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# Correcting LCD Luminance Non-Uniformity for Threshold Saccadic Vector Optokinetic Perimetry (SVOP)*

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***Abstract*— The accurate assessment of visual field function can provide valuable information on a range of visual disorders. Saccadic Vector Optokinetic Perimetry (SVOP) is a novel instrument for measuring supra-threshold visual fields in young children who are otherwise unable to perform Automated Static Perimetry (ASP). However, limitations in Liquid Crystal Display (LCD) technology restrict the ability of SVOP to determine threshold values at various points in the visual field, often required in detailed perimetry examinations. This paper introduces a purpose-specific LCD luminance non-uniformity compensation approach to address this limitation. Thorough quantitative evaluation identifies the effectiveness of the proposed approach in (i) compensating for luminance non-uniformities across an LCD, and (ii) enabling SVOP to perform accurate and precise threshold visual field tests. The findings demonstrate that SVOP provides a promising alternative to the current threshold ASP standard (Humphrey Field Analyser).**

## I. Introduction

The detection and monitoring of visual field defects is crucial in the management of a wide range of ophthalmic and neurological disorders, including glaucoma, stroke, and brain tumours. Perimetry quantifies the extent of the visual field by determining differential light sensitivity. This is achieved by presenting stimuli at various, predetermined locations across the visual field. There are two main testing strategies in presenting these stimuli, namely, (i) supra-threshold testing, during which stimuli of a constant luminance are presented establishing whether each stimulus has or has not been seen, and (ii) threshold testing, during which the light sensitivity is tested by changing the luminance of the stimulus until a threshold is established. The Humphrey Field Analyser (HFA) (Carl Zeiss Ltd) [1] performs threshold Automated Static Perimetry (ASP) testing by projecting a series of white stimuli on a uniform (darker) white background (bgrd). Stimuli of known luminance are generated through the use of a projection system and a series of light-attenuation filters. Table I lists some of the luminance levels employed by the HFA, expressed as the attenuation level (in dBs) with respect to the maximum luminance (0 dB). While HFA is the standard for ASP testing in adults, it requires (i) understanding of the test and cooperation from the patient on a physically complex task, (ii) continuous fixation on a stationary central target, and (iii) physical contact between the device and the patient in a sometimes uncomfortable posture. Such requirements restrict its application on the assessment of visual fields in children [2, 3]. Saccadic Vector Optokinetic Perimetry (SVOP) [3] addresses these limitations enabling user-friendly assessment (supra-threshold) of visual fields in children. In order to extend the current system to a reliable threshold perimetry test, SVOP is required to accurately and precisely replicate the HFA background and stimuli luminance levels. Stimuli brighter than HFA 14dB correspond to severe visual loss and are beyond the scope of the SVOP threshold visual field test.

SVOP utilises a flat panel Liquid Crystal Display (LCD) to display bright stimuli on darker background. LCD technology has improved considerably over the years, however, LCDs still suffer from non-uniform luminance across the screen area [4, 5]. In order to successfully utilise LCDs during perimetry examinations: (i) an accurate Look Up Table (LUT) pairing grey-levels to their corresponding luminance levels needs to be generated, and (ii) the luminance non-uniformity across the LCD for each grey-level needs to be estimated and compensated accordingly. This accurate assessment and compensation of luminance non-uniformity is crucial for the SVOP as a stimulus can be presented almost anywhere on the LCD. Even modest uniformity variations may result in a given stimulus being of varying luminance in different locations across the LCD.

A range of approaches have been previously proposed for assessing and compensating luminance non-uniformities across LCDs. Simple solutions have utilised a luminance meter in order to make measurements on a limited number (5 to 9) of control points (CPs) across the LCD. The luminance variability over all grey-levels (typically 0-255) was recorded and an appropriate compensation was derived. However, such techniques are known to compensate only for low frequency luminance non-uniformities. Other techniques have utilised high-end scientific cameras to acquire a sequence of images that characterise the LCD screen in its entirety [6]. While such an approach can provide an exact characterisation and correction for each individual pixel in the display, the high acquisition and processing requirements

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restrict their applicability. This paper introduces a novel purpose-specific algorithm that characterises the LCD and compensates for luminance non-uniformities in order to accurately and precisely replicate the HFA background and various stimuli luminance levels across the entire display.

