Quantifying the Magnitude of Visual Impairment with Multi-Flash Campimetry

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1. Introduction

Multi-flash campimetry is a computer implemented clinical psychophysical technique that uses the ability to detect flicker to distinguish between healthy observers and ophthalmological patients[1-3]. On each trial, a computer randomly selects a point from a 36 point display and begins to flicker it at 5 Hz. The duty cycle of this flickering point (the proportion of the flicker period that is lit), is decreased from 100% in 1.4% steps each cycle until the observer makes a manual response indicating that flicker has been detected.

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Based on the duty cycles that occurred at the time of the response, two and three dimensional maps can be created depicting the temporal resolving power of the visual system across 40 degrees of the visual field as shown in Fig. 4. For both types of visual field maps, an interpolation algorithm is used to estimate the temporal resolving power of areas of the retina that lie between tested points.

The main benefit of two and three dimensional visual field maps is the ease with which they can be interpreted. In the two dimensional display, a seven category grey scale is used with darker shadings indicating areas of poorer temporal resolution. Thus patients who have either a general decrease in temporal resolving power or patients who have highly localized areas of poor flicker detection capability, will both be readily distinguished from the field maps of healthy individuals. Similarly, by presenting such areas of poor temporal resolution as elevations corresponding to the severity of the resolution loss, the clinician can immediately visually distinguish these "mountains" from "valleys" of normal resolution.

While the ease with which both these types of presentations can be interpreted is clearly a major benefit, both two and three dimensional data representations have inherent drawbacks. Three dimensional representations, because of the problem of occlusion, may require a number of different viewing orientations to illustrate any collection of data in its entirety, while two dimensional grey scales rely on the ordinal categorization of data, preventing the portrayal of small but potentially meaningful differences in score values within a given category.

If numbers could be provided in conjunction with the maps, the clinician would be able to both visually discriminate between the visual fields of patients and healthy observers, as well as use quantitative methods to increase the power of this discrimination process.

The base unit which we have adopted to quantify the degree of visual impairment in patients tested using multi-flash campimetry was derived from a study investigating two different luminance presentations and their effect on temporal resolution. Until very recently the form of flicker employed in multi-flash campimetry was of a constant pulse variety in which a light pulse was turned on to a predetermined luminance level and then turned completely off. Unfortunately, reducing the duty cycle in this type of flicker also reduces the time-average luminance and subsequently the Talbot brightness of the point. Thus it could be argued that patients might base their responses on this reduction of the apparent brightness of the point rather than on the detection of flicker.

Such a confound can be easily avoided by holding the time-average luminance of the point constant. This is accomplished merely by increasing the intensity of the on-period in proportion to any reductions in its duration. Furthermore, evidence from early critical fusion frequency (CFF) literature concerning the effect of duty cycle reduction on these two types of luminance displays suggests another advantage of maintaining a constant time-average luminance. While constant pulse luminance displays reveal inverted U-shaped temporal resolution functions with the highest resolvable frequencies at a 50% duty cycle[4], time-average luminance displays afford monotonically increasing temporal resolution curves as the duty cycle of the stimulus is reduced[5]. If these relationships were maintained in multi-flash campimetry, then holding the pulse luminance constant would result in flicker becoming easier to see from duty cycles between 100% and 50%, whereupon further reductions in this parameter would cause flicker detection to become more difficult. A preferable situation would involve the implementation of a time-average luminance display in multi-flash campimetry, whereby the systematic reduction of duty cycle would elicit a continuous increase in flicker sensitivity. The question of empirical interest, therefore, was whether the relationships found in CFF studies, where variable frequencies are used to assess flicker detection capability, could be extrapolated to multi-flash campimetry, in which duty cycle is reduced in order to assess temporal resolution at a fixed frequency of 5 Hz. In order to address this question a depth of modulation experiment was conducted to test subjects' sensitivity to both time-average and constant pulse luminance stimuli.

2. Method

The sensitivity of subjects to 7 different duty cycles (20, 30, 40, 50, 60, 70 and 80%) and two different luminance presentations (time-average and constant pulse luminance) was assessed using a depth of modulation technique. The stimulus display consisted of a line of six points spaced at retinal eccentricities of 0.625, 1.25, 2.5, 5, 10 and 20 degrees of visual angle. This line of points appeared on one of 8 meridians, either the temporal horizontal or rotated by 45, 90, 135, 180, 225, 270 or 315 degrees away from this meridian.

