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Individual differences in the shape of the nasal visual field

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ABSTRACT

Between-subject differences in the shape of the nasal visual field were assessed for 103 volunteers 21–85 years of age and free of visual disorder. Perimetry was conducted with a stimulus for which contrast sensitivity is minimally affected by peripheral defocus and decreased retinal illumination. One eye each was tested for 103 volunteers free of eye disease in a multi-center prospective longitudinal study. A peripheral deviation index was computed as the difference in log contrast sensitivity at outer (25–29° nasal) and inner (8° from fixation) locations. Values for this index ranged from 0.01 (outer sensitivity slightly greater than inner sensitivity) to −0.7 log unit (outer sensitivity much lower than inner sensitivity). Mean sensitivity for the inner locations was independent of the deviation index ($R^2 < 1\%$), while mean sensitivity for the outer locations was not ($R^2 = 38\%$, $p < 0.0005$). Age was only modestly related to the index, with a decline by 0.017 log unit per decade ($R^2 = 10\%$). Test-retest data for 21 volunteers who completed 7–10 visits yielded standard deviations for the index from 0.04 to 0.17 log unit, with a mean of 0.09 log unit. Between-subject differences in peripheral deviation persisted over two years of longitudinal testing. Peripheral deviation indices were correlated with indices for three other perimetric stimuli used in a subset of 24 volunteers (R^2 from 20% to 49%). Between-subject variability in shape of the visual field raises concerns about current clinical visual field indices, and further studies are needed to develop improved indices.

1. Introduction

Scientists have studied the visual field since the time of Hippocrates and Euclid, and in modern perimetry the influential work of Traquair led to the concept of a "hill of vision" (Traquair, 1938). For the small stimuli used in perimetry, sensitivity declines monotonically with increased eccentricity, which gave the idea of a "hill." Contemporary perimetric methods use normative data derived from monocular testing of hundreds of people free from disease, documenting changes in the hill of vision with age and detecting visual field defects by comparing patient data with age norms (Bengtsson & Heijl, 1999). The emphasis is on the shape of the hill of vision, which becomes steeper with age, and an adjustment in the overall "height" of the hill of vision due to factors such as subject criterion and clarity of optical media (Heijl, Lindgren, Olsson, & Asman, 1989).

These normative values for the hill of vision are specific for the 0.4° diameter circular luminance increment that was introduced to perimetry in the first half of the 20th century (Goldmann, 1999) and became the clinical standard in the second half. It is now known that there are substantial between-subject differences in peripheral defocus, sufficient to affect contrast sensitivity for the small stimulus that was used to gather these norms (Horner, Dul, Swanson, Liu, & Tran, 2013). Furthermore, it has been found that the adapting luminance used to gather the norms was not high enough for Weber's law to hold, so variations in pupil size and lenticular density can affect sensitivity (Swanson, Dul, Horner, Liu, & Tran, 2014). It seems likely that some of the reported effects of age on the shape of the visual field measured with this small stimulus may be due to age-related optical factors such as pupillary miosis and increased lenticular density. Furthermore, with low-spatial-frequency sinusoidal stimuli it has been found

Abbreviations: CAP, conventional automated perimetry, Goldmann size III in the 24-2 test pattern; CSP, first generation of contrast sensitivity perimetry (Hot, Dul, & Swanson, 2008); CSP-2, second generation of contrast sensitivity perimetry (Swanson et al., 2014) where stimulus size varies with location; FDP, frequency-doubling perimetry in the 24-2 test pattern; MS, mean sensitivity, the average log contrast sensitivity across all locations tested with CSP; PDI, Peripheral deviation index. This is the difference in log contrast sensitivity for outer and central locations and is negative when outer sensitivity is lower than inner sensitivity.

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that the "hill" of vision can be rather flat (Anderson & Johnson, 2003; Pointer & Hess, 1989). The purpose of the current study was to assess between-subject differences in the shape of the monocular hill of vision, and the effects of age, using a low-spatial-frequency sinusoid that is resistant to peripheral defocus and an adapting luminance high enough that Weber's law holds even for small pupils.

The primary focus of this study was on the nasal visual field, because the asymmetric decline in perimetric sensitivity between the nasal and temporal visual field is the opposite of the corresponding decline in ganglion cell density (Keltgen & Swanson, 2012). We have modeled this in terms of local spatial scale (Watson, 1987) being determined by cortical rather than retinal factors (Pan & Swanson, 2006). With monocular perimetry, for a given vertical coordinate in the nasal visual field, horizontal location between 4° and 15° had little or no impact on local spatial scale (Keltgen & Swanson, 2012). With binocular perimetry, what is nasal in one eye is temporal in the other eye, so the region of the visual field that contains the physiological blind spot in one eye is part of this unusually flat region of the nasal visual field in the other eye. Horizontal location has been found to affect binocular contrast thresholds between 4° and 15° (Strasburger, Rentschler, & Juttner, 2011), so we wanted to know how much individuals varied from the mean shape of the nasal visual field. Furthermore, the region of the nasal visual field that we studied corresponds to the retinal region that includes the temporal raphe, where it is possible to image the beginnings of retinal nerve fiber bundles (Huang, Gast, & Burns, 2014; Huang et al., 2015). This region is therefore of interest in structure-function studies in patients with glaucoma. The combination of basic and clinical interest led us to focus on the nasal visual field, but results apply more broadly across the visual field.

2. Material and methods

2.1. Participants

Over the duration of the multi-center study, volunteers were tested at four different locations. Three locations were at Indiana University School of Optometry and one location was at State University of New York (SUNY) College of Optometry. The research for this study adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review boards at Indiana University and SUNY College of Optometry. Informed consent was obtained from each participant after explanation of the procedures and goals of the study, before testing began.

Volunteers were recruited in the age range 21–85 years and were required to have regular eye exams, be free of visual disorder, have spherical equivalent refractive error between −6 D and +2 D, with cylinder ⩽−2.5 D, and corrected visual acuity of 20/20 or better (20/25 over age 70). These volunteers were experienced and reliable on perimetric testing (Marin-Franch & Swanson, 2013; Swanson, Malinovsky, et al., 2014).

Volunteers were tested with contrast sensitivity perimetry (CSP), which refers to perimetry with Gabor stimuli (Harwerth et al., 2002). A reliable CSP test was defined as one with false negative rate no greater than 5%, false positive rate no greater than 10% and fixation loss no greater than 30%. These criteria removed 4 out of 107 people and 79 of 491 tests. The remaining 103 volunteers ranged in age from 21 to 85 years, median 53 years (mean ± standard deviation = 51 ± 18 years) and participated in testing from 1 to 10 times, median 3 tests (4.0 ± 2.6 tests), over periods ranging from 0.0 to 2.8 years, with 43% tested over at least 1 year and 29% tested over at least 2 years.

For the comparison of the CSP results with clinical perimetric sensitivities, data were analyzed for 24 of the volunteers who had participated in a published study in which conventional automated perimetry (CAP), a second generation of contrast sensitivity perimetry (CSP-2) and frequency doubling perimetry (FDP) were used. These volunteers ranged in age from 46 to 84 years, median 67 years (63 ± 11 years) and participated in CSP testing from 2 to 10 times, median 7 tests (6.1 ± 2.5 tests). Details of these methods are available elsewhere (Swanson, Malinovsky, et al., 2014).

2.2. Equipment

Two different designs for custom testing stations were used during the longitudinal investigation. Initially a 40 cm test distance was used (Hot, Dul, & Swanson, 2008), and this was later replaced by a 33 cm test distance (Swanson, Malinovsky, et al., 2014). The details of stimulus display, calibration, fixation monitoring, refractive correction for ametropia and test distance, stimulus configuration, test protocol and threshold algorithm for the CSP testing are available elsewhere (Hot et al., 2008; Horner et al., 2013; Swanson, Malinovsky, et al., 2014).

2.3. Stimuli

For the complete dataset of 103 volunteers, we used the CSP stimulus developed by Hot et al. (2008), a Gabor pattern (two-dimensional Gaussian multiplied by a sinusoidal grating) in sine phase with peak spatial frequency of 0.375 cycle/degree and a one-octave spatial bandwidth. The temporal presentation was a Gaussian pulse centered in a 600 msec window with a standard deviation (SD) of 100 msec. These spatial and temporal properties yield a stimulus resistant to variations in retinal illumination and peripheral defocus (Horner et al., 2013; Swanson, Dul, et al., 2014).

A second-generation CSP visual field test on the 33 cm testing stations used a broader spatial bandwidth for the Gabor stimuli and peak spatial frequency varying with visual field location. This is referred to as "CSP-2," and is described in detail elsewhere (Swanson, Malinovsky, et al., 2014). This was used with the subset of 24 volunteers tested with alternate forms of perimetry.

2.4. Analysis

This was an exploratory data analysis, so we examined effect size using correlation, linear regression, and F-tests (Wasserstein & Lazar, 2016). These statistical methods have good power to detect even modest effects: with 103 individuals, $p < 0.05$ is attained with $R^2 > 4\%$ and $F > 1.4$. P values are listed for any effects with $p < 0.05$ to provide a sense of likelihood that the result was due to chance.

A "mean sensitivity" (MS) index was computed as the average log contrast sensitivity across all 26 locations tested by CSP. A "peripheral deviation index" (PDI) was computed as the difference between outer and inner log contrast sensitivities. For the primary analysis, the outer value was computed as the average log contrast sensitivity for 4 locations 25–29° from fixation in the nasal visual field, and the inner value was computed as the average log contrast sensitivity for 4 locations 8° from fixation (Fig. 1, left panel). A negative value for PDI means that outer sensitivity was lower than inner sensitivity, and a PDI of zero or greater means that outer sensitivity was equal to or greater than inner sensitivity. For each volunteer, values for age, MS, inner sensitivity, outer sensitivity and PDI were averaged across all reliable tests, and these means were analyzed to assess individual differences.

Between-subject variability for the PDI was examined with non-parametric statistics (quartiles, box-and-whisker plot) and Gaussian statistics. Age effects were assessed by linear regression, and the remaining variability was expressed as the standard deviation (SD) of the residuals from the regression. Test-retest