TABLE I. HFA STIMULI LUMINANCE VALUES (SAMPLE)

| HFA dB level | Luminance contrast between stimuli and background (cd/m$^2$) | Stimulus luminance (cd/m$^2$) |
|---|---|---|
| 0 | 3183.10 | 3193.10 |
| **14** | **126.69** | **136.69** |
| 25 | 10.19 | 20.19 |
| 30 | 3.18 | 13.18 |
| 35 | 1.02 | 11.02 |
| 36 | 0.80 | 10.80 |
| 37 | 0.64 | 10.64 |
| 38 | 0.51 | 10.51 |
| 39 | 0.41 | 10.41 |
| 40 | 0.32 | 10.32 |

## II. LUMINANCE DATA ACQUISITION

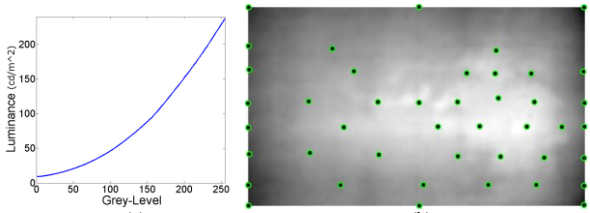
### A. Data Acquisition Rig and Display Setup

A data acquisition rig was developed for the characterisation of LCDs. A scientific luminance meter (Konica Minolta, LS100) performed a sequence of measurements on a number of CPs across the LCD being assessed. Two rails enabled the linear translation of the display with respect to the luminance meter, while spirit levels along with a 3-axis rotating stage ensured that the measurement axis was perpendicular to the LCD plane. All relevant data acquisition parameters were set in accordance to the Video Electronics Standards Association's (VESA) Flat Panel Display Measurements Standard (FPDM) Version 2.0 [5]. Custom software enabled the acquisition of multiple luminance measurements over a sequence of grey-levels, from the darkest black (0) to the brightest white (255), providing flexibility in (i) the number of examined CPs across the LCD, and (ii) the ascending grey-level step size.

Throughout this study an 8-bit, 24" Dell UltraSharp LCD display with maximum brightness of 400cd/m$^2$ was used. The display was controlled by an AMD Radeon HD6350 graphics card. The brightness, contrast and gamma settings of the display were adjusted for optimal performance in visual fields testing ensuring: (i) maximum luminance ≥137cd/m$^2$ (HFA dB14), (ii) minimum luminance ≤10cd/m$^2$ (HFA background), and (iii) the reproduction of maximum number of greyscale steps corresponding to low luminance levels (10 to 12cd/m$^2$). Luminance measurements were performed in darkroom conditions with ambient light below VESA's suggested upper limit (0.32cd/m$^2$) [5]. For accurate and repeatable results an adequate display warm-up period (>60min) was allowed prior to any measurement.

### B. Optimal Sampling and Data Acquisition

A display-specific sampling approach was developed to accurately and efficiently represent luminance variations across a display over a range of grey-levels (0-255). In order to determine an optimal set of grey-levels that upon interpolation accurately represent the display gamma, an exhaustive set (0-255) of luminance measurements were performed at the centre of the display (Fig. 1a). Starting from grey-level 0 to 255, the algorithm automatically identified the largest step (up to 25 grey-levels) for which the difference between the original and the interpolated gamma curves was less than 20% of the corresponding inter-level step. In order to determine an optimal set of CPs, that upon interpolation, accurately represents the luminance non-uniformity across the LCD (Fig. 1b), an image of the display at grey-level 125 was acquired using a 24.2MPixel camera (Nikon D3200). The camera provided sufficient spatial resolution (2xdisplay resolution) to avoid sampling related artefacts such as aliasing and moiré patterns. Using middle range grey-level (125), along with optimal camera exposure provided a good trade-off between the accurate representation of luminance non-uniformity and high levels of noise. The acquired image was subsequently low-pass filtered and contrast enhanced to further remove unwanted noise and highlight areas with high non-uniformity, enabling an experienced operator to select a representative set of CPs across the LCD (Fig. 1b). Throughout the process an interpolated representation of non-uniformity was generated and compared with the original image. Regions demonstrating large difference between the original and the interpolated images were highlighted while the correlation, mean and maximum difference between the two images were displayed to the operator enabling him to recursively refine the CP selection. All luminance measurements required to characterise non-uniformity across an LCD were performed on the CPs and grey-levels derived through this process.