The type of flicker employed was either of a mean constant pulse luminance (MCPL) variety, where the average of the maximum and minimum luminance levels remained at 3.1 cd/m^2 regardless of duty cycle, or alternatively, these luminance levels were manipulated as a function of duty cycle such that the time-average luminance (TAL) was maintained at a steady state level of 3.1 cd/m^2.

The experiment utilized the following split plot design: eight meridii X six eccentricities X seven duty cycles X two luminance types. Subjects were blocked only by meridian; each subject was exposed to all other treatment combinations. On any given trial, subjects were told to focus on a central fixation cross and to indicate with a manual paddle press whether flicker was detected in any of the six presented points. Points were flickered using a randomly chosen combination of duty cycle, luminance type, and eccentricity. The minimum depth of modulation required to see flicker for this stimulus combination was determined using a randomized staircase procedure with a stopping criterion of four reversals.

Thirty-two subjects with corrected or uncorrected acuities between 6/4.5 (20/15) and 6/7.5 (20/25) in their best eye were used in the experiment. The ages of these subjects ranged from 20 to 39. All viewing was monocular with subjects wearing corrective lenses for far vision if so required.

3. Results and Discussion

Panels A and B of Fig. 1 illustrate the results of this sensitivity experiment. In order to detect flicker: a) subjects required greater depths of modulation for peripheral compared to foveal points, and b) within an eccentricity, inverted U-shaped functions were obtained for *both* time-average and constant-pulse displays. Panels A and B of Fig. 2 present the amplitudes of the fundamental Fourier frequency component for each of the threshold stimuli that comprise the data in Fig. 1. A further analysis of this data reveals a significant effect of eccentricity on the amplitude of the fundamental $F(5,120) = 61.21$ $p<0.01$ (omega squared = 22% of the variance accounted for). Also, a significant effect of duty cycle was found $F(6,144) = 56.69$ $p<0.01$ (omega squared = 4% of the variance accounted for).

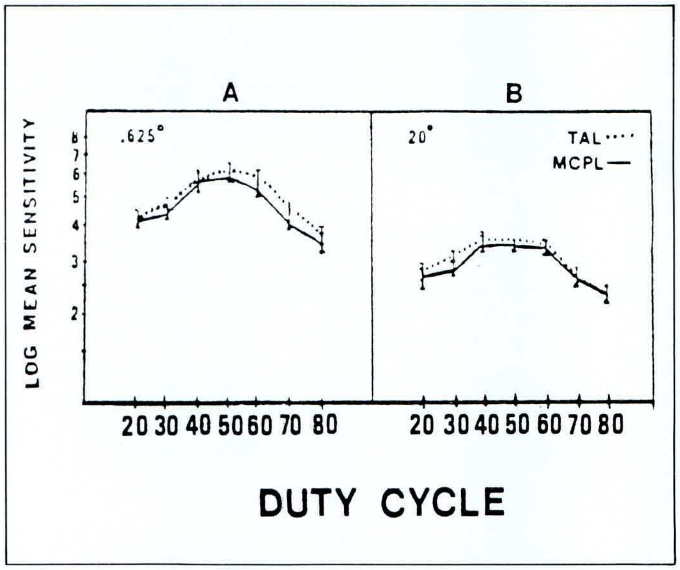

Figure 1. Log mean sensitivity (1/Threshold Contrast) over duty cycle for retinal eccentricities of 0.625 and 20 degrees.

The initially surprising discrepancy between the monotonically increasing TAL function obtained when CFF is plotted over duty cycle and the inverted U-shaped function acquired for the time-average luminance display in the sensitivity study may be explained in terms of the amplitude of the fundamental Fourier frequency component. Essentially, the idea is that manipulations in the characteristics of the flickering stimuli that lead to increases in this amplitude will in turn elicit increases in temporal resolving power. Evidence for this postulate comes from studies in which decreasing the duty cycle of a time-average luminance stimulus elicited monotonic increases in the amplitude of the fundamental and consequently, monotonic increases in temporal resolution as measured by CFF[5]. Further evidence comes from similar studies using constant pulse luminance displays where reductions in duty cycle caused increases in amplitude, and thus CFF, between 100% and 50% duty cycles, with further reductions in duty cycle evoking decrements in both the amplitude of the fundamental and CFF[4]. If one assumes that the amplitude of the fundamental would also underlie the detection of flicker in a sensitivity study, then in such a study, there should be a constant threshold amplitude above which subjects would be able to detect flicker.

