REPEATABILITY AND REPRODUCIBILITY OF VISUAL FIELD TESTS IN PEOPLE WITH ESTABLISHED VISUAL FIELD LOSS.

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The thesis investigated the repeatability of the Esterman Visual Field Test (EVFT) on the Humphrey Field Analyser (HFA), and the reproducibility of the EVFT on the HFA and Henson Pro 5000 Perimeter. The reproducibility of the Ring of Sight (ROS) 24-2 full threshold (FT) examination was also evaluated. These were investigated with participants with established visual field loss (VFL) using case control studies.

The reduced sensitivity that influences test-retest variability in those with VFL and differences within the perimeter methodologies, including the influence of background luminance were considered. Agreement in sensitivity threshold values or the Esterman Efficiency Scores (EES) between perimeters were analysed and pointwise analysis was undertaken. Any change in fitness-to-drive status or ability to determine/rule out disease was investigated.

Principal Findings:

The EVFT possesses poor repeatability and reproducibility for individuals with VFL with significant change in EES on test-retest at different sessions and significant lack of agreement when comparing EES on the HFA and the Henson Pro 5000 Perimeter.

The EVFT possesses good repeatability and reproducibility in fitness-to-drive status. The significant variation in EES and location of defect in those with VFL does not impact upon on an individual's fitness-to-drive status.

It is recommended that a repeat examination is performed on the HFA for those with VFL who fails the EVFT on initial examination to account for variability of test-retest and the significantly lower EES recorded by the Henson Pro 5000 Perimeter.

There is a large proportion of those with VFL (33.33%) who are unable to see a target, which is required to be seen, in order to conduct a visual field test on the ROS. There is significant lack of agreement in defect depth, defect location, mean deviation and sensitivity threshold values found on the ROS 24-2 FT examination compared to the SITA Standard 24-2 examination performed on the HFA. The ROS possesses a sensitivity value of 33.33%.

Perimetry; Esterman Visual Field Test; Humphrey Visual Field Analyser; Henson Pro Perimeter; Ring of Sight; Visual Field Loss.

For Alex and Adam.

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List of abbreviations and acronyms.

Abbreviation/Acronym	Explanation
AFOV	Attended field of view
A.M.A.	American Medical Association
AMD	Age-related macular degeneration
Asb	Apostilb
AUC	Area under the curve
dB	Decibel
cd/m^2	Candela per square metre.
CFD	Central field defect
CFL	Central field loss
CI	Confidence interval
Cpd	Cycles per degree
CRI	Colour rendering index
D	Dioptre
DICOM	Digital Imaging and Communications in Medicine
DVLA	Driving Vehicle Licensing Agency
EES	Esterman Efficiency Score
EVFT	Esterman visual field test
FDP	Frequency doubling perimetry
FT	Full threshold
G.B.	Great Britain
HFA	Humphrey Field Analyser
HPA	Hodapp-Parrish-Anderson
HPT	Hazard Perception Test
IVF	Integrated Field of View
LED	Light emitting diode

LOA	Limit of agreement
MD	Mean deviation
MHR	Mean Hit Rate
MMDT	Moorfields Motion Displacement Test
MVC(s)	Motor vehicle collision(s)
NFD	Nerve fibre defect
PFD	Peripheral field defect
PFL	Peripheral field loss
POAG	Primary open angle glaucoma
PSD	Pattern standard deviation
RCO	Royal College of Ophthalmologists
ROS	Ring of Sight
SAP	Standard automated perimetry
SITA	Swedish Interactive Thresholding Algorithm
SSPS	Statistical Package for the Social Science.
ST	Suprathreshold
SWAP	Short wavelength automated perimetry
UFOV	Useful field of view
UK	United Kingdom
Un	Unknown or unclassifiable defects
VA	Visual acuity
VFL	Visual field loss
VFQ-25	Visual Function Questionnaire-25

Glossary.

Term	Definition
Advanced Vision Assessment	An examination involving the assessment of contrast acuity and detection, colour vision and motion perception.
American Committee on Optics and Visual Physiology	A committee whose focus is on raising standards in ophthalmology and other optical professions.
American Medical Association	A professional association aiming to better public health. Made up of the membership of physicians.
Ametropia	A refractive defect of the eye. Light entering the eye from a distant object fails to fall on the macula. Results in blurred vision without correction.
Amsler	A name given to a chart used to measure the central 10º of visual field. Made up of a grid of horizontal and vertical lines with a central fixation point.
Apostilb	A unit for luminance. 3.14 asb=1 candela per square metre.
Area under the curve	A measure of a parameters ability to distinguish between two diagnostic sets.
Attended field of view test	A binocular peripheral location test presented via a computer.
Average defect	Average difference between age-adjusted and measured sensitivities at each tested location of the visual field on the Medmont automated perimeter.
Candelas (cd/m^2)	A SI unit for luminance.
Center for Epidmiology Studies Depression Scale	A recognised 20 symptom depression scale in the public domain. The scale ranges from 0 (not at all) to 4 (nearly every day for 2 weeks).