(a) (b)

**Figure 1.** (a) LCD gamma and (b) luminance non-uniformity with corresponding CPs.

## III. LUMINANCE NON-UNIFORMITY CORRECTION

Interpolating splines were used to derive all intermediate luminance values amongst the irregular, display-specific sample grid (Section II.B). Given control points $P_1$ to $P_n$, a set of points $S_i$ were derived defining a *relaxed uniform cubic B-Spline* interpolating through $P_1$ to $P_n$ [7]:

$$\begin{pmatrix} 4 & 1 & 0 & 0 & 0 \\ 1 & 4 & 1 & 0 & 0 \\ 0 & 1 & 4 & 1 & 0 \\ & 0 & \dots & & 1 \\ & & & & 4 \end{pmatrix} \times \begin{pmatrix} S_2 \\ S_3 \\ S_4 \\ \dots \\ S_{n-1} \end{pmatrix} = \begin{pmatrix} 6P_2 - P_1 \\ 6P_3 \\ 6P_4 \\ \dots \\ 6P_{n-1} - P_n \end{pmatrix} \quad (1)$$

with $S_1 = P_1$ and $S_n = P_n$. The interpolating curve was then modeled as a series of uniform cubic B-Spline segments [7]:

$$T = \sum_{l=0}^{3} B_l(u) S_{i+l} \quad (2)$$

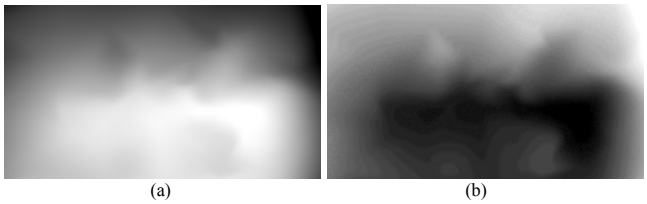
where $i = \{1,\dots,n\}$, $u \in [0, 1]$ and $B_l$ represented the $l$-th basis function of the B-Spline. Such cubic splines generated smooth, 2nd order continuous interpolations providing closer representations of the actual (i) gamma curves, and (ii)

luminance non-uniformity across the assessed LCD, when compared to the corresponding linear interpolations. Fig. 2a illustrates the interpolated luminance variability across the assessed LCD for a given, uniform grey-level.

Having derived a luminance estimate for each pixel and each grey-level across the display, a binary search was performed to identify the grey-levels that produced a uniform luminance representation to each luminance level required throughout an SVOP threshold perimetry test (Table I):

$$\arg \min_{i,j,k,N} \left| L_D(i,j,k) - L_H(N) \right| \quad (3)$$

where $L_H$ ($N$) corresponds to the luminance of an $N$ dB stimulus in HFA, $\{N \in \mathbb{Z} : 14 \leq N \leq 40\}$, while $L_D$ ($i$ ,$j$, $k$) denotes the luminance generated by the LCD at pixel ($i$, $j$) and grey-level $k$, $\{k \in \mathbb{Z} : 0 \leq k \leq 255\}$. At the end of the process, a sequence of 2D matrices (each with grey-level values for every pixel of the LCD) was generated (Fig. 2b). These matrices provided SVOP the closest and most uniform representation of each HFA luminance level achievable by the assessed LCD. The Floyd-Steinberg dithering algorithm [8] was employed to diffuse quantisation errors along the grey-level boundaries to neighbouring pixels generating visually smoother transitions.



(a) (b)

**Figure 2.** Example of (a) interpolated non-uniformity across the assessed LCD and (b) dithered grey-levels required to produce a uniform background luminance of 10cd/m$^2$ across the whole display.

## IV. Assessment of Non-Uniformity Correction

### A. Quantitative Assessment

In order to assess the effectiveness of the proposed non-uniformity characterisation and compensation approach, for each luminance level that SVOP requires to replicate, HFA 14 to 40dB, (i) 64 luminance measurements were performed over a regular 8x8 grid across the display, and (ii) the non-uniformity (*NU*) across the LCD was derived as [5]:

$$NU = 100 * \frac{L_{\max} - L_{\min}}{L_{\max}} \quad (4)$$

where, $L_{max}$ and $L_{min}$ correspond to the maximum and minimum luminance across the 64 locations.

### B. Clinical Visual Field Testing

10 healthy volunteers, aged between 29 and 70 years (38.5±13.4 years) participated in this study. Threshold visual fields were measured monocularly, on one eye only, with the SVOP threshold test and the HFA SITA 24-2 Fast [1, 9]. A brief description and instructions were given to the subjects prior to each test. Both tests were repeated on the same eye in order to determine the repeatability for each instrument. The order of testing was randomized to eliminate bias in the results. Bland Altman analysis [10] was performed to derive (i) the level of repeatability of visual fields performed with each instrument, and (ii) the level of agreement between corresponding HFA and SVOP visual fields. The *Mean Difference* indicates the presence of any bias while the -2*SD* and +2*SD* (Standard Deviation) intervals provide the lower and upper limits of agreement between the compared fields.

## V. Results and Discussion

Tables II and III compare the proposed irregular sampling approach against sampling at regular intervals on how accurately they characterise the LCD non-uniformity over a range of luminance levels. Table II provides the difference between the original and interpolated gamma curves as a percentage with respect to the corresponding inter-grey-level step. Table III provides the Normalised Cross Correlation (NXC) as well as the mean and maximum difference between the original and the interpolated non-uniformity images. Both tables demonstrate that, the display-specific, irregular sampling approach (i) reduces the acquisition and processing requirements (>60% reduction in total samples), and (ii) enhances the accuracy of the interpolated profiles (>60% reduction on maximum difference).

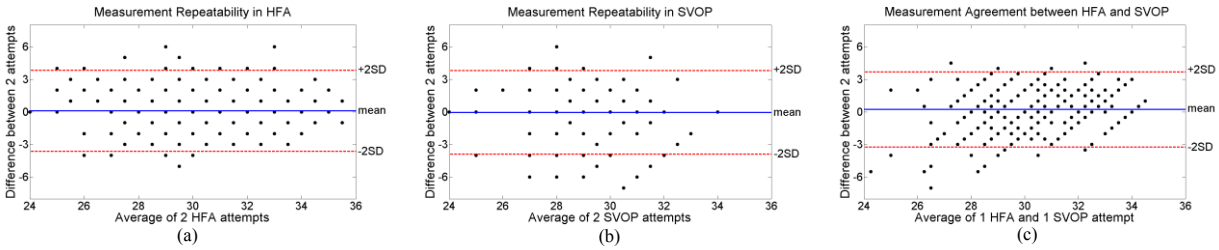
TABLE II. Gamma: Regular VS Variable Step

| | Original VS Interpolated Diff. (%) | | |
|---|---|---|---|
| Grey-Levels | Mean | Max | SD |
| 85 (step 3) | 8.95 | 71.31 | 11.12 |
| 128 (step 2) | 6.29 | 59.83 | 9.95 |
| **58 (display-specific)** | **7.16** | **20.00** | **6.45** |

TABLE III. CPs: Regular Grid VS Manually Identified

| | Original VS Interpolated | | |
|---|---|---|---|
| CPs | NXC | Mean Diff. | Max Diff. |
| 81 (9x9) | 0.988 | 0.62 | 3.95 |
| 121 (11x11) | 0.993 | 0.45 | 3.67 |
| **87 (display-specific)** | **0.992** | **0.44** | **2.57** |

The original non-uniformity across the assessed LCD ranged from 19 to 21.5% and increased with decreasing luminance. Consequently, a reliable direct match between the LCD grey-levels and the HFA luminance levels was not feasible. Specialised radiology displays provide a 10-bit colour-depth, and claim luminance non-uniformity levels of as low as 5% [4]. However, similar to the assessed LCD, the level of non-uniformity is luminance dependent. By employing the non-uniformity compensation approach introduced in this paper, the 28 luminance-levels required for assessing visual fields were reproduced with a non-uniformity of 3.63%±0.42%. The non-uniformity was found to be independent of the corresponding luminance level. Table IV demonstrates that the mean luminance across the compensated LCD provides a very accurate representation (±0.6% of actual value) for each HFA luminance level. However, the lower and upper limits for some levels overlap, which could potentially cause inaccurate results in the derivation of visual field thresholds. In order to avoid such luminance overlaps and any consequent unreliable results, some luminance levels (highlighted in Table IV) were discarded during the SVOP visual fields assessment. Table V demonstrates that by discarding a small subset of levels, the compensated LCD can achieve accurate (mean value within ±10% of actual value) and precise (Relative Standard Deviation [RSD] <10%) inter-level steps.




(a) (b) (c)

**Figure 3.** Bland Altman plots indicating the repeatability of visual fields measurements using (a) HFA and (b) SVOP as well as (c) the agreement between measurements using the HFA and SVOP. Bias (mean), as well as upper/lower limits of agreement (±2SD) are also included.

TABLE IV. HFA STIMULI LUMINANCE VALUES

| HFA dB level | Expected (HFA) Luminance (cd/m$^2$) | Actual (SVOP) Luminance (cd/m$^2$) Min | Mean | Max |
|---|---|---|---|---|
| bgrd | 10.00 | 9.83 | 10.00 | 10.19 |
| **40** | **10.32** | **10.13** | **10.28** | **10.48** |
| 39 | 10.41 | 10.21 | 10.37 | 10.54 |
| **38** | **10.51** | **10.29** | **10.45** | **10.63** |
| **37** | **10.64** | **10.35** | **10.55** | **10.73** |
| 36 | 10.80 | 10.57 | 10.74 | 10.99 |
| **35** | **11.02** | **10.75** | **10.94** | **11.17** |
| 34 | 11.27 | 11.07 | 11.24 | 11.50 |
| **33** | **11.59** | **11.36** | **11.54** | **11.76** |
| 32 | 11.91 | 11.64 | 11.84 | 12.06 |
| 31 | 12.55 | 12.31 | 12.52 | 12.76 |
| 30 | 13.18 | 12.90 | 13.13 | 13.39 |
| 14 | 136.69 | 134.00 | 136.40 | 138.80 |

TABLE V. EXPECTED VS ACTUAL LUINANCE STEPS

| HFA Step (dBs) | Expected (HFA) Step (cd/m$^2$) | Actual (SVOP) Step Mean (cd/m$^2$) | RSD (%) |
|---|---|---|---|
| bgrd - 39 | 0.41 | 0.37 | 8.59 |
| 39 - 36 | 0.39 | 0.38 | 8.91 |
| 36 - 34 | 0.47 | 0.50 | 6.06 |
| 34 - 32 | 0.64 | 0.60 | 4.61 |
| 32 - 31 | 0.64 | 0.68 | 5.24 |
| 31 - 30 | 0.63 | 0.60 | 6.76 |
| 15 – 14 | 26.10 | 26.07 | 2.96 |

The Bland Altman analysis enables the comparison of repeated threshold tests performed using the two instruments and consequently the assessment of the effectiveness of the proposed non-uniformity compensation approach on its intended application. Figure 3 and Table VI demonstrate that the repeatability levels of tests performed by either instrument are very comparable with no outliers or considerable measurement bias. Furthermore, the level of agreement in visual fields performed with both instruments is marginally higher than the repeatability levels achieved by each individual instrument. A modest bias of 0.21 indicates a tendency of SVOP to underestimate the threshold levels when compared to HFA. This agreement bias is attributed to the absence of specific luminance levels that were discarded by SVOP in order to avoid luminance overlaps corrupting the visual field results. By normalising the HFA thresholds to the corresponding levels available in SVOP (e.g. 35dB to 34dB), the bias in measurement agreement drops to a negligible 0.06 indicating that HFA and SVOP can provide equivalent threshold visual fields. Utilising a display that provides a native 10-bit support (1024 grey-levels) will increase the available search-space enhancing the non-uniformity compensation capabilities of the proposed algorithm. By achieving uniformity levels consistently lower than 3%, luminance levels of down to HFA 37dB can be accurately and precisely reproduced, removing any agreement bias between the two instruments.

TABLE VI. REPEATABILITY

| Technique | -2SD | Mean Diff. | +2SD | CR |
|---|---|---|---|---|
| HFA | -3.63 | 0.09 | 3.81 | 3.72 |
| SVOP | -3.90 | -0.05 | 3.78 | 3.84 |
| Agreement | -3.25 | 0.21 | 3.68 | 3.46 |

## VI. CONCLUSIONS

This paper proposes a purpose-specific LCD luminance non-uniformity characterisation and compensation approach that enables SVOP to perform accurate and repeatable threshold visual field tests. Quantitative assessment verifies the suitability of the approach, demonstrating that SVOP can provide a user-friendly alternative to the current standard (HFA). Future work includes the characterisation and purpose-specific compensation of LCD limitations such as the viewing-angle dependence of the perceived luminance.

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