To test this hypothesis, the amplitudes of the fundamental were calculated using the sensitivity data portrayed in Fig. 1. As can be ascertained by looking at the relatively flat functions depicting amplitude over duty cycle in Fig. 2, this prediction appears to be confined, for within a given retinal eccentricity, regardless of the duty cycle of the presented stimulus, the same amplitude of the fundamental seemed to be required in order for flicker to be detected. Statistically, however, there was a

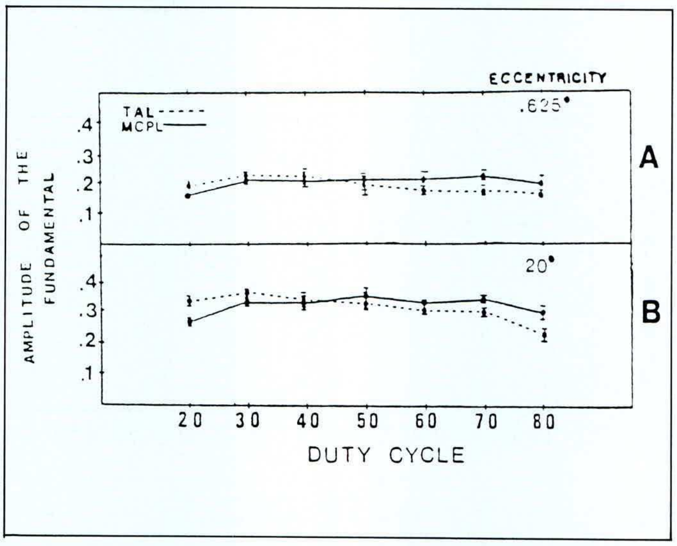

Figure 2. Amplitude of the fundamental required to detect flicker plotted over duty cycle for retinal eccentricities of 0.625 and 20 degrees.

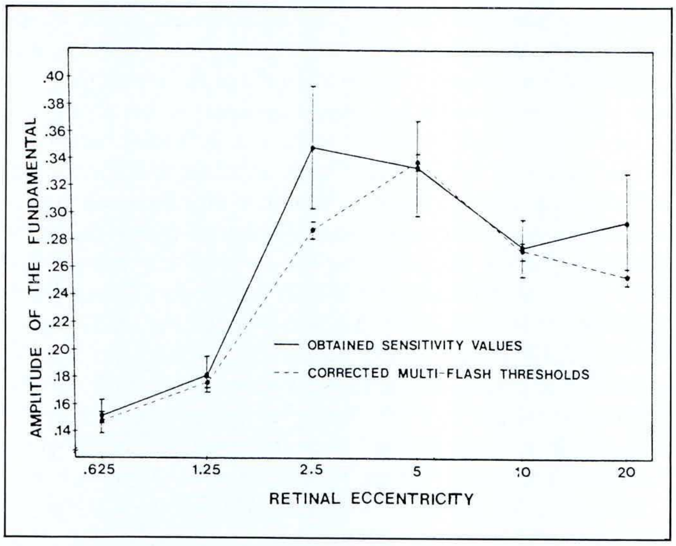

Figure 3. Amplitudes of the fundamental required to detect flicker in sensitivity experiment and in multi-flash campimetry for six retinal eccentricities. Multi-flash amplitudes are corrected for spurious increases due to reaction time.

main effect of duty cycle on the amplitude of the fundamental indicating that these functions did not have a slope of zero. Despite such statistical significance the finding that this effect accounts for only 4% of the variance causes us to conclude that these amplitudes are virtually the same for all duty cycles, and as such the amplitude of the fundamental is the principal determinant of flicker detection in this sensitivity study. Because these amplitudes seem to underlie the detection of flicker in both CFF studies, as well as the sensitivity study, it seemed reasonable to postulate that it would also account for duty cycle detection thresholds in the multi-flash paradigm. If this postulate is correct then we should be able to use the amplitude of the fundamental required to detect flicker in the sensitivity experiment to predict the performance of subjects in the multi-flash paradigm. Before we could test this hypothesis, however, it was necessary to equate the multi-flash procedure with the sensitivity task in terms of the effect of reaction time on the threshold amplitude of the fundamental.

In the multi-flash procedure, since the duty cycle of the flickering stimulus is decremented every 200 ms, the obtained amplitudes that occurred at the time of a manual response were comprised of two components, the amplitude at threshold, and increases in this amplitude due to reaction time. 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.

To this end, eight subjects who participated in the sensitivity experiment, were administered both the time-average luminance version of the multi-flash procedure and a single quadrant of the multi-flash display which was used to measure reaction time. In the latter display, rather than systematically reducing the duty cycle of flicker only threshold duty cycles were presented, and based on the average of six replications for each of 30 points, reaction times were determined for each of the six retinal eccentricities common to both the sensitivity study and the multi-flash procedure. Increases in the amplitudes of the fundamental due to reaction time were then calculated using these average reaction times, and these reaction time induced increases were then subtracted from the obtained multi-flash amplitudes. Figure 4 compares these corrected multi-flash amplitudes to the amplitudes required by the same subjects in the sensitivity experiment. Overlap among the standard error bars indicate that differences between these amplitudes within a given eccentricity are due to chance. Because one can use the amplitude of the fundamental to predict the performance of subjects on the multi-flash paradigm based on their performance in the sensitivity experiment, it seems that this amplitude underlies the detection of flicker in both procedures.

4. Discussion

The reliance of flicker detection on the amplitude of the fundamental in the CFF paradigms, as well as the sensitivity and multi-flash paradigms suggests that regardless of the task used to assess temporal resolution, this single measure may be used to quantify the magnitude of visual impairment reflected by any observed losses in temporal resolving power. The equivalence of the amplitudes required by normals in multi-flash and in the sensitivity study suggests that this amplitude could be used to compare healthy individuals' performance to that of patients, both between different paradigms, or within a particular design. For our present purposes, we have chosen to represent numerically the severity of any visual deficits that are illustrated using the multi-flash procedure by comparing the amplitude of the fundamental required by a patient in multi-flash to that required by a normal using this same temporal resolution technique.

In order to ascertain the best estimate of the normal amplitudes of the fundamental that are required to detect flicker, the amplitudes required by the eight subjects tested using the time-average luminance version of multi-flash were averaged to form a "control map". This control map was then used as a reference for evaluating patient performance in this task.

Figure 4 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 serve to numerically summarize these data.

The first two statistics, the Average Deficit and the Local Deficit, draw on the work of Flammer *et al.*[6]. The Average Deficit, as the name suggests, reflects any overall increase in

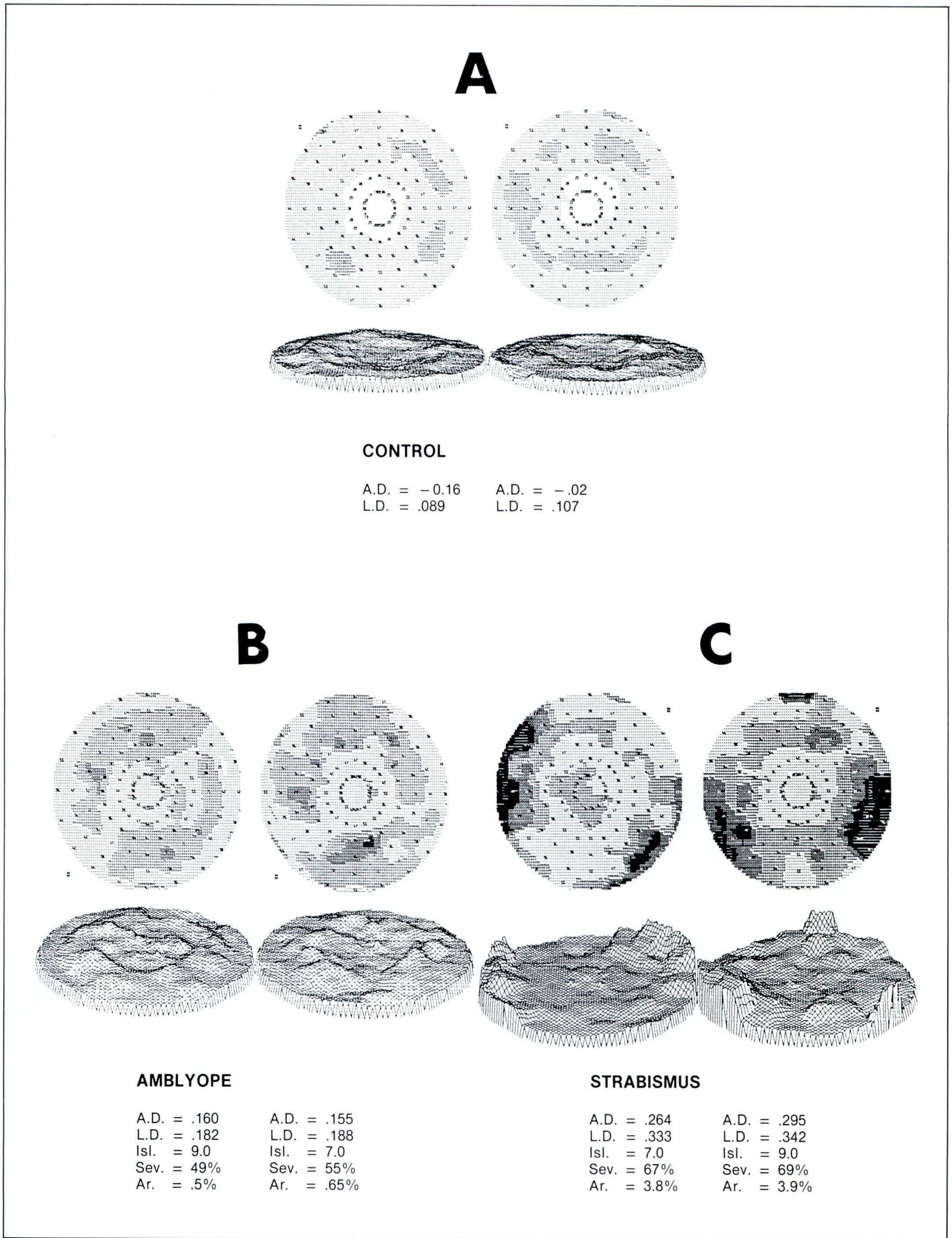

Figure 4. Average Deficit (A.D.), Local Deficit (L.D.), Islands (Isl.), Average Severity (Sev.), and Average Area (Ar.) statistics, along with two and three dimensional field maps for a control subject, an anisometropic amblyope, and a strabismic amblyope.

the amplitude of the fundamental required to detect flicker in the Multi-flash paradigm. It is calculated by 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 Fig. 4 the value of the average deficit for a healthy observer is near zero, but for the two patients is elevated by amounts corresponding to the severity of their condition.

The second statistic, the Local Deficit, is a measure of dispersion around this Average Deficit. Patients with localized areas of dysfunction in an otherwise normal field would show high variability around the Average Deficit, and therefore display high Local Deficit values. A patient with a uniform elevation in required amplitudes spread across the visual field, on the other hand, would show little variability around their obtained Average Deficit, thus affording low Local Deficit values. The strong localized nature of deficit in the two patients in Fig. 4 is illustrated by the elevation of this statistic. Interestingly, even normals show some elevation in Local Deficit because of the irregular placement of patches of reduced sensitivity beyond 1.25 degree of visual angle. Despite the irregularity of the location of such areas between subjects, the test-retest reliability of the technique was 0.87 when the subject depicted in panel A was given two administrations of this test.

The second strategy for quantifying visual impairment makes use of statistics that can be said to more 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 the previously mentioned interpolation algorithm, and as such are subject to the same constraints as the maps themselves.

> By using the amplitude of the fundamental as a measurement of visual deficit, we feel that we have chosen a measure that will enable researchers to predict performance on any temporal resolution task.

The "Islands" statistic reflects the number of areas in the visual field in which higher amplitudes of the fundamental than normal are required to detect flicker. 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 Fig. 4, patches of reduced temporal resolving power are noted throughout areas of the visual field beyond 1.25 degrees. Because all healthy observers tested using multi-flash campimetry displayed such patches, they are considered to be part of a normal visual field. Because these patches are found only beyond 1.25 degrees (the second circle on the map), areas associated with this shade of grey that occur *within* 1.25 degrees of the fovea would be considered an Island of dysfunction. Beyond 1.25 degrees 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 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. The correspondence between what is visually depicted by the maps and this average severity statistic is attested to by the fact that the strabismic patient has higher Average Severity values than the anisometropic amblyope.

Finally, the Average Area 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 Fig. 4 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. By using the amplitude of the fundamental as a measurement of visual deficit, we feel that we have chosen a measure that will enable researchers to predict performance on any temporal resolution task. As such, it reflects 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 ocular pathologies that affect the human visual system.

5. References

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