Central field defect	A reduction in sensitivity in the visual field within the central 30º from fixation. Also termed central field loss.
Central field loss	Another term to describe the loss in visual field sensitivity within the central 30º from fixation.
Colour rendering index	A scale from 0 to 100 (ideal) indicating the ability of a light to render colour accurately.
Confidence interval	The range of values either side of the presented value, in which the true value may fall.
Contrast sensitivity	A measure of an individuals' ability to determine the lowest difference in luminance (or colour) between an object and its background at which they can still distinguish the object.
Cycles per degree	A measure of spatial frequency. Indicates the number of cycles (a lined pair) subtended at the eye for every degree.
Deary-Liewald Reaction Time Task	A four choice computer based reaction time test in the public domain.
Decibel (dB)	A relative scale measurement of stimulus intensity expressed as 0.1 log-unit of attenuation from the maximum intensity of the stimulus.
Detection acuity perimetry	A perimetry methodology whereby targets are presented via two luminance levels, one above, and one below background luminance. The target is either resolvable or unresolvable to the observer.
Digital Imaging and Communication in Medicine	A greyscale standard commonly used in radiography.
Dioptre	Unit of refractive power. Defined as the reciprocal of the focal length.
Driving Vehicle Licensing Agency	An executive agency of the Department of Transport in the United Kingdom.
Error greyscale	The chance of the loss in sensitivity occurring in <5, <2, <1 and <0.5% of the age-matched population. Provided on the Ring of Sight perimeter.

Esterman Efficiency Score	The ratio of seen points over presented points provided as a percentage on the Esterman Visual Field Test.
Esterman visual field test	A binocular suprathreshold visual field test examining 150º.
Fieldmaster	An automated visual field screener.
Foot-candles	Unit of illumination. 1 foot-candle=10.764 lux.
Frequency doubling perimetry	A visual field testing methodology based on a flicker illusion.
Full threshold	A visual field testing methodology that measures the depth of visual field loss.
Geriatric Depression Scale Short Form	A 15 symptom depression questionnaire. Answers indicate depression scores. Overall score of 0-5 is considered normal. If the score is over the person is considered depressed.
Glaucoma Grading Scale/Hodapp Scale	A scale indicating change in the visual field/progression of glaucoma developed by Hodapp, Parrish and Anderson. The scale utilises the mean deviation score and clusters of depressed points.
Goldmann Visual Field Test	A kinetic visual field test.
Halogen light.	An illumination source. Light is emitted when a tungsten filament is heated.
Hazard perception test	A binocular road simulation hazard identification test measuring the speed that the hazard was detected.
Henson Pro Perimeter	An automated visual field screener.
Hodapp-Parrish-Anderson	A criteria for classifying glaucomatous damage/progression based on the mean deviation and clusters of defective locations.
Humphrey Visual Field Analyser	An automated visual field screener.
Illuminance	A term to quantify luminous flux incident upon a surface per unit area. Measured in lux.
International Committee of Illumination.	An international authority on lighting and colour. Denoted CIE.

Intergrated Visual Field	Purpose written computer software that merges right and left monocular visual fields to create a binocular visual field.
Light emitting diode	A semi-conductor light source. Photon energy is released when a current flows through the source.
Limit of agreement	An interval estimate whereby a proportion of the differences will lie between the measurements.
Luminance	A term describing light intensity emitted from a surface per unit area in a given direction. Measured in candelas per square metre.
Lux	SI measurement of illumination measuring luminous flux per unit area.
Mean deviation	The average difference between age-adjusted and measured sensitivities at each tested location of the visual field.
Mean hit rate	A value to determine seen microdots over presented microdots on the Rarebit visual field test.
Medmont automated perimeter	An automated visual field screener.
Mesopic vision	Also termed as twilight vision. It is the area between photopic and scotopic vision.
Microphthalmus	Congenital condition of an undersized eye.
Moorfields Motion Displacement Test	A perimetry methodology using moving line stimuli presented via a laptop.
Octopus	An automated visual field screener.
Panretinal photocoagulation	A treatment (laser) for proliferative diabetic eye disease.
Pattern defect	The average deviation at each tested location of the visual field after adjustment of the sensitivity values for an overall shift in sensitivity used by the Medmont automated perimeter.
Pattern standard deviation	The average deviation at each tested location of the visual field after adjustment of the sensitivity values for an overall shift in sensitivity.

Peripheral field defect	A reduction in sensitivity in the visual field beyond 30º from fixation. Also termed peripheral field loss.
Peripheral field loss	Another term to describe the loss in visual field sensitivity beyond 30º from fixation.
Peristat	An on-line perimetry tool.
Preferred retinal locus	An undamaged area of the retina preferred by people with a central scotoma to view objects.
PROGRESSOR	A programme that determines a person's baseline sensitivity estimate of their visual field and the rate of change in sensitivity in that field to determine progression of visual field loss.
Rarebit	A visual field screening methodology able to be performed on a personal computer.
Resolution acuity perimetry	A perimetry methodology whereby targets are presented via two luminance levels, one above, and one below background luminance. The target is either resolvable or unresolvable to the observer and direction of target is indicated.
Ring of Sight	A novel perimetry program delivered via method of computer screen.
Royal College of Ophthalmologists	A Royal Medical College. The regulator of ophthalmologists in the U.K. in conjunction with other Royal Colleges.
Scotoma	An area of reduced sensitivity in the visual field.
Scotopic vision	Also termed as night-time vision. Mediated by the rod photoreceptors of the neural retina.
Sensitivity (relating to methodology)	Correctly identifying those with disease.
Short wavelength automated perimetry	A visual field examining methodology using blue stimuli and a yellow background
Specificity	Correctly excluding those without disease.
Standard automated perimetry	A computerised measurement of the visual field using white-on-white stimuli, determining the detection of the minimum luminance to invoke a response by using lights of varying luminance.

Statistical Package for Social Science	Software for statistical analyses.
STATPAC	A software program employed by the Humphrey Visual Field Analyser which compares means of plot deviations to age matched data and takes into account the normal variability at testing locations.
Suprathreshold	A perimetry methodology that presents a stimulus at a level that is expected to be seen if the visual field under examination is normal.
Swedish Interactive Threshold Algorithm	A full threshold algorithm for measurement of the visual field based on previous knowledge of normal and damaged visual fields.
Temporal modulation perimetry	A perimetry methodology examining the central 27º of visual field from fixation via sinusoidal flickering stimuli.
The International Council of Ophthalmology	An international organisation representing professional associations of ophthalmologists.
Threshold sensitivity	The measurement of the dimmest light source that can still be detected by the visual system.
Total deviation	A value of deviation from the normal visual field, determined by the maximum deviation value in the integrated visual field.
Useful Field of View	A psychophysical test. Designed to examine visual attention.
Vigabatrin	A medication that is used in the treatment of epilepsy.
VirtualEye	A head mounted perimeter.
Visual acuity	The ability of the visual system to resolve detail of an image.
Visual field loss	A reduction of sensitivity in the visual field.
Visual Function Questionnaire-25	A questionnaire measuring self-reported dimensions of health that are vision related.
Wacom pad	A graphics pad allowing free hand movement on a computer screen via a compatible graphics pen.

1. Introduction

1.1. The Visual Field.

The visual field enables objects to be detected away from the point of fixation. The visual system in humans possesses high resolution central vision (Rijn. 2002), the fovea, combined with a wide field of view. Light is processed by the photoreceptors in the neural retina of which there are two types. Cones, concentrated within the fovea, which contain colour pigments and dominate our daytime vision; and rods, which are more sensitive to light and concentrated in the peripheral retina. Rods allow us to detect motion in the peripheral field of view and are more dominant when lighting levels decrease (Sammarco *et al*. 2009, Eloholma *et al*. 2005) but provide poor resolution (Rijn. 2002, Fotios 2005).

There are approximately 65 million cones and 115 million rods within the neural retina. Light signals are received by the photoreceptors, which are then transformed into nerve impulses that are capable of being relayed by the bipolar and ganglion cells of the neural retina and along the visual pathway. The signals are relayed from the retina to the lateral geniculate bodies by approximately 1,200,000 myelinated ganglion cell axons within the optic nerve. These axons synapse in the lateral geniculate bodies and the signals continue along the optic radiations to finally be processed in the visual cortex of the brain (Snell & Lemp. 1998). The resultant area of vision produced is known as the visual field.

The visual field is defined as

> ‘All the space an individual can see at any given instant in time’ (Cubbidge. 2005, p.2. Rauscher *et al*. 2007, p15)

1.1.1. Light Perception.

As well as sensing light, the retina also determines differences of light in the visual field. Receptive fields within the retina are termed ‘on’ and ‘off’ receptive fields. ‘On’ receptive fields are activated when light falls into the receptive field centre. Conversely, the ‘off’ receptive fields activate the ganglion cells when light ceases. Within the central 25° of the visual field the majority of ganglion cells are the ‘on’ centre type. The visibility of a stimulus within a receptive field of the retina is related to the density of the ganglion cells within that area (Mutlukan & Damato. 1992). The peripheral retina is not uniform anatomically with the superior retina being thicker (Silva *et al*. 2010) presenting with more photoreceptors and ganglion cells (McCourt *et al*. 2015). The superior retina

relates to the lower visual field and this also has larger representation within the visual cortex (Liu *et al*. 2006).

1.1.2. The Normal Visual Field.

The normal visual field is approximately 90-100º temporally, 60º nasally and superiorly, and approximately 60-75º inferiorly from fixation (Heijl *et al*. 2012). The vertical visual field extends approximately 135° and the total horizontal visual field is approximately 200° (Racette *et al*. 2005) and composed of two monocular crescents with a binocular overlap of approximately 120° (Figure 1-1).

The exact extent of the visual field a person will have depends on their facial features (Rauscher *et al*. 2007.). Differences arise due to the shape and depth of the eye socket (Dorosz *et al*. 2002), relative location and size of the cheeks, nose including prominence of the nasal bridge (Henson. 2001) and brow (Rijn. 2002).

The overlap of the visual field is made up of the sensitivities of both eyes, which is referred to as binocular summation. Various models are used to predict binocular summation and sensitivity of the binocular field can be expected to increase by approximately 25-40% compared to the individual monocular fields (Lema & Blake. 1977). Conditions such as glaucoma can give rise to differences in sensitivity between both eyes dependent upon the size, depth and location of individual defects. This means that the visual field loss (VFL) may or may not overlap. There is a smaller improvement in binocular sensitivity compared to the best sensitivity in the one eye, if the difference in sensitivity between eyes is large (Nelson-Quigg *et al.* 2000).

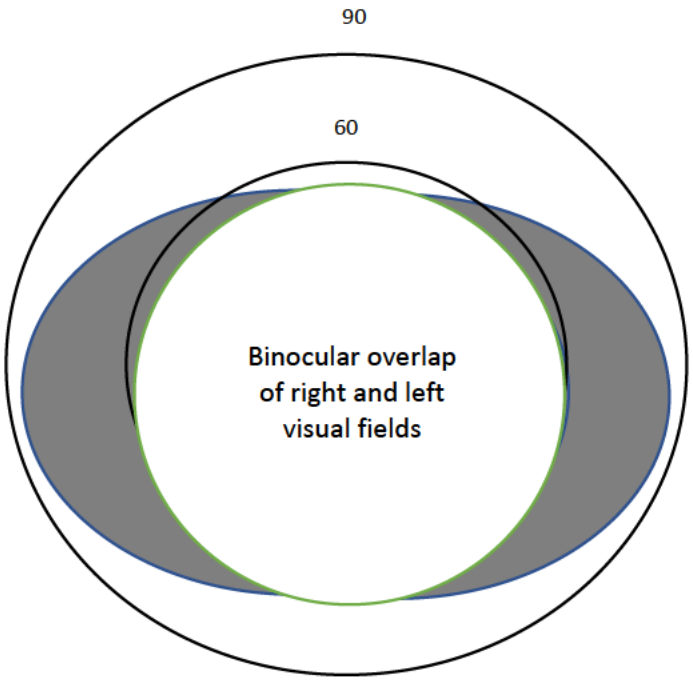

Figure 1-1. The 200° horizontal visual field. The 120° binocular visual field produced by the overlap of the right and left visual fields. The shaded areas represent the two monocular crescents of the right and the left visual field.

Figure 1-2. Duane's hill of vision (Heijl *et al*. 2012. P. 21). The retinal sensitivity for the right eye (dB) across the retina. Black line indicates the level of 10 dB.

The sensitivity of the normal visual field, in daylight, is highest at the foveola (Dorosz *et al*. 2002) and lowest in the peripheral retina. This alteration in sensitivity is generally referred to as the 'hill of vision' (Figure 1-2). The hill of vision parameters can differ

between individuals. One contributing and normal factor is age (Gardiner *et al*. 2006b). A significant deviation from this normal field is known as a defect.

1.2. Visual Field Loss (VFL).

The term visual impairment is the functional consequence resulting from disease. This can relate to a loss of visual acuity (VA), reduction in contrast sensitivity, colour vision loss, glare sensitivity and a loss of visual field (Macnaughton. 2005). A location in the visual field whereby there is reduced sensitivity is termed a scotoma (Heijl *et al*. 2012). This can be absolute, where there is complete loss of sensitivity, or relative, whereby the reduction in sensitivity is selective to the level of light, colour, contrast or motion (Rauscher *et al,* 2007). There are many reasons why there can be reduced sensitivity in the visual field (Rijn, 2002).

1.2.1. Central Visual Field Loss (CFL).

1.2.1.1. Macular Degeneration.

Age-related macular degeneration (AMD) is a multi-factorial progressive condition (Mitchell & Bradley. 2006). It is either exudative or non-exudative (Owsley *et al*. 2007), affecting the central retinal area (macular region) demonstrating a reduction in cone mediated function (Neelam *et al*. 2009) and parafoveal rod photoreceptors in the early stages (Medeiros & Curcio. 2001), The disease impacts on dark adaption (Owsley *et al*. 2007), causes a reduction in VA (Rauscher e*t al,* 2007) and results in CFL (Friedman *et al,* 2004) that is usually bilateral with the likelihood of asymmetry (Kanski. 2007). Exudative AMD causes the most rapid vision loss, which is also more profound compared to the slower progressing non-exudative disease, which generally only causes mild central vision loss. AMD is the leading cause of severe sight impairment in the Western world and the prevalence of this condition increases with age (Mitchell & Bradley. 2006).

1.2.1.2. Stargardt's Disease.

Stargardt's disease is a form of juvenile macular degeneration. It is the most common form of the macular dystrophies forming in the juvenile years. The geographic atrophy (Kanski. 2007) at the macula will result in VFL within the central visual field.

1.2.1.3. Macula Hole.

This is a retinal break at the fovea. A retinal break occurs when an area of the neurosensory retina has broken away from the retinal pigment epithelium (Kanski. 2007). The fovea is responsible for central vision and hence the resultant visual field defect will be within the central field.

1.2.2. Nerve Fibre Damage (NFD).

VFL due to nerve fibre damage (NFD) is the result of a reduction in ganglion cells of the retina (Gardiner *et al*. 2006).

The presenting visual field defects relate to the area of ganglion cell axons affected and their distribution. Figure 1-3 illustrates the arcuate path taken by the ganglion cell axons to the optic disc.

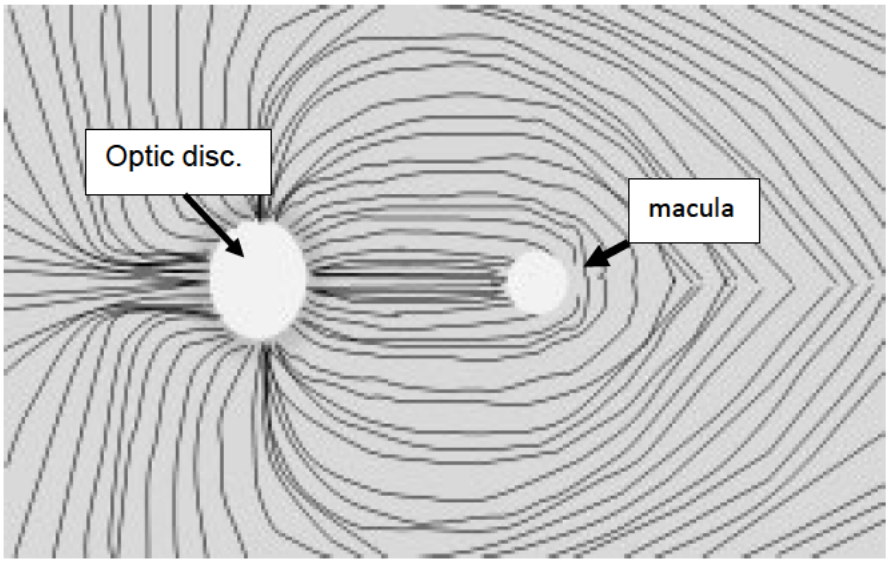

Figure 1-3. Retinal nerve fibre pattern. The axons of the retinal ganglion cells follow an arcuate path. The temporal nerve fibres arch around the macula and meet at the temporal raphe (adapted from Heijl *et al*. 2012. P. 79).

Optic disc damage will lead to vision loss resulting from the corresponding projection of the retinal nerve fibres (Suzuki *et* al. 2001) to the area of optic disc where the damage has arisen. When the damage at the optic disc is partial, it will only involve some of the fibres corresponding to the area and will give rise to a paracentral scotoma (Heijl *et al*. 2012). Representing a more advanced stage of disease, with more nerve fibres corresponding to the area of damage, the blind spot and paracentral scotomas amalgamate giving rise to Seidal's scotoma (Drance. 1972), this then extends to form an arcuate scotoma (Henson. 2001). The arcuate pattern of the scotoma is due to the arrangement of the nerve fibres as illustrated in figures 1-3 and 1-4.

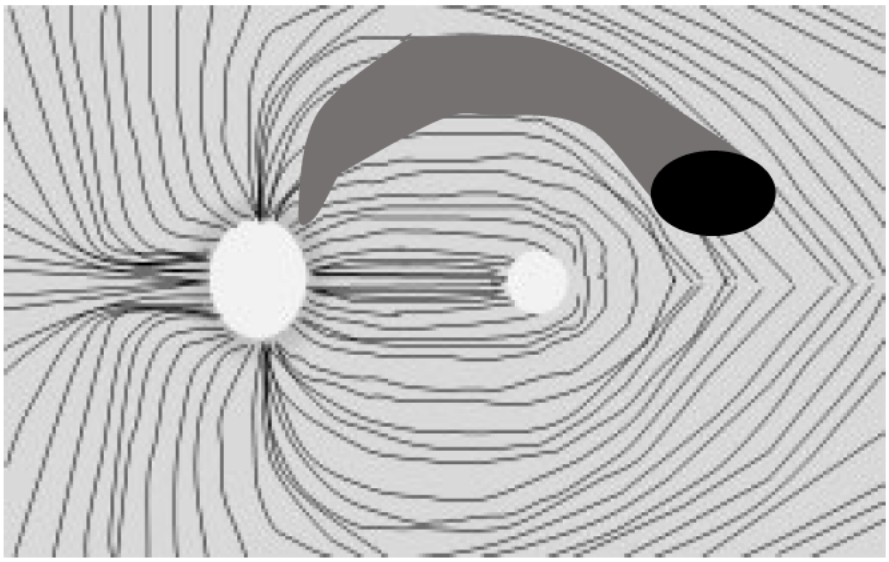

Figure 1-4. Damage along the retinal nerve fibre distribution arising from focal optic disc damage. The damaged fibres project in an arcuate manner represented by the grey area. These fibres will be of similar length. The dark area represents the corresponding ganglion cells. The damaged ganglion cells will be represented on a visual field result as a paracentral scotoma. On progression, with more damage to the nerve fibres, the resultant scotoma will be arcuate (adapted from Heijl *et al*. 2012. P. 82).

The arcuate scotoma respects the distribution of the nerve fibre arrangement. The nerve fibres do not cross over the horizontal mid-line (figure 1-3). Hence, the arcuate scotoma will either be above or below the blind spot (Hatt *et al*. 2006). Progression results in a double arcuate scotoma. The two arcuate scotomas meet, but not exactly, giving rise to a nasal step. In essence the visual defects that arise respect the distribution of the retinal nerve fibres (Henson. 2001). The commonest condition resulting in the reduction of ganglion cells is glaucoma.

1.2.2.1. Glaucoma.

Glaucoma is one of the most common conditions that results in irreversible VFL (Bergin. 2011, de Vries e*t al*. 2012), and is hence, considered one of the most important diseases to detect. It causes optic neuropathy (Henson, 2001) and retinal ganglion cell loss leading to visual field defects and is characterised by progression (Ayala. 2012, Kanski. 2007, Crabb e*t al*. 2010, Brunsini e*t al*. 2004, Hatt *et al*. 2006). Glaucoma can be sub-classified into primary and secondary. Primary can be further sub-classified into primary open-angle (POAG), closed angle and congenital. POAG accounts for the majority of glaucoma cases (Henson. 2001) and is a slow progressing chronic condition (Gray *et al*. 1997, Owen *et al*. 2008).

Glaucoma presents with shallow and localised depressions (Wrobleski *et* al. 2014). VFL presents in the mid-periphery in the early stages (Jampel *et al*. 2002) or approximately 25-30º from fixation in the nasal region. The VFL that occurs in glaucoma follows the pattern previously discussed in section 1.2.2. Representing a more advanced stage of the disease, and with more involvement of more nerve fibres there is progression to peripheral field loss resulting in tunnel vision and eventually the central area within later stages of the disease (Rijn. 2002, Jampel e*t al*. 2002). At this point the patient can be termed with suffering complete vision loss (Barton *et al*. 2015, Bozzani *et al*. 2012).

POAG is bilateral, but usually there is asymmetry between the eyes, across the horizontal meridian between the superior and inferior visual field (Henson. 2001) on the nasal side. One eye is usually at a more advanced stage than the fellow eye (Hatt e*t al*. 2006).

According to the World Health Organisation glaucoma accounts for 12% of blindness globally (World Health Organisation. 2017) affecting approximately 60 million people across the globe. It is one of the three main causes of visual impairment worldwide (Nazemi *et al*. 2007. Patel e*t al*. 2007) and within the developing world (World Health Organisation. 2017, Wood & Black. 2016, Bergin. 2011, Crabb *et al*. 2010). It is the second leading cause of visual impairment (Bozzani *et al*. 2012) within the Western world (Kasneci *et al*. 2014). The prevalence of glaucoma increases with age (Rijn. 2002, Brusini e*t al*. 2005), with the odds ratio for the white population being 2:1 per decade of life. After the age of 70 the white population prevalence is estimated at 16%. For the black population this figure is 6% and for the Asian population it is lower at 3%. It is estimated to increase by one-third in England and Wales from 2008 to the year 2023 (Owen *et al*. 2008) along with an increasing ageing population (Wood & Black. 2016).

Within developed countries, up to 50% of those with the disease are unaware that they have it (Owen e*t* al. 2008) even when presenting with peripheral field loss (Johnson *et al*. 1983). Even when there is intervention to control the disease, 20% of people still experience progression (Wood & Black. 2016).

Many glaucoma patients within the developing world are seen in optometric practice after diagnosis (National Health Service Clinical Commissioning Group. 2019, College of Optometrists. 2019, National Health Service. 2017).

1.2.2.2. Optic Atrophy.

Optic atrophy is not in itself a specific disease but essentially the last stage of optic nerve damage whereby there is death of the retinal ganglion cell axons. This can be seen in the final stages of glaucoma and can result in total and absolute VFL. The hereditary form of optic atrophy can be slow to progress (Kanski. 2007). VFL will be dependent upon the cause of the optic atrophy (Henson. 2001).

1.2.2.3. Optic Neuropathy.

The non-arteritic anterior ischaemic optic neuropathy is the most common form in the older population. One cause of the disease is diabetes mellitus. The VFL associated is inferior altitudinal but is not always limited to this. Nerve fibre bundle defects similar to those found in glaucoma can be presented (Heijl *et al*. 2012). Optic neuropathy can also be found in those with thyroid eye disease (Kanski. 2007).

1.2.2.4 Optic Neuritis.

This condition can be caused by multiple sclerosis and can produce variable visual field defects (Henson. 2001). It is a demyelinating disease (Henson *et al*. 2000) which affects both eyes (Rauscher *et al*. 2007) but can also provide a unilateral central scotoma (Heijl *et al*. 2012). There is commonly a generalised depression within the central 30 degrees of the visual field, which is followed by nerve fibre bundle defects, which are subsequently followed by central focal defects (Kanski. 2007). Defects can show recovery (Werring *et al*. 2000) however, residual localised defects can remain (Keltner *et al*. 2010).

1.2.3. Peripheral Visual Field Loss (PFL).

1.2.3.1. Retinitis Pigmentosa.

This term describes a diverse range of rod-cone retinal dystrophies which mainly affects the rod photoreceptors (Henson. 2001). It presents with progressive PFL (Henson. 2001). The condition may be inherited and VFL is consistent within families. Inheritance patterns can be X-linked, autosomal dominant or autosomal recessive and impacts on dark adaption (Moore e*t al*. 1992). This condition is bilateral, but asymmetry can occur between the two eyes (Rausher *et al*. 2007). The VFL presented by this condition is an annular mid-peripheral scotoma that can result in residual tunnel vision as it progresses (Kanski. 2007).

1.2.4. Other Forms of Visual Field Loss.

1.2.4.1. Monocular Vision.

This term relates to a person having vision in only one eye and inevitably results in a restricted visual field (Racette *et al*. 2005). There are many causes for this, such as a vascular occlusion in the ophthalmic artery (Hayreh & Zimmerman. 2017), or within the central retinal vessels (Kanski. 2007) and trauma.

1.2.4.2. Vascular Trauma.

This condition can affect only one eye and arises from the occlusion of a blood vessel (Rauscher e*t al*. 2007). The field defect can vary dependent upon where in the blood supply the occlusion occurs. If occurring in the ophthalmic artery it can give rise to complete loss of monocular field (Hayreh & Zimmerman. 2017). Involvement of a wedge-shaped area of the retina can occur when the occlusion occurs in the retinal branch artery (Shute. 2018) or vein (Wong *et al*. 2010) and the visual field defect correlates to the area of perfusion of the obstructed vessels (Cochran e*t al*. 2019).

1.2.4.3. Quadrantanopia.

Quadrantanopia is VFL in one quadrant of the visual field. It can be caused by a lesion affecting the optic nerve radiations (Daniel & Jacobson. 1997) which can result from a vascular accident.

1.2.4.4. Retinal Detachment.

A retinal detachment is a term that describes when the neurosensory retina has released from the retinal pigment epithelium (Henson. 2001). The resultant defect is dependent upon the area of detachment and whether, it is a complete detachment or a retinal break. A detachment can produce relative scotomas with indiscreet borders (Heijl e*t al*. 2012). A complete detachment can cause full VFL. A retinal break will result in a localised area of field loss at the location of the visual field that area of the retina projects to. A retinal break can be classified as a tear or as a hole (Kanski. 2007).

1.2.4.5. Posterior Vitreous Detachment.

This can result in a tear forming in the retina. Field loss can occur at the time of the posterior vitreous detachment, or can also occur a few weeks after the posterior vitreous detachment. A tear formed by an acute posterior vitreous detachment is U-shaped and within the upper retina (Kanski. 2007).

1.2.4.6. Diabetic Eye Disease.

Diabetes can lead to complications in the eye. One of the common ophthalmic complications arising from diabetic eye disease is retinopathy (Kanski. 2007). Diabetic

retinopathy is a vascular disorder of the retina (Matza *et al*. 2008) that can result in VFL (Trento *et al*. 2013). Lee *et al* (2015) defines vision-threatening diabetic retinopathy as severe non-proliferative or proliferative diabetic retinopathy, or the presence of macular oedema (Lee *et al*. 2015). The primary feature of proliferative diabetic retinopathy is neovascularisation. Complications leading to vision loss in proliferative diabetic retinopathy include neovascularisation with haemorrhage and fibrosis associated with neovascularisation that increases the risk of tractional retinal detachment (Kanski. 2007). Proliferative retinopathy is the most common vision-threatening lesion, but diabetic macular oedema is the most common cause of vision loss (Lee *et al*. 2015). The eye can present with patchy visual field defects and central defects if macula involvement is present. Panretinal photocoagulation is currently the gold standard of treatment for proliferative diabetic retinopathy (Muquit e*t al*. 2010) and this in itself causes patchy field loss due to the laser burns that arise from the treatment.

1.2.4.7. Albinism.

The cortical reorganisation found in albinism presents with superior/inferior and nasal/temporal asymmetries (Sheth *et al*. 2014). Structural abnormalities in the retina relate to reduced detection thresholds of visual stimuli. The retinal thickness correlates to detection thresholds and to visual field deficits (Sheth *et al*. 2014).

1.3. Perimetry.

1.3.1. The Value of Perimetry.

The measurement of the visual field is known as perimetry (Cubbidge. 2005). Perimetry allows clinicians to assess the visual function (Hatt *et al*. 2006, Malik *et al*. 2005), with a non-invasive technique, usually performed with standard automated perimetry (SAP). SAP is the standard for measuring glaucomatous functional loss (Patel *et al*. 2007). This assessment of visual function makes perimetry an important test (Houston e*t al*. 2010), locating the consequence of disease (Miranda & Henson. 2008) in the form of visual field abnormalities and hence assessment allows the detection of disease (Swanson *et al*. 2005, Swanson *et al*. 2014) or confirms the absence of disease (Wyatt et *al*. 2007). Perimetry has the ability to localise the vision loss to an anatomic location (Wroblewski *et al*. 2014).

At the 2015 International Glaucoma Symposium at Moorfields, glaucoma was considered underdiagnosed (Barton *et al*. 2015). Management and detection can be challenging with this condition (Spry *et al*. 2000). There is a large amount of ganglion cell redundancy which results in the masking of visual field defects until a large number

of cells have diminished (Nouri-Mahdavi e*t al*. 2011). The disease is therefore symptomless (de Vries *et al*. 2012) until its advanced stage (Lowry *et al*. 2016). There is no cure for the disease, but it is manageable. It is therefore important to reliably detect glaucoma early to prevent VFL. Early detection allows early management by commencing appropriate treatment (Viswanathan *et al*. 1997, Nazemi *et al*. 2007) to slow progression (Rijn. 2002) and aim to maintain an individual's quality of life (Alqudah *et al*. 2016). Examination of the visual field is one of the triage of tests to screen for glaucoma. Screening is valuable for open-angle glaucoma and an essential test within the eye exam (Brunn-Jensen. 2011) of high risk patients (Lowry *et al*. 2016). Perimetry is therefore considered essential in its detection and for its management (Bergin. 2011, Brusini *et al*. 2005, Bengtsson e*t al*. 1997). The VFL caused by glaucoma is irreversible (Hatt *et al*. 2006) and can lead to a reduction in quality of life (Hejil *et al*. 2012).

Perimetry also allows the monitoring of patients with diseases that affect the visual pathway and determine progression (Wroblewski *et al*. 2014) and stage (Crabb *et al*. 2010) in diseases such as glaucoma (Swanson *et al*. 2014, Vesti *et al*. 2003). Intra ocular pressures can present as normal in those with POAG and therefore this method is not always able to monitor progression. Changes in the optic nerve head are thought to occur before VFL is evident, however, this is not considered to always be the case (Hatt *et al*. 2006). Progression in VFL will be monitored in these patients with perimetry within hospitals such as Moorfields (Owen *et al*. 2008). National Institute for Health and Care Excellence guidelines advise that discharge of patients from hospital eye services to optometric practice should occur if no change has been detected within 5 years, or even earlier if there is confirmation of normality (Barton *et al*. 2015). Therefore, perimetry remains a valuable tool in the management of glaucoma in Optometric practice.

Visual field testing is usually concentrated on the central 30º (Heijl *et al*. 2012) and can be done monocularly or binocularly. Monocular examination is important to determine the presence of disease whilst binocular testing allows the ability to examine function. In real-world vision both eyes are utilised to obtain information from the working visual field (Jampel e*t al*. 2002b).

1.3.2. Luminance Contrast.

Luminance contrast is a relationship between the luminance of the object and its background (Sammarco *et al*. 2009). How brightness is distributed within the visual field has a direct impact on vision processing (Dorosz *et al*. 2002). Threshold relates to

detection or discrimination of the stimulus (Seim & Valberg. 2015). The contrast detection threshold is given by the following formula (Uchida & Ohna. 2015).

$$C = \frac{L_b - L_t}{L_t}$$ Eqn. 1.

L_b=background illuminance.

L_t=target illuminance.

In standard automated perimetry (SAP), contrast sensitivity is defined by Weber's contrast over the majority of the cone-mediated dynamic range of vision. Where the response is proportional to the contrast and can be defined with the following formula (Eqn. 2).

$\frac{\Delta L}{L}$ (Gardiner e*t al*. 2006. P. 440, Virsu & Lee. 1983. P. 865. Rudd & Rieke. 2016. P. 1) and is the luminance difference threshold. Eqn. 2.

The ability of the eye to determine just noticeable differences of luminance changes can be expressed by the inverted Weber fraction. Sensitivity is defined as

$\frac{L}{\Delta L}$ (Johnson. 2013. P. 28, Seim & Valberg. 2015. P. 341, Virsu & Lee. 1983. P. 865). Eqn. 3.

ΔL is the minimum light energy required to cause a response known as the visual threshold (Cubbidge. 2005). *L* is the background luminance to which the visual system is adapted to (Rudd & Rieke. 2016). Perimetry measures sensitivity in logarithmic steps (Malik *et al*. 2005).

1.3.3. Unit of Measurement: The Decibel (dB).

The intensity of a stimulus is measured in dB. Although the dB makes reference to retinal sensitivity rather than the intensity of the stimulus (Heijl *et al*. 2012). This unit of measurement is expressed as 0.1 log-unit of attenuation from the maximum intensity of the stimulus available (Imaging and Perimetry Society. 2010, Kalloniatis & Khuu. 2016) hence it is a relative scale and can differ between different perimeter manufