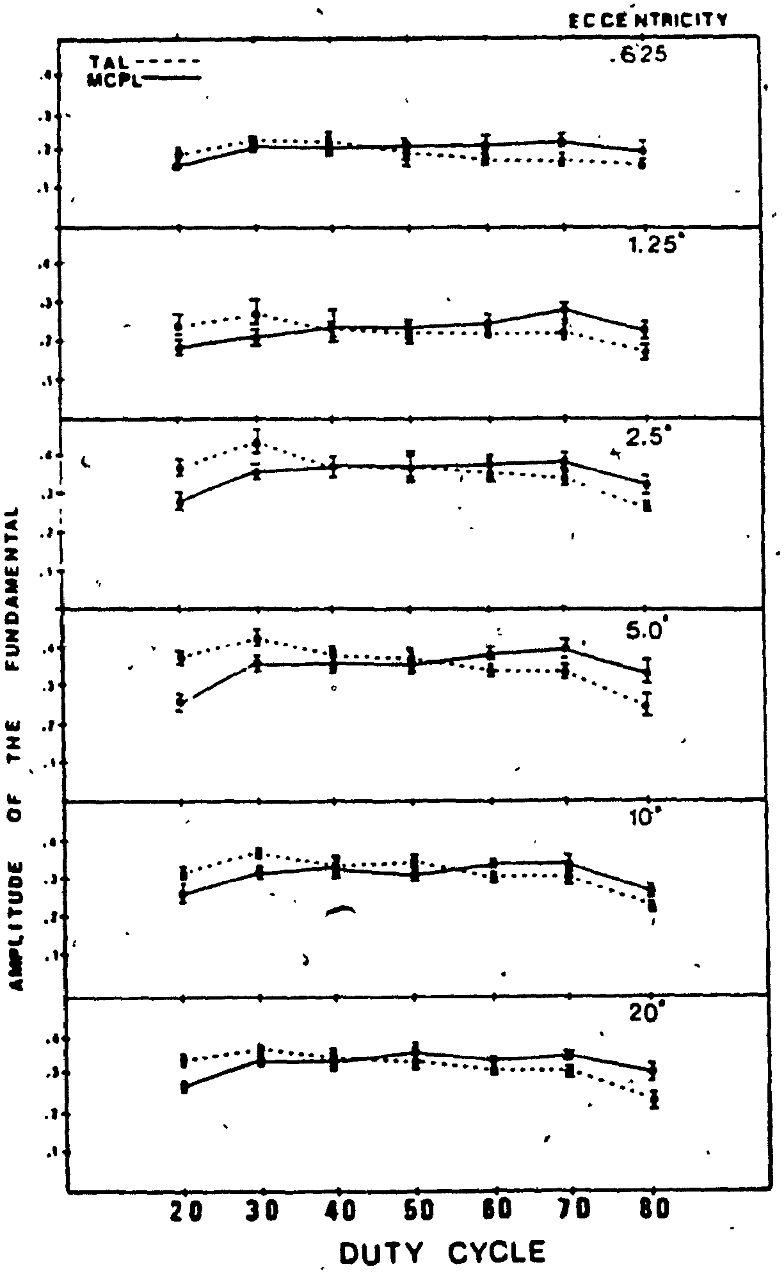

Figure 8. Mean amplitudes of the fundamental required by 32 subjects to detect flicker in time-average luminance (TAL) and mean constant pulse luminance (MCPL) stimuli composed of 7 duty cycles, and presented at 6 eccentricities.

amplitudes of the fundamental. Graphically, this main effect is represented by the differing elevations above the abscissa in each panel of Figure 8. This figure indicates that the two points closest to the fovea (.625, and 1.25 deg.) are associated with lower amplitudes of the fundamental, while the remaining 4 eccentricities show larger amplitudes of the fundamental.

Despite the relative complexity of the four factor split plot factorial design used in this study, the principle findings of this experiment are relatively simple. When the depth of modulation data is analysed in terms of sensitivity values, both duty cycle and eccentricity have significant non-trivial influences on subjects ability to detect flicker. Subjects are most sensitive to flicker in points presented near the fovea, and in terms of duty cycle, subjects show inverted u-shaped sensitivity functions, with peak sensitivity near a 50% duty cycle, and decreases in sensitivity values with either higher or lower duty cycle presentations. When the data is analysed in terms of the amplitudes of the fundamental Fourier frequency component, the results indicate that lower amplitudes are associated with points flickered near the fovea, and higher amplitudes are associated with more peripheral point presentations. These conclusions are based on the combination of significant F ratios, indicating that the obtained effects were probabalistically not merely due to chance, and the omega squared statistic, indicating that these effects were accountable for a reasonably large proportion of the variance within the dependent variable.

Discussion

Most of the critical fusion frequency studies that were reviewed indicated that the way in which temporal resolution varied with duty cycle depended on whether or not the time-average luminance of the stimulus was maintained. Temporal resolution curves for CFF paradigms using constant pulse luminance flicker presented at low luminance levels were characterized by inverted U-shaped functions, with peak temporal resolution around a 50% duty cycle, and poorer temporal resolution for both lower and higher duty cycle values. CFF studies maintaining a constant time-average luminance, however, showed monotonic increases in temporal resolution as the duty cycle of the stimulus was reduced.

Based on these findings certain predictions were made concerning how subjects would perform in a temporal sensitivity task where, instead of quantifying temporal resolution using CFF measurements, temporal sensitivity was assessed by determining the minimum depth of modulation required to detect different types of flicker. Specifically, it was predicted that for constant pulse luminance stimuli, the required depths of modulation would be smallest for duty cycles around 50% with greater modulation depths required to detect flicker presented using either lower or higher duty cycles. In terms of sensitivity values (the reciprocal of these depths of modulation), an inverted U-shaped function was predicted with the highest sensitivity values occuring at a 50% duty cycle. For time-average luminance stimuli, it was predicted that the depth of modulation required to detect flicker would increase as the duty cycle of the flicker increased. In sensitivity terms, it was predicted that sensitivity values would increase monotonically as the duty cycle of the flicker presented was reduced from 80%, with the highest sensitivity values occuring at 20%, the smallest duty cycle tested.

Contrary to these predictions, inverted U-shaped functions were obtained for both constant pulse and time-average luminance flicker. One possible means of reconciling these apparently disparate findings involves the amplitude of the fundamental Fourier frequency component, and how this amplitude varies with duty cycle in both CFF paradigms, and in a sensitivity paradigm such as the one used in the present study.

Consider first, how this amplitude varies with duty cycle in CFF paradigms where the depth of modulation remained invariate at 100%. The lower left panel of Figure 9 presents the calculated values of the amplitudes of the fundamental for 7 different, 100% modulated, time-average luminance stimuli. These values represent stimuli in which the time-average luminance remained constant, while the duty cycle of these stimuli ranged from 20% to 80%. This figure illustrates an inverse relationship between duty cycle and the amplitude of the fundamental; as the duty cycle of the stimuli is decreased, the amplitude of the fundamental frequency for that stimulus increases. The shape of this amplitude of the fundamental curve is markedly similar to the shape of the time-average luminance temporal resolution curves found in a number of previously mentioned studies (Ives, 1922; Cobb, 1934; Bartley 1958). It can be postulated that the similarity between CFF curves and amplitude of

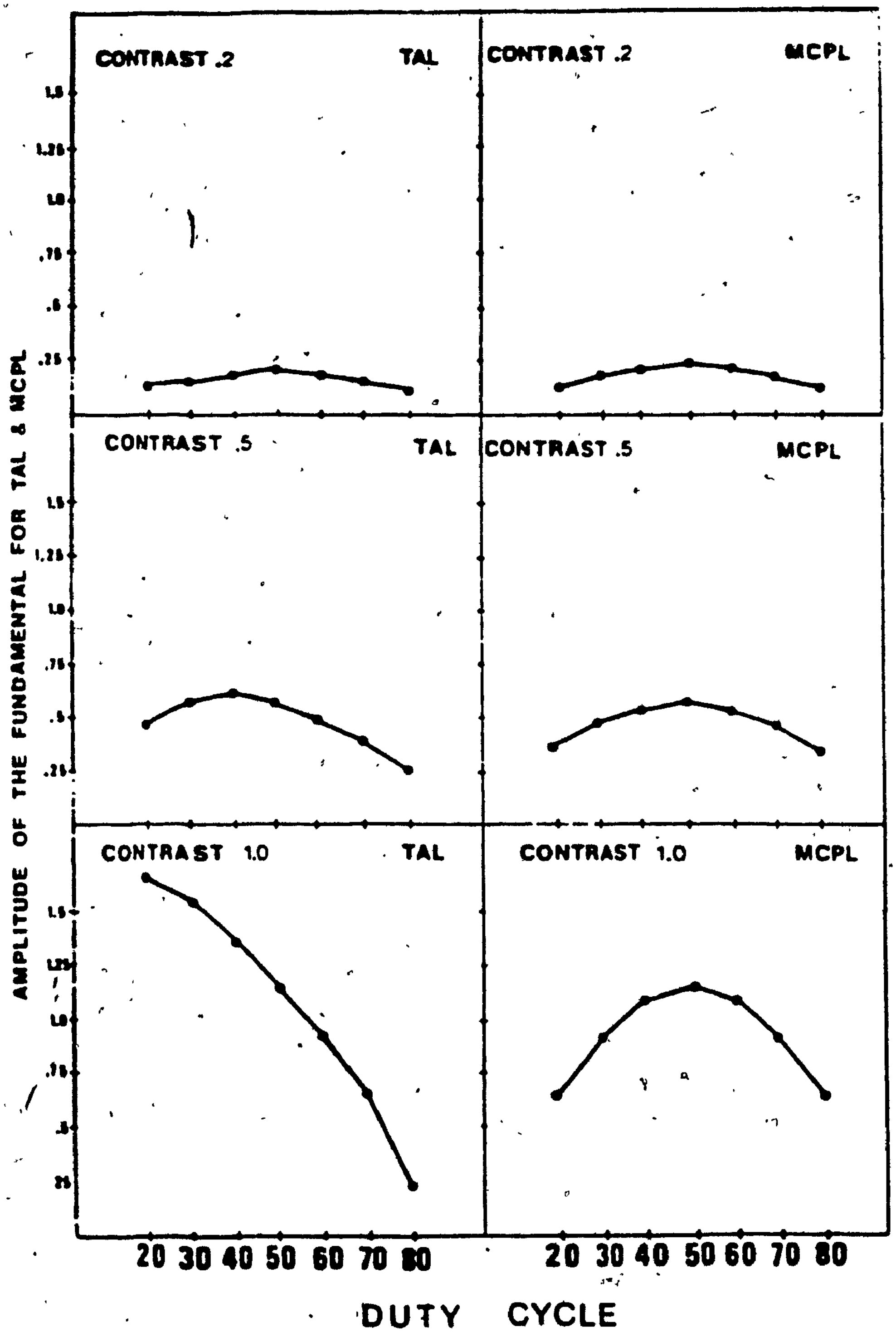

Figure 9. Theoretical amplitudes of the fundamental over duty cycle, for time-average and constant pulse stimuli, plotted for three levels of contrast.

the fundamental curves was more than just coincidental. Ives (1922) in fact, concluded that temporal resolution for many different waveforms (including flicker comprised of various duty cycles) was primarily dependent on this amplitude of the fundamental Fourier frequency component (Ives, 1922). From this postulate, it can be surmised that since the effect of decreasing the duty cycle of a time-average luminance stimulus is to increase the amplitude of the fundamental of that stimulus, this manipulation will serve to elevate temporal resolution as measured by CFF.

Further evidence which serves to illustrate the reliance of temporal resolution on the amplitude of the fundamental can be derived from CFF studies using constant pulse luminance stimuli. The lower right panel of Figure 9 illustrates the calculated amplitudes of the fundamental for seven constant pulse luminance stimuli flickered using different duty cycles. This figure indicates that the amplitude of the fundamental increases as the duty cycle of the flicker is reduced down to a 50% duty cycle, whereupon further reductions in duty cycle cause decreases in the amplitude of the fundamental. Once again the shape of the amplitude of the fundamental curve is similar to the shape of the temporal resolution curves obtained when CFF is used to assess temporal resolving power to stimuli comprised of different duty cycles (Porter, 1902; Ives, 1922b)

The ability of the fundamental amplitude to account for subject's temporal resolving power to both time-average and constant pulse luminance flicker suggests that temporal resolution is not uniquely dependent on stimulus attributes such as peak luminance and duty cycle, but rather on how each of these attributes influences the amplitude of the fundamental of the presented stimulus. Stated as a general postulate, any manipulation which serves to increase the amplitude of the fundamental will increase temporal resolution.

In the CFF studies mentioned thus far, frequency was the dependent variable. In CFF studies concerned with the investigation of duty cycle, test fields were flickered using a variety of different duty cycles, and maintained either a constant pulse luminance or a constant time-average luminance. According to the postulate stated above, manipulating the duty cycle caused alterations in the amplitude of the fundamental of the presented stimulus which in turn were reflected in variations in the critical fusion frequency. In such studies, only the duty cycle variable had a direct influence on the amplitude of the fundamental.

In a sensitivity paradigm such as that used in the present research, rather than maintaining a constant depth of modulation, this depth of modulation is used as the dependent variable, and as such, is free to assume values between 0% and 100%. The depth of modulation of the stimulus has a direct relationship with the amplitude of the fundamental. Increasing the depth of modulation, serves to increase the fundamental amplitude of the presented stimulus, while decreasing the modulation depth decreases this amplitude. Thus, while in the CFF studies only duty cycle influenced the amplitude of the fundamental, in the present sensitivity study both duty cycle, and the depth of modulation influenced the amplitude of the fundamental.

In the sensitivity study, temporal resolving power to time-average and constant pulse stimuli comprised of different duty cycles was measured by using a staircase procedure to assess the smallest depth of modulation required to detect flicker in such stimuli. In looking at the data in terms of the amplitude of the fundamental, each stimulus, regardless of its waveform (i.e. duty cycle, and maximum and minimimum luminances) is broken down into a number of discrete frequency components. According to authors such as Kelly, and De Lange above ripple ratios of 2%, the visual system attenuates all high frequency components and responds only to the fundamental frequency of the stimulus. Given this assumption, it is reasonable to assume that this fundamental frequency must have a certain threshold amplitude above which the visual system will be able to detect flicker, and below which the stimulus will be seen as uniform. Because the depth of modulation is known to be directly related to the amplitude of the fundamental, the staircase data can be viewed as depicting the depth of modulation necessary for a given stimulus to achieve this threshold amplitude. Since stimuli comprised of different duty cycles are known to have different amplitudes of the fundamental (prior to any manipulations in the depth of modulation), it is not suprising that certain stimuli require greater depths of modulation increases in order to push their fundamental amplitudes above this threshold amplitude value. These differences are graphically represented by the different sensitivity values for each duty cycle in Figure 7. The high sensitivity values associated with 50% duty cycle stimuli, indicated that small depths of modulation were necessary to elevate the fundamental amplitudes for such stimuli up to the threshold amplitude of the fundamental required to detect flicker. A 20% duty cycle stimulus, on the other hand, having a much smaller amplitude of the fundamental than a 50% duty cycle stimulus, requires greater increases in the depth of modulation (yielding lower sensitivity values) to push the fundamental amplitude up to this threshold value.

Thus, when the staircase data is plotted in terms of sensitivity, differences between duty cycles can be accounted for by the different increases in the modulation depth necessary to push amplitudes beyond the threshold necessary to detect flicker. When the data is plotted in terms of the actual amplitude of the fundamental associated with each duty cycle after such a manipulation, within any given retinal eccentricity these amplitudes should be similar to one another, reflecting the absolute value of the threshold amplitude of the fundamental required to detect flicker at this eccentricity. Ideally, therefore, if one were to graph the amplitude of the fundamental over duty cycle, the resulting functions within any given eccentricity should have a slope of zero and a Y-intercept equal to this threshold amplitude. Since the only meaningful finding to emerge from an analysis of variance using these fundamental amplitudes was an effect of retinal eccentricity, it can be assumed that the functions in each panel of Figure 8, are indeed flat, and that the Y-intercept values corresponding to each panel represents the threshold amplitude required to detect flicker at this eccentricity.

Having established that flicker detection is dependent on the amplitude of the fundamental for both CFF and sensitivity studies, it can now be shown why the TAL and MCPL functions could both be described by inverted U-shaped functions. The lower panels of Figure 9 illustrates how the amplitude of the fundamental varies with duty cycle when the depth of modulation remains fixed at 100%, as in the CFF studies previously mentioned. The upper four panels depict the relationship between duty cycle and the amplitude of the fundamental at lower contrasts. While the MCPL curve retains its inverted U-shape irrespective of the depth of modulation, the shape of the TAL curve is directly dependent on the depth of modulation. As the depth of modulation decreases, the duty cycle with the highest amplitude shifts from lower to higher duty cycles reaching a 50% contrast by about a 24% depth of modulation. Although different depths of modulation or contrast levels were required for each duty cycle, light type, and eccentricity combination, the entire range of modulation depths required to see flicker in this experiment varied only between 18% and 44%. Within this range the peak modulation amplitudes for the duty cycles tested were always 40% for modulation depths above 24% and 50% for modulation depths below this value. Since the amplitudes corresponding to 40% or 50% duty cycles were invariably higher than those associated with any other duty cycles, these mid-duty cycle stimuli would require the smallest depth of modulation increases in order to surpass the threshold amplitude required to detect flicker. Because only small depths of modulation were required to detect flicker in such stimuli, these duty cycles were always associated with the highest sensitivity values, thereby explaining the unexpected inverted U-shaped sensitivity functions obtained for time-average luminance stimuli.

Experiment 2

By assuming as Ives, Kelly and De Lange did, that the visual system responds preferentially to the amplitude of the fundamental Fourier frequency component of a stimulus presented at threshold, both the obtained sensitivity functions, and the obtained amplitude functions can be accounted for. In addition, the amplitude of the fundamental may provide the conceptual link between the sensitivity experiment and multi-flash campimetry neccessary to provide the empirical justification for implementing a time-average luminance display into this clinical psychophysical technique.

The findings from the sensitivity experiment suggest that at threshold, flicker detection is primarily determined by the amplitude of the fundamental Fourier component of the flickering stimulus. It was determined that for time-average luminance stimuli, at low contrast levels such as those used in the sensitivity experiment, that when the amplitudes of the fundamental are plotted over duty cycle an inverted U-shaped function is obtained. If 100% modulation depths are used to present time-average luminance stimuli, however, the amplitude of the fundamental should increase monotonically with decreases in duty cycle. Since multi-flash campimetry uses a 100% depth of modulation, it is reasonable to assume that if the time average luminance of the multi-flash points was kept constant, as the duty cycle of the flicker is systematically reduced temporal resolution to these points should increase due to the increasing fundamental amplitudes of the presented stimuli. If such is the case, then implementing a time-average luminance display in multi-flash campimetry will circumvent the problem of subject's basing their responses on the reduction of the apparent brightness of one point compared to all the rest, as well as provide an experimental situation in which decreases in duty cycle will be associated with monotonic increases in temporal resolution.

The notion that the amplitude of the fundamental provides the conceptual link between multi-flash campimetry and the sensitivity experiment rests on the assumption that the amplitude of the fundamental is the principle determinant of flicker detection in multi-flash campimetry. If this assumption is valid then it is reasonable to surmise that there is a threshold amplitude of the fundamental above which subjects in the multi-flash paradigm will detect flicker. Because the sensitivity experiment was conducted using identical retinal eccentricities, and approximately the same luminance levels as multi-flash campimetry, it should be possible to predict these threshold multi-flash amplitudes based on the threshold amplitude values obtained in the sensitivity experiment. In order to test this hypothesis a second series of experiments were conducted.

Method

Apparatus

The same PDP 11/10 computer, and Hewlett Packard monitor that were used in the sensitivity experiment, were used for this second experiment.

Subjects

Eight subjects, four males and four females, each of whom had participated in the previous experiment were recalled for further testing. Subjects ranged in age from 22 to 28, with a mean age of 24. All subjects had 20/20 corrected or uncorrected acuity.

Procedure

Upon entering the testing room, subjects were asked to place an eye patch over one of their eyes. The eye that was patched was the eye with the best acuity as determined by the Keystone Visual Skills Test. Subjects were then seated in front of the CRT and informed that they would be administered a test which measures their peripheral vision.

In order to familiarize the subjects with the multi-flash procedure, and ensure that subjects were dark adapted, subjects were administered a practice test version of multi-flash campimetry. In this practice test, 12 six min points were displayed along with a small central fixation cross. These 12 points were arranged to form 2 arcs, each arc being comprised of 6 equally spaced points. These arcs were located 2.5 deg, and 14 deg eccentric to the central fixation cross. The computer would randomly select one of these points and begin to flicker it at five Hz. The duty cycle of this flickering point was systematically reduced from an initial value of 100% in steps of 1.4% every 200 ms. Subjects were instructed to glance around the screen and indicate the detection of flicker by making a manual paddle press response. After becoming familiar with the appearance of the flicker in this informal manner, subjects were then asked to place their chins in a chin rest located 57 cm away from the center of the CRT and fixate their gaze on the small central fixation cross.

In order to ensure that the subject was fixating properly, the locations of the 12 six min points in this practice display were arranged such that one of the points was located in the subject's blind spot. Thus, the subject's ability to fixate properly could be determined by ensuring that flicker in this point remained undetected.

Upon completing the practice procedure, the eye patch was switched over to the other eye, and the administration of a time-average luminance version of the multi-flash campimetry technique was initiated. This procedure began with the appearence of a square stimulus display comprised of six min points arranged so that each retinal location which was to be stimulated by the upcoming multi-flash presentation, was presented in this adaptation square. The purpose of this presentation was to light adapt the eye which was to be tested to the mesopic luminance level used throughout this procedure.

Following the presentation of this adaptation display, the computer would randomly select one of the four quadrants in Figure 2, present the fixation cross associated with this quadrant for 5 seconds, and then display the selected quadrant. The computer then randomly selected one of the points within this quadrant and flickered it at 5 Hz. The duty cycle in this point would be systematically decreased until the subject depressed the paddle indicating that flicker had been detected, or, until the duty cycle reached a value of 0%. In either case a new point was selected and the procedure was repeated until all 30 points had been tested. When all of the points within a given quadrant had been sampled the stimulus display disappeared, and the subject was allowed to take a short rest. By pressing the paddle, the subject initiated the appearence of the square adaptation display, followed by the presentation of the next quadrant. This procedure was repeated until all four quadrants of each eye had been tested.

After 120 points in each eye had been tested, the computer printed out the dark interval durations associated with each of the tested points. For each point the computer noted whether the off-period was statistically deviant from either the mean of points flickered at the same retinal eccentricity as the point in question, or the mean of all the points within that eye. The criterion for deviance was set at 7 standard errors above the eccentricity mean, and 21 standard errors above the single eye mean. All such abberant points were replicated to ensure that differences in obtained critical off-periods were due to actual discrepancies in temporal resolving power, rather than artifacts such as fatigue or momentary lapses in attention.

Results and Discussion

Although data was collected for each of the subject's eyes, only the multi-flash data from the eye that was used in the sensitivity paradigm was retained for analysis. The first stage of this analysis involved using the obtained critical off-periods for each of the 120 tested points to calculate 120 amplitudes of the fundamental associated with the detection of flicker in each of these points. For the purposes of this study, rather than considering each of these 120 amplitudes individually, the amplitude of the fundamental required to detect flicker at each of the six retinal eccentricities was estimated by taking the average of the 20 amplitudes associated with each 20 point circle in Figure 2. Thus the multi-flash data for each individual subject was reduced to six amplitudes per subject, representing the amplitude of the fundamental neccessary to detect flicker at each of six eccentricities.

The amplitudes of the fundamental required by these same subjects in the sensitivity study were calculated in the following manner. The average of the four amplitudes coinciding with the four staircase reversals was calculated for each subject, yielding a total of (6 eccentricities by 7 duty cycles) 42 mean amplitudes per subject. The threshold amplitude of the fundamental required to detect flicker at any given retinal eccentricity was calculated by taking the mean of the seven duty cycle amplitudes associated with that eccentricity. Thus, like the multi-flash data analysis, the data from each of the eight subjects was reduced to six amplitudes reflecting the threshold amplitude of the fundamental required to detect flicker at each of six retinal eccentricities.

In order to see if the amplitudes of the fundamental obtained in the sensitivity study could predict the amplitudes of the fundamental at which flicker would be detected in the multi-flash paradigm, these threshold amplitudes were compared using an analysis of variance. The raw data used in this analysis consisted of the fundamental amplitudes necessary for each of eight subjects to detect flicker at the six eccentricities used in the multi-flash paradigm, and the six fundamental amplitudes necessary to detect flicker at the same eccentricities in the sensitivity paradigm. Figure 10 graphically illustrates the results of this analysis, while the source table for this analysis appears in Table 3.

The main effect of eccentricity ($F(5,35) = 23.451$, $p<.001$), indicates that different amplitudes of the fundamental were required to detect flicker at each eccentricity. An inspection of Figure 10 reveals that for either test, relatively low amplitudes are required to detect flicker at the first two retinal eccentricities, while higher amplitudes of the fundamental are required for flicker detection in peripheral points. The significant main effect of type of test ($F(1,7) = 16.78$, $p<.01$), indicates that the amplitudes of the fundamental required to detect flicker depended on which test was administered. Figure 10 indicates that higher amplitudes of the fundamental were required to detect flicker in the multi-flash procedure for all eccentricities.

The significant differences between the amplitudes of the fundamental required by subjects in the sensitivity study and in the

Table 3

Analysis of Variance for Sensitivity Threshold Amplitudes Compared to Multi-flash Amplitudes.

2 Factor Repeated Measures Design

	Source	SS	df	MS	F	Omega Squared
1.	Subjects	.088	7			
2.	Test	.206	1	.206	16.798**	.19
3.	Error	.086	7	.012		
4.	Eccentricity	.442	5	.084	23.451**	.43
5.	Error	.126	35	.003		
6.	Test x eccentricity	.013	5	.002	1.630	
7.	Error	.055	35	.001		
8.	Total	.999	95			

** $p < .01$

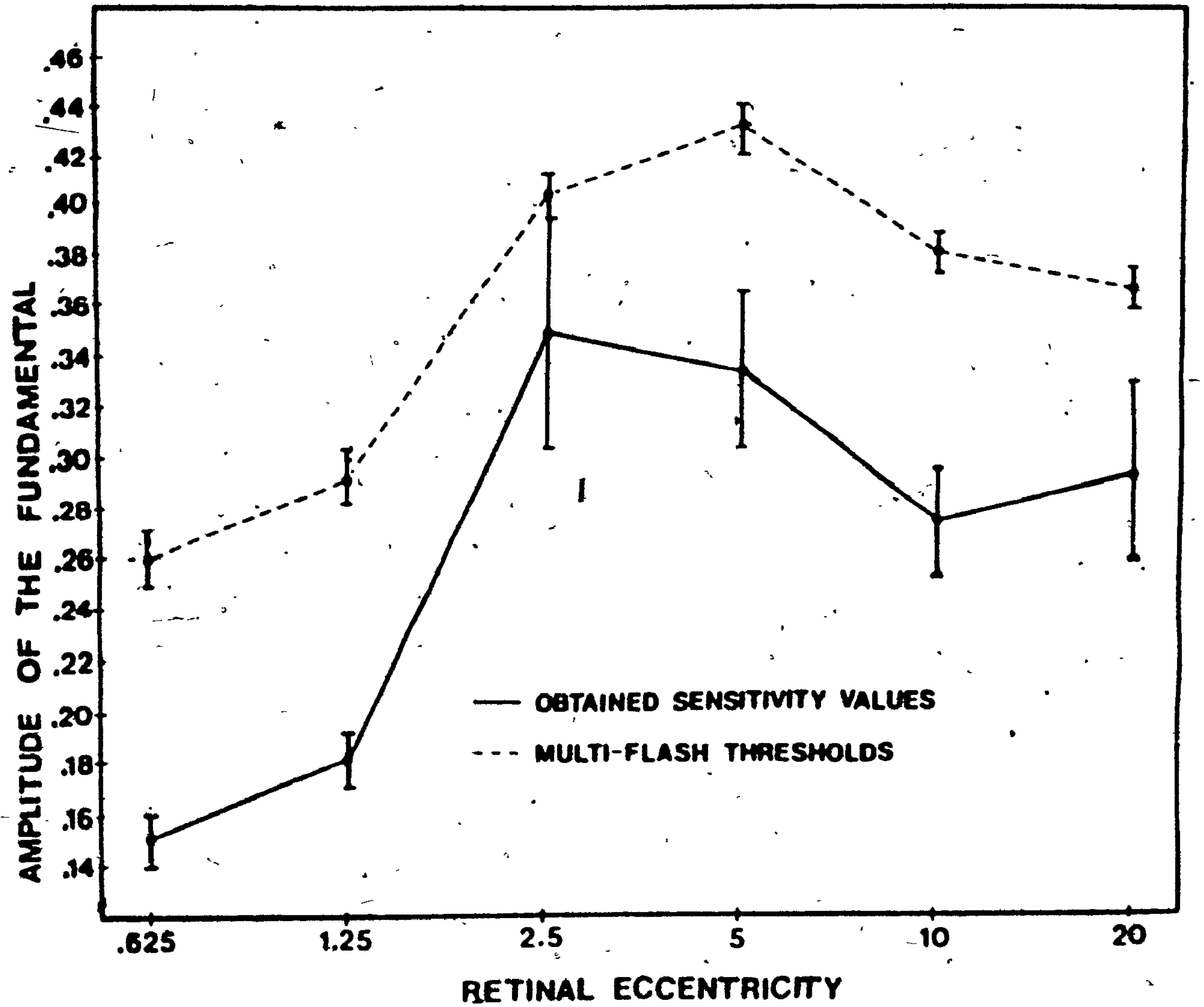

Figure 10. Mean amplitudes of the fundamental required by eight subjects tested using a depth of modulation procedure and multi-flash campimetry.

multi-flash procedure, can be interpreted in a number of different ways. One interpretation is that the amplitude of the fundamental does not underly flicker detection in both paradigms, and that subjects are basing their responses on specific attributes of the stimulus such as duty cycle and maximum luminance values. An alternative, and perhaps more viable interpretation is that flicker detection is determined by the amplitude of the fundamental, and that the discrepancies between the threshold amplitudes in the two paradigms can be explained by an important procedural difference between the two techniques; the reaction time component inherent in the multi-flash procedure.

In the multi-flash procedure, since the duty cycle of the flickering stimulus is decreased every 200 ms, the obtained amplitudes that occured at the time of a manual response were comprised of two components, the amplitude at threshold, and increases in this amplitude due to the reaction time. For example, assume that the duty cycle threshold of a subject was 90%. If the subject has an 800 ms reaction time, the actual recorded duty cycle threshold would be 85% because of the systematic decrease in duty cycle inherent in the multi-flash procedure. Such a small discrepancy in duty cycle can have a substantial effect in terms of the amplitude of the fundamental. In the present example, the amplitude of the fundamental associated with a 90% duty cycle is .54, while the fundamental amplitude corresponding to an 85% duty cycle is .65. Thus because of the systematic reduction in duty cycle every 200 ms, the multi-flash procedure would consistently overestimate the "threshold" amplitudes of the fundamental at which flicker can be detected. Such a bias is not present in the sensitivity experiment, for on any given trial subjects were presented a flickering stimuli made up of unchanging stimulus attributes, and allowed as much time as necessary to decide whether or not flicker was detected. In order to equate the sensitivity and multi-flash procedures therefore, it was necessary to evaluate and subtract out increases in the amplitude of the fundamental due to reaction time. A third experiment was therefore conducted to quantify the magnitude of the reaction times in the multi-flash technique.

Experiment 3

In designing an experiment to assess the reaction time of subjects to flickering points in the multi-flash display, a number of factors were considered. One such factor concerns the direct relationship between reaction time and retinal eccentricity. As points are flickered further out in the periphery, reaction times to these points are known to increase (Poffenberger, 1912). In addition, reaction times are known to increase as the number of non-target stimuli, are presented along with the target (Brussell & Dixon, 1986). Finally, the reaction times for threshold stimuli are longer than for stimuli presented well above threshold (Chocholle, 1945). In order to get valid estimates of reaction time in the multi-flash procedure, subjects were presented with a single quadrant of the multi-flash display, and the reaction times to each point, flickered using a duty cycle value which was just above threshold, were assessed.

Method

Subjects

The four male and four female subjects who participated in the multi-flash campimetry experiment were recalled one week after the completion of the multi-flash test.

Luminance Presentations

While the actual point display in this experiment was identical to a single quadrant in the multi-flash display, the manipulation of duty cycle in this reaction time study differed from duty cycle manipulation in multi-flash campimetry. Rather than systematically decreasing the duty cycle of the presented point until flicker was detected, within a single trial a point was repetitively flickered using a constant duty cycle, and the reaction time to this point was measured by the computer. For all flicker presentations, the time average luminance of the point was maintained at 3 cd/m^2.

Procedure

Subjects were seated in front of the monitor, and instructed to place a patch over one eye. Subjects were then given the same set of instructions that were administered in the multi-flash procedure, namely, to make sure that they were always fixating on the small cross, and to press the paddle in front of them as soon as they detected flicker. After dark adapting for 10 minutes, each of these subjects were then presented with a single quadrant of the multi-flash display. The quadrant which was presented was preselected to include the radius of points that the subject was presented in the sensitivity study.

Within a single quadrant presentation, the computer would randomly select one of 30 points and flicker it at 5 Hz for a total of 3 seconds. The reaction time to this flicker was computed by subtracting the time at which flicker was first initiated, from the time at which a manual response was recorded. Criterion values of valid reaction times were established as being above 150 ms, and below 1500 ms. Once a manual response was made, or alternatively, after the 3 second limit was exceeded, a new point was randomly selected, and the procedure described above was repeated. A single session lasted until all 30 points had been tested, whereupon the display would disappear, and the subject was allowed to rest before the beginning of the next session.

Prior to the actual point display presentation, initial duty cycle values were entered for each point location. These values were purposely chosen so that the points would appear to be steadily on; no flicker was detectable. For any given point, if a valid reaction time was not obtained within that session, in the following session the duty cycle of this point would be decreased by 2.5%. If, however, a valid reaction time was obtained, the same duty cycle would be used to flicker this point in all subsequent sessions. Thus by starting at duty cycles well above the fusion point, adequate mesopic light adaptation was ensured, and by decreasing the duty cycle by small amounts (2.5%) when stimuli were not responded to, reaction times were obtained to stimuli that were only slightly above threshold.

In order to complete the reaction time experiment, a total of 5 reaction times were assessed for each of the 30 points tested. The duration of the entire experiment was approximately 45 minutes.

Results

The results for each of the eight subjects were analysed in the following manner. First, the mean of the 5 reaction times was calculated for each of the 30 tested points. These 30 means were then used to calculate the subject's mean reaction time for each of the 6 retinal eccentricities. These values were calculated by taking the average of the 6 means associated with each eccentricity. Thus the data for each subject consisted of six values representing the mean reaction time for points flickering at each of the six retinal eccentricities tested in this experiment. The averages of these means were then calculated for all six retinal eccentricities, in order to estimate the average reaction time required by these eight subjects at each retinal eccentricity. These values as well as individual subject means are presented in Table 4.

For each subject, the six group mean reaction times for each retinal eccentricity were transformed into off-period values representing the magnitude of the decrease in the off-periods of the multi-flash stimuli, due to these reaction times. For example, since the off-periods of the multi-flash stimuli are reduced by 2.8 ms every cycle, a reaction time of 1000 ms, would account for a 14 ms increase in the off-period of the multi-flash stimulus.

These reaction time off-periods were then subtracted from the critical off-periods obtained for each point in the multi-flash procedure. For example, the mean reaction time of the eight subjects for points located at the first retinal eccentricity was, 1026 ms, which translates to an off-period increase of 14 ms due to

Table 4

Reaction Time Data for Six Retinal Eccentricities

Individual and Group Means

	Eccen 1	Eccen 2	Eccen 3	Eccen 4	Eccen 5	Eccen 6
S1	889.2	905.4	967.0	1062.8	943.2	998.0
S2	903.2	962.4	1072.8	1119.2	1163.6	1123.0
S3	942.1	1013.5	1123.6	1198.8	1118.1	1122.8
S4	967.4	1135.9	1163.6	1239.5	1263.7	1215.1
S5	1081.6	1167.4	1272.7	1243.7	1206.7	1160.6
S6	1074.3	1145.3	1219.8	1216.7	1209.7	1139.9
S7	1218.3	1234.7	1289.7	1236.6	1245.5	1254.4
S8	1134.8	1208.1	1131.3	1197.3	1200.3	1235.3
X	1026.4	1096.9	1155.1	1189.3	1168.9	1156.3

reaction time. For each individual subject, this 14 ms increase in off-period was subtracted from each of that particular subject's multi-flash critical off-periods associated with this first eccentricity. The mean increase in the off-period due to reaction time for points located at the second retinal eccentricity for these eight subjects was 15 ms. Thus 15 ms was subtracted from that subjects critical off-periods associated with each point located at this second retinal eccentricity.

After subtracting reaction time increases in the off-periods for all six eccentricities, the resulting reaction time corrected, critical off-periods were then converted to amplitudes of the fundamental for comparison with the fundamental amplitudes obtained in the sensitivity experiment. As in the previous analysis comparing the uncorrected multi-flash amplitudes, rather than considering each of the 120 amplitudes individually, the amplitude of the fundamental required to detect flicker at each retinal eccentricity was calculated by taking the average of the 20 amplitudes associated with each of eccentricity (the mean of points comprising the circles in Figure 2). Thus the corrected multi-flash data for each subject consisted of the six amplitudes of the fundamental necessary to detect flicker at each eccentricity.

These reaction time corrected amplitudes of the fundamental were compared to the threshold sensitivity amplitudes of the fundamental using an analysis of variance. The source table for this analysis appears in Table 5. Unlike the similar analysis conducted on the uncorrected amplitudes of the fundamental, the corrected amplitudes of the fundamental are not significantly different from

Table 5

Analysis of Variance for Sensitivity Threshold Amplitudes Compared to Corrected Multi-flash Amplitudes

2 Factor Repeated Measures Design

Source	SS	df	MS	F	Omega Squared
1. Subjects	093	7			
2. Test	.021	1	021	1.717	
3. Error	.089	7	.012		
4. Eccentricity	.443	5	.088	21.099**	.497
5. Error	.147	35	.004		
6. Test x eccentricity	.012	5	.002	2.173	
7. Error	.039	35	.001		
8. Total	.847	95			

** p <.01

the amplitudes obtained in the sensitivity study (F(1,7)=1.717, p>.05). The latter analysis revealed only a significant main effect of eccentricity (F(5,35)=21.09, p<.001). This main effect indicated that different amplitudes of the fundamental were required to detect flicker at each of the six different retinal eccentricities. An inspection of Figure 11 indicates that for both techniques, lower amplitudes were required to detect flicker in points near the fovea, while relatively higher amplitudes of the fundamental were required to detect flicker in peripheral points.

Discussion

As was previously stated, the amplitudes of the fundamental that were obtained in the multi-flash procedure were comprised of two components. One component consisted of the actual amplitude of the fundamental required by the subject to detect flicker, while the second component consisted of increases in this amplitude due to reaction time. Thus, it was assumed that if the magnitude of the reaction time component could be estimated and subtracted from the obtained multi-flash amplitudes, then the resulting amplitudes should represent the actual threshold amplitudes of the fundamental required to detect flicker in the multi-flash procedure. In order to estimate the influence of reaction time on the obtained amplitudes of the fundamental in the multi-flash procedure, assessments of the reaction time to multi-flash stimuli were required. In making such reaction time assessments as accurate as

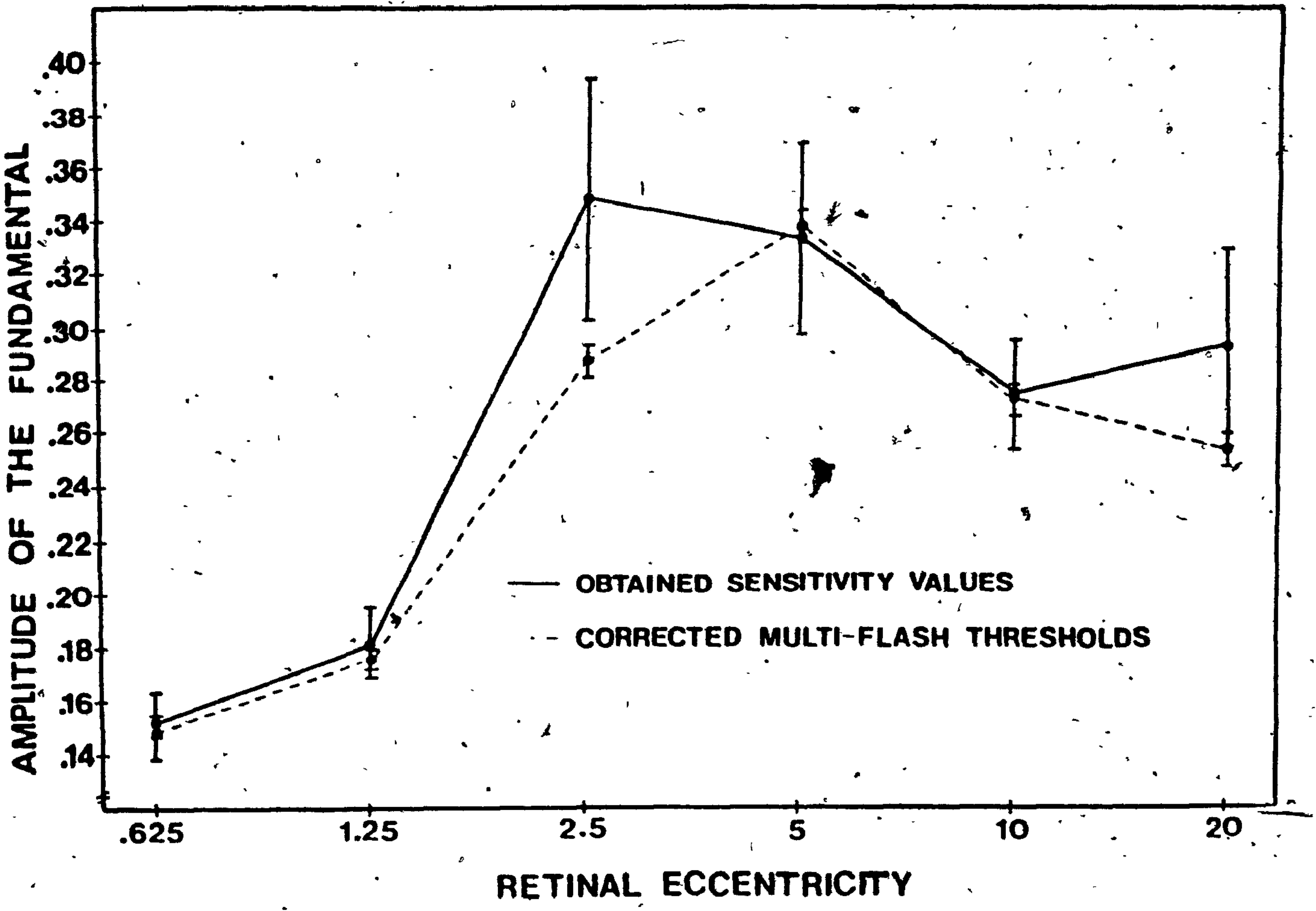

Figure 11. Mean amplitudes of the fundamental corrected for the influence of reaction time compared to amplitudes of the fundamental required to detect flicker in a depth of modulation technique.

possible a number of factors which were known to influence reaction time had to considered. These factors include, the low luminance level of the multi-flash stimuli, the number of such stimuli, the eccentricities at which these stimuli were presented, and finally, the fact that subjects were required to respond to stimuli that were flickering only slightly above threshold.

It has often been observed that reaction time varies inversely with the strength of the presented stimulus (Woodworth and Schlosberg, 1938, p. 19). As the physical intensity of the stimulus presented increases, the reaction times to such stimuli decrease. In addition to the low luminance of the points presented in the multi-flash display (3 cd/m^2), the presented points were also quite small, subtending only 6 min. of visual angle. Furthermore all of these points were presented eccentric to the fovea, a situation which is also known to increase reaction time (Poffenberger, 1912). Thus by using a single multi-flash quadrant as the stimulus display for the reaction time study, the combined influence of factors such as stimulus size, intensity and retinal location, would be reflected in the reaction times acquired for such points in the reaction time display.

An additional reason for using a single multi-flash quadrant as the display for the reaction time study concerned the influence of the the number of stimuli, on reaction time. Eriksen and Hoffman (1972), for example, have found that reaction time varied directly with the number of competing stimuli displayed along with the target stimuli. Another study illustrating the influence of the number of displayed stimuli and reaction time was conducted by Brussell and

Dixon (1986). In this study the multi-flash thresholds (the duration of the off-periods required to detect flicker) were assessed for displays containing different numbers of stimuli. These multi-flash thresholds were found to increase from an average of 71 ms when 6 points were tested, to a maximum off-period duration of 82 ms when 30 points were tested. An 11 ms increase in multi-flash threshold, translates to a diffence of over 500 ms in terms of the average reaction time associated with the points in each of the respective displays. Thus by using a single multi-flash quadrant as the reaction time display, the influence of the 35 competing stimuli on reaction time in multi-flash campimetry, was reflected in the reaction times obtained for each of the points in the reaction time study.

Another factor which is known to influence reaction time, involves the proximity of stimuli to their detection threshold. Previous research in the auditory domain, reveals that reaction times to threshold stimuli are almost three times as large as those obtained for sounds of greater intensity (Chocholle, 1945). Although these results were based on auditory stimuli similar findings would be expected in the visual modality. Thus, because the comparison between multi-flash campimetry and the sensitivity procedure involved comparing the threshold amplitudes of the fundamental obtained in each procedure, in the reaction time study, an attempt was made to measure the reaction times to stimuli that were as close to the multi-flash thresholds as possible.

While it was extremely important to consider how such stimulus attributes may have contributed to the reaction times in the multi-flash experiment, reaction time also is known to depend on the preparatory set of the observer (Woodworth and Schlosberg, 1965, p. 27). The preparatory set is in part controlled by the experimenters instructions, but also by the way in which the experimental situation is interpreted by the subjects. In a typical reaction time study, subjects are told that the purpose of the study is specifically to measure reaction time. In the multi-flash paradigm subjects are informed that the test they are about to be administered will assess the functional capabilities of their peripheral vision. Thus while subjects are asked to make a paddle press as soon as flicker is detected, the reaction time component of the experiment may be interpreted by the subject as being of secondary importance. Such differences in the preparatory set of the subjects in the multi-flash procedure may serve to increase reaction times above those noted in formal reaction time studies. Thus in the reaction time study, care was taken to ensure that subjects received the same instruction set for both the multi-flash campimetry procedure, and for the reaction time study.

In summary, using a single multi-flash quadrant as the stimulus display in the reaction time study, ensured that accurate estimates of reaction time in the multi-flash procedure would be obtained. That is, factors such as point size, intensity, number, and location which would serve to influence the reaction times in multi-flash campimetry, would also influence the data obtained in the reaction time study.

The purpose of determining the reaction times in the multi-flash study was to see if such a factor could account for the discrepancy between the amplitudes of the fundamental in the sensitivity study, and the amplitudes of the fundamental required to detect flicker in the multi-flash procedure.

When the increases in the amplitudes of the fundamental due to reaction time are subtracted from the obtained fundamental amplitudes, the remaining values reflect the threshold amplitudes of the fundamental necessary to detect flicker in the multi-flash procedure. Differences between these values and the amplitudes of the fundamental obtained in the sensitivity study were small and can be attributable to chance. Given the fact that the amplitude of the fundamental underlies the detection of flicker in both CFF paradigms and in the sensitivity paradigm, it is not suprising that they also underly flicker detection in the multi-flash paradigm. Furthermore, because the sensitivity and multi-flash paradigms used the same low luminance level, and presented flicker at the same retinal locations, it is not suprising to find that within a given retinal eccentricity, the same amplitudes of the fundamental underly flicker detection in both paradigms.

General Discussion

When the results of the depth of modulation experiment were analysed in terms of the Fourier components of the presented stimuli, flicker detection was found to depend on the amplitude of the fundamental frequency component. Within a given retinal eccentricity, the depth of modulation required by subjects to detect flicker did not depend on the specific stimulus attributes of the stimulus such as duty cycle and maximum and minimum luminance per se, rather, subjects were able to detect flicker when manipulations in these stimulus attributes caused the amplitude of the fundamental Fourier frequency component of the presented stimulus to attain a certain hieght. This finding was maintained for all duty cycles within a given eccentricity, for both time-average luminance and constant pulse luminance stimuli.

The reliance of flicker detection on the amplitude of the fundamental has ramifications for research involving both clinical psychophysical techniques such as multi-flash campimetry, as well as for experimental investigations of how temporal stimuli are processed by the healthy visual system. In terms of multi-flash campimetry, this finding provides the necessary empirical justification for implementing a time-average luminance display into this technique, while from a purely experimental viewpoint, the sensitivity experiment represents the first time the amplitude of the fundamental has been shown to underly flicker detection for various duty cycles using a depth of modulation technique.

If, as the present research suggests, the ability to detect flicker depends on the amplitude of the fundamental Fourier frequency component of the presented stimulus, then manipulations of the stimulus attributes which serve to increase this amplitude will result in consequent increases in flicker detection capability, while manipulations which serve to decrease this amplitude will evoke reductions in the ability to detect flicker. In a 100% modulated time-average luminance stimulus such as those usually employed in critical fusion frequency paradigms, decreases in duty cycle should cause increases in the amplitude of the fundamental, resulting in increases in temporal resolution. In a constant pulse luminance stimulus, however, the amplitude of the fundamental, and consequently temporal resolution, should increase with duty cycle reduction in duty cycle between 100% and 50%, but further reductions in duty cycle below this duty cycle should afford decreases in the amplitude of the fundamental, thereby eliciting reductions in temporal resolving power.

The results of a constant pulse luminance study conducted by Porter (1902), revealed results were consistent with the amplitude of the fundamental hypothesis. In this study five different levels of disc illumination were used, and CFF was measured for a number of different duty cycles. Porter found that while CFF increased with disc illumination (the Ferry-Porter Law), the relationship between CFF and duty cycle remained constant for all luminance levels, yielding a symmetrical inverted U-shaped function where the highest

CFF values were associated with a 50% duty cycle, and reductions in CFF occured as duty cycle was either increased or decreased. Although Porter explained his CFF data in terms of the duration of the on-period inherent in a given stimulus presentation, the shape of the obtained CFF-duty cycle function is consistent with the amplitude of the fundamental hypothesis.

Another study which supports the hypothesis that the amplitude of the fundamental is the principal determinant of CFF, is a time-average luminance study conducted by Winchell and Simonson (1951). Because CFF was found to vary inversely with duty cycle, it can be concluded that CFF also varied directly with the amplitude of the fundamental. Unlike Porter, these authors surmised that CFF was dependent on the duration of the off-period of the presented stimulus. Once again, however, the shape of the obtained CFF-duty cycle function for this time average luminance stimuli, is consistent with the amplitude of the fundamental hypothesis.

A third study which supports the notion that the critical fusion frequency varies directly with the amplitude of the fundamental was conducted by Cobb (1934). In this study CFF was assessed for duty cycles between 6.7% and 98%. The time-average luminance of these stimuli was maintained at a constant level. Although Cobb found that the critical frequency deviated from a linear relation to the logarithm of the fundamental amplitude, in general decreases in the amplitude of the fundamental were associated with decreases in the critical fusion frequency of the presented stimulus.

While the data from the present study, as well as studies by

Porter (1902), Cobb (1934) and Winchell and Simonson (1951), all support the hypothesis that the amplitude of the fundamental is the pricipal determinant of flicker detection, results from a number of studies cannot be accounted for in this fashion.

A series of investigations concerning temporal resolution to duty cycle were conducted by Bartley and Nelson (1961). In these studies constant pulse luminance stimuli were employed. According to the Fourier analysis of such stimuli, the highest amplitude of the fundamental should invariably be associated with stimuli flickered using a 50% duty cycle. Contrary to the hypothesis that there is a direct relationship between temporal resolution and the amplitude of the fundamental, in many of the subjects tested, the highest CFF values were obtained for stimuli flickered using much lower duty cycles. While inverted U-shapes were obtained when low luminance levels were employed, when higher luminance levels were employed, the obtained functions resembled those usually associated with time-average luminance stimuli; that is, CFF was found to increase monotonically with the reduction of duty cycle (Bartley and Nelson, 1961).

A possible explanation for the results of Bartley and Nelson was postulated by Kelly (1961). Kelly noted that these authors failed to employ an artificial pupil in their study. Thus it is possible that the natural pupil compensated for changes in the total energy of the stimulus due to duty cycle manipulation, causing the retinal illuminance to be maintained at a constant level. For example, at very low duty cycles, the pupil would dilate allowing more light to become incident on the retina, while at higher duty cycles the pupil would contract allowing less light to pass through to the retina. Such a situation would effectively hold the retinal illuminance at a constant time-average level. Since variations in pupil size would be expected at high luminance levels, such a situation could explain why at high luminances the data obtained by Bartley and Nelson was similar to functions obtained when CFF is measured for time-average luminance stimuli.

Such a postulate cannot however, account for the constant pulse luminance data of Ross (1942), for in this study subjects viewed the stimuli through a 3 mm artificial pupil. When subjects were presented stimuli in the fovea, inverted U-shaped functions were found for low luminance stimuli, but for high luminance stimuli, CFF increased monotonically with the reduction of duty cycle. For peripherally presented stimuli, the opposite relationship was found. Low luminance stimuli caused CFF to vary inversely with the duty cycle of the stimulus, while higher luminances were associated with inverted U-shaped functions. Such findings are difficult to reconcile with the postulate that CFF varies with the amplitude of the fundamental. It is not clear, however, why these data differ so radically from the constant pulse luminance measurements of Porter (1902) which can be accurately accounted for in terms of the amplitude of the fundamental of the presented stimuli.

With the exception of Cobb's 1934 study in which the effect of duty cycle was investigated with respect to the amplitude of the fundamental, the authors of each of the previously mentioned CFF studies chose to interpret their CFF data in terms of the stimulus attributes rather than in terms of the amplitude of the fundamental

Fourier frequency component. A number of investigators using CFF paradigms, however, have recognized the importance of this fundamental amplitude (Ives, 1922a; De Lange, 1952; Kelly, 1965). Ives, for example indicates that the fusion frequency for a number of different waveforms including stimuli comprised of different duty cycles, was solely dependent on the amplitude of the fundamental. Using low luminance flicker, and neutral density filters to maintain a constant time average luminance, Ives found that CFF varied directly with increases in this fundamental amplitude, due to the decreases in the duty cycle of the presented stimulus. This relationship was maintained for all stimuli tested in this study, with the duty cycles of presented stimuli ranging from 91% down to a 12% duty cycle.

In addition to this time-average luminance study, Ives also conducted an experiment in which constant pulse luminance stimuli were flickered using different duty cycles. Once again Ives found that variations in the amplitude of the fundamental caused variations in CFF. When the amplitudes of the fundamental are calculated for various duty cycles flickered using a 100% modulated, constant pulse luminance stimuli, the highest amplitude of the fundamental is associated with a 50% duty cycle, while lower amplitudes are associated with both higher and lower duty cycle values. The results of Ives' constant pulse luminance study were consistent with the idea that the amplitude of the fundamental is the principal determinant of CFF. Unlike the monotonically decreasing function obtained when CFF was plotted over duty cycle in Ives' time-average luminance experiment, the CFF-duty cycle curve took on ~~an~~ inverted U-shape when stimuli were flickered at a constant pulse luminance level.

Perhaps the greatest proponent of the postulate that the amplitude of the fundamental determines the ability to detect flicker is H. De Lange. De Lange used constant pulse luminance flicker to assess the temporal resolution to stimuli whose duty cycles ranged from 3% to 98%. In this study, the contrast between the lit part of a rotating sector disk and the dark portions of this disk was calculated to be 98%. For this contrast level, the duty cycle associated with the highest ripple ratio (amplitude of the fundamental divided by the average luminance) was a 20% duty cycle. The ripple ratio of this stimulus was 171%. Stimuli flickered using a 50% duty cycle, and a 3% duty cycle were calculated to have smaller ripple ratios equal to 122%. The key findings relating temporal resolution to the amplitude of the fundamental involve the fact that the 20% duty cycle was found to have the highest critical fusion frequency (30 Hz), while the 50% and 3% duty cycle stimuli were associated with an equal, but lower CFF value of 27 Hz. While the finding that the stimulus with the highest amplitude of the fundamental was associated with the highest critical fusion frequency, indicates the existence of a direct relationship between temporal resolution and the fundamental amplitude, the strength of this relationship is attested to by the fact that stimuli comprised of different duty cycles, but having similar fundamental amplitudes, were found to have the same critical fusion frequency.

In De Lange's, original study, he wished to investigate the low frequency characteristics of the visual system. In order to produce flicker he used a series of rotating disks which differed along a number of dimensions including duty cycle. Using these disks, he found that the lowest ripple ratio he could produce was 2%, and that the critical fusion frequency for this disk was 9 Hz. In order to reduce the amplitude of the fundamental to values lower than that associated with a 2% ripple ratio, De Lange was forced to reduce the contrast, or depth of modulation of the stimulus. Because black and white rotating disks were inappropriate for such purposes, De Lange devised an optical system in which an approximately sinusoidal stimulus could be varied along two dimensions, frequency and amplitude. Using these sinusoidal stimuli, De Lange was able to assess visual sensitivity to a wide range of frequencies, including those below 9 Hz.

In Fourier terms, a sinusoidal stimulus is the simplest of all stimuli, for it is comprised of a single sine wave of given frequency, with no additional higher frequency components. Because De Lange tested both complex stimuli (rectangular wave flicker) and sine wave stimuli, he was able to test the hypothesis that the amplitude of the fundamental was the principle determinant of CFF, by comparing the CFF values for complex stimuli of a given amplitude of the fundamental, to the CFF values obtained for sine waves with similar amplitudes. The results of such a comparison supported the hypothesis that the amplitude of the fudamental determined CFF for the CFF values obtained for pure sine waves were found to be equal to the CFF values obtained for rectangular waveforms whose amplitudes of the fundamental matched these sine waves.

The present series of experiments also supports the hypothesis that the amplitude of the fundamental underlies flicker detection. Unlike De Lange's paradigm which assessed the critical fusion frequency for sine wave stimuli at a number of different depths of modulation, in Experiment 1 the the minimum depth of modulation required to detect 5 Hz flicker in a number of rectangular waveforms was determined. The results of this study indicate that within a given retinal eccentricity, there existed a threshold amplitude of the fundamental above which flicker was detected and below which subjects were unable to detect flicker (within the constraints of signal detection theory). In De Lange's study CFF depended, not on the duty cycle but rather on the amplitude of the fundamental of the presented stimulus. Similarily, in the present study, for each duty cycle the depth of modulation required to detect flicker, was the depth of modulation required to elevate the amplitude of the fundamental above a threshold value.

Thus the results of the present experiment illustrate that the amplitude of the fundamental not only underlies flicker detection experiments in which CFF is used to determine temporal resolution to duty cycle (De Lange 1952; De Lange, 1954; Ives, 1922a; Ives, 1922b; Cobb, 1934) but also in an experiment where temporal sensitivity to such stimuli was assessed by determining the minimum depth of modulation required to detect flicker. As such, in attempting to gain insight into the temporal mechanisms of the eye, it would seem that breaking down complex stimuli into their specific Fourier components will continue to be a profitable research strategy.

In addition to providing support for the postulates of Ives, De Lange and Kelly, concerning the processing of temporal stimuli, the present studies finding that flicker detection depended on the amplitude of the fundamental has specific ramifications for the multi-flash campimetry technique.

Because the amplitude of the fundamental was able to account for flicker detection in CFF experiments, and in the present sensitivity study, it seemed reasonable to assume that the amplitude of the fundamental would be able to account for flicker detection in the multi-flash campimetry procedure. In order to test this hypothesis a second experiment was conducted in which observers were administered a time-average luminance version of multi-flash campimetry. The amplitudes of the fundamental required to detect flicker in the depth of modulation experiment were then compared to the calculated amplitudes of the fundamental required to detect flicker in the multi-flash procedure. An initial comparison of these amplitudes revealed that the multi-flash amplitudes were consistently higher than those required to detect flicker in the sensitivity task. It was soon realized however, that the amplitudes of the fundamental associated with flicker detection in the multi-flash task were comprised of two components: one component consisting of the actual amplitude of the fundamental required to detect flicker, and a second component consisting of increases in this amplitude due to the influence of reaction time inherent in the multi-flash procedure. Experiment 3 allowed an empirical assessment of the influence of reaction time on the amplitudes of the fundamental in multi-flash campimetry, and when these increases were subtracted from the amplitudes of the fundamental required to detect flicker in the multi-flash procedure, the resulting amplitudes were comparable to the fundamental amplitudes required to detect flicker in the sensitivity experiment.

Thus the combined results of experiments 1, 2 and 3 provided empirical evidence that the amplitude of the fundamental was the principle determinant of flicker detection in multi-flash campimetry. The common dependence of flicker detection on the amplitude of the fundamental in both CFF paradigms and multi-flash campimetry provides a conceptual link between these two techniques and as such, allows a number statements to be made concerning the effects of implementing a time-average luminance display into the multi-flash technique. It is known from CFF studies that temporal resolution improves as the duty cycle of a time-average luminance stimulus is reduced. Such improvements in temporal resolution are attributable to increases in the amplitude of the fundamental of the presented stimulus. Since the amplitude of the fundamental has been shown to underly flicker detection in multi-flash campimetry, the systematic reduction of duty cycle in the multi-flash technique will therefore afford a situation in which the subjects sensitivity to the flicker will increase monotonically with the reduction of duty cycle.

It will be recalled that when constant pulse luminance flicker is used in the multi-flash campimetry technique the Talbot brightness of the point is reduced with the reduction of duty cycle. In such a situation, observers have the potential to base their responses on the reduction of the apparent brightness of one point in the multi-flash display compared to all the rest of the presented points. Such a situation would result in the underestimation of deficiencies in flicker detection capability, for in order to detect changes in apparent brightness the point must still be seen as fused.

The implementation of a time-average lumiance display into the multi-flash technique would therefore, have two major advantages. In such a display, the Talbot brightness of the flickering point would remain constant, thereby eliminating the potential of subjects basing their responses on criterion other than flicker. In addition, the results of the series of experiments described above indicate that implementing a time average luminance display into the multi-flash procedure would provide a situation in which temporal resolution to flicker systematically improves with the systematic reduction of the duty cycle of the presented stimulus.

While the relationship between temporal resolution and the amplitude of the fudamental frequency of the presented stimulus is important for multi-flash campimetry in particular, it may also have applications for clinical psychophysics in general. Because the ability to detect flicker has been shown to be dependent on the amplitude of the fundamental in CFF studies, in depth of modulation studies, and in multi-flash campimetry, this single measusure provides an ideal metric for quantifying the functional capabilities of the temporal aspects of the visual system. Thus using the amplitude of the fundamental as a general measure of the ability to detect flicker, allows the performance of patients or healthy observers on different temporal tasks to be evaluated, or alternatively, by comparing the amplitude of the fundamental required by patients to detect flicker, to the amplitudes required by normals, allows specific techniques to be evaluated in terms of their ability to differentiate between patient performance and normal performance.

Furthermore since both the multi-flash campimetry experiment and the depth of modulation study, indicate that the amplitudes of the fundamental that are required to detect flicker depend on the retinal location of the stimulus presentation, this measure would be suitable for quantifying the functional integrity of the visual field. For example the severity of visual deficts can be quantified by comparing the amplitude of the fundamental required by a patient in multi-flash campimetry, to the amplitudes required by a healthy observer in this same temporal resolution technnique. Figure 12 depicts the visual field maps of a healthy observer, a patient with anisometropic amblyopia and a patient with strabismic amblyopia. Presented along with these two and three dimensional representations are five statistics which use the amplitude of the fundamental to numerically summarize these multi-flash campimetry map data.

The Average Deficit (A.D.) statistic, and the Local Deficit (L.D.) statistic are modifications of statistics used by Flammer, Drance, Augustiny and Funkhouser (1984) to quantify glaucomatous visual fields. The Average Deficit statistic numerically describes the presence or absence of any visual deficit within a given patient's visual field by comparing the amplitudes of the fundamental required by patients to the amplitudes of the fundamental required by control observers. In order to best estimate the amplitudes of the fundamental required by normal observers, the amplitudes required by the eight subjects in

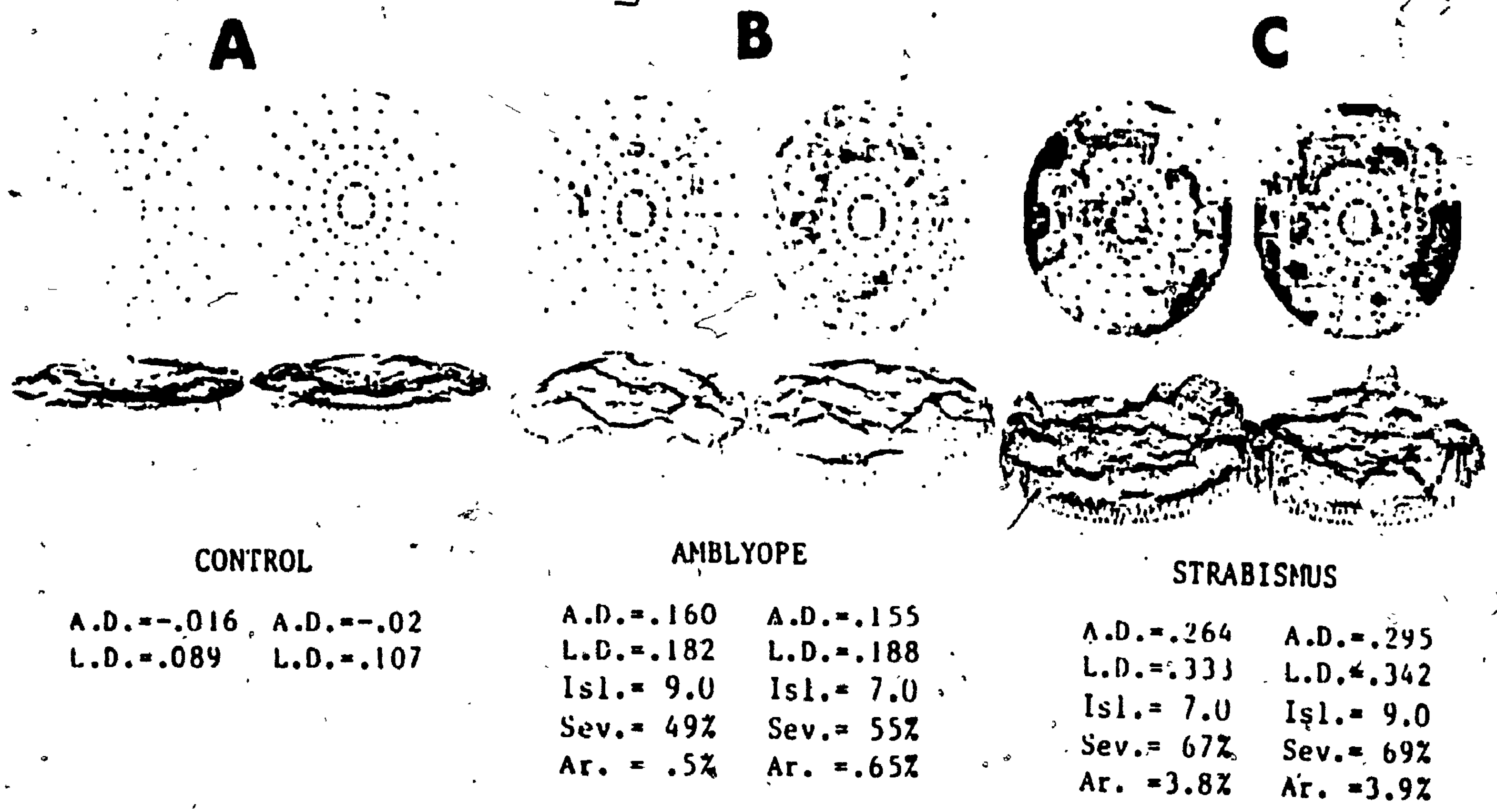

Figure 12. Average Deficit (A.D.), Local Deficit (L.D.) Islands (Isl.), Average Severity (Sev.), Average Area (Ar.) Statistics for Control Subject Amblyope, and Strabismic Amblyope

experiment 2, were averaged to form a "control map". The calculation of the Average Deficit involved taking the amplitude required for each point on the patient's map, and subtracting the corresponding amplitude from the control map. These differences are summed and divided by the number of points (120) tested. As can be seen in Figure 12 the value of the average deficit for the healthy observer is near zero, but for the two patients is elevated by amounts corresponding to the visual consequences of their respective disorders.

The second statistic, the Local Deficit (L.D.), is a measure of dispersion around this Average Deficit value. Patients with highly localized areas of dysfunction in an otherwise normal field would show high variability around the Average Deficit, and therefore display high Local Deficit values. Alternatively, patients with a unifom elevation in required amplitudes throughout the visual field, would illustrate above normal Average Deficit values, but small Local Deficit values. The highly localized deficit patterns exhibited by the two amblyopes is characterized both by the localized areas of dysfunction evident in the two and three dimensional visual field maps, as well as by the high Local Deficit statistic values.

The presence or absence of these local areas of dysfunction are also reflected by the second category of statistics used to quantify the magnitude of visual impairment in multi-flash campimetry. This second strategy for quantifying visual impairment makes use of statistics that can be said to accurately reflect what is visually depicted by the two-dimensional visual field maps. Unlike the

Average and Local deficit statistics, this latter category of measures makes use of values arrived at through an interpolation algorithm which uses an inverse weighting by distance strategy.

The first of such measures is the "Islands" (Isl.) statistic. This statistic quantifies the number of areas within the visual field which are associated with higher than normal amplitudes of the fundamental. The criterion used to determine whether an amplitude is to be considered abnormal involves the grey scale categories used in the two dimensional maps. Such grey scales are composed of ranges of amplitudes. Looking at the healthy observer in Panel A of Figure 12, patches of reduced temporal resolving power are noted throughout areas of the visual field beyond 1.25 deg. Because all eight of the healthy observers tested using multi-flash campimetry displayed such patches, they are considered to be part of a normal visual field. Thus, in order to qualify as an Island, areas associated with this shade of grey must occur <u>within</u> 1.25 deg. of the fovea. Beyond this 1.25 deg. radius, only areas reflecting amplitudes of the fundamental that are more severe than those associated with this shade of grey qualify as an Island. An example of a foveal Island can be found in the left eye of the strabismic amblyope, while parafoveal Islands are dispersed throughout the four fields of both patients.

The Average Severity (Sev.) statistic indicates how severe the deficiency is within a typical Island for a given map. Since the different shades of grey represent seven different ranges of amplitudes, an Average Severity measure can be obtained by taking all the points that are above normal amplitude values, assigning these points values equal to the midpoint of their respective range, summing these midpoint values and dividing by the total number of points. For ease of interpretation, the resulting value is then expressed as a percentage of the maximum possible severity. As can be seen in Figure 12, the Average Severity values in the strabismic amblyope are 67% OD, and 69% OS while the anisometropic amblyope displays severity values of 49% OD, and 55% OD. The correspondence between what is visually depicted by the maps and this average severity statistic is attested to by the fact a typical Island within the maps of the strabismic patient are more severe than the typical Island in the maps of the anisometropic amblyope.

Finally the Average Area (Ar.) statistic reflects the average size of these Islands of deficit. This statistic is calculated by summing the number of sampled and interpolated points that have abnormal amplitudes, and dividing by the number of Islands. Once again for clarity of interpretation this statistic is expressed as a percentage of total map area in order to provide an upper limit as a point of reference. Panels B and C of Figure 12 indicate that the Islands of dysfunction in the strabismic map are larger than those found on the anisometropic amblyope.

To summarize, the Average Deficit and Local Deficit can be used to determine whether a patient has visual field deficiencies and whether such deficits involve local areas of reduced temporal resolving power, or are uniformly spread across the visual field. The Island, Average Severity and Average Area statistics serve to both corroborate these statistics and in so doing, numerically depict what is portrayed visually by the two and three dimensional maps.

Previous researchers have postulated that the amplitude of the fundamental underlies flicker detection in many CFF studies (Ives, 1922a, 1922b; Cobb, 1934; De Lange, 1952; De Lange, 1954; Kelly, 1961). The present study revealed that the amplitude of the fundamental also underlies flicker detection for rectangular wave flicker in a depth of modulation study. Finally, the amplitude of the fundamental was shown to also underly temporal resolution in multi-flash campimetry. Thus regardless of how temporal processing is assessed, this single measure is able to account for a broad range of findings. Such a conclusion suggests that in future investigations concerning temporal information processing in the healthy visual system, the specification of collected data in terms of the amplitude of the fundamental will prove to be a profitable research strategy.

In addition to its pure research implications, the reliance of flicker detection on the amplitude of the fundamental frequency of the presented stimulus, has ramifications for clinical psychophysics. Specifically, the direct relationship between the amplitude of the fundamental and temporal resolution indicates that if a time-average luminance stimulus was implemented into the multi-flash campimetry display, not only would the problem of subjects basing their responses on apparent brightness cues be circumvented, but also, the systematic reduction of duty cycle would cause the observers sensitivity to the flickering point to monotonically increase. Furthermore, the use of the amplitude of the fundamental as a measurement of visual deficit, will reflect the functional capability of an integral part of the visual system, and will therefore enable the clinician to accurately distinguish between a healthy individual and a patient afflicted with one of the many ophthalmalogical pathologies that affect the human visual system.

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APPENDIX A

Maximum and Minimum Luminances

For Time-average and Constant Pulse Luminance Stimuli

The maximum and minimum luminances for both time-average and constant pulse luminances depend on the contrast at which these stimuli are to be presented. Recall that Michelson's formula is defined as

$$C = (M1 - M2)/(M1 + M2)$$

where C is the Michelson contrast (the depth of modulation), M1 is the maximum luminance and M2 is the minimum luminance. If one assumes M2 to be equal to unity then the following formula for the minimum luminance can be derived algebraically.

$$M1 = (1 + C)/(1 - C)$$

By assuming for the moment that the minimum luminance is 1 then the ratio of M2/M1 is merely 1/M1. Calling this ratio K we have

$$K = 1/M1$$

The real minimum luminance and maximum luminances for the prechosen mean luminance of 3 cd/m^2, therefore, can be defined by

$$M1 = 3/ (K - (K * t) + t) \text{ and } M2 = K X M1$$

where t is the duty cycle expressed as a proportion, Since t is the variable that takes into account the relative duration of minimum and maximum luminances, for the TAL conditition this value was always equal to the duty cycle of the presented stimulus. Because the MCPL condition does not take into account the duration of the maximum and minimum luminances, when calculating these luminances, this value was made to equal .5 regardless of the actual duty cycle of the presented stimulus. Using these formulas the maximum and minimum luminances for contrasts ranging from .01 to 1.0 were calculated for both the TAL condition, and the MCPL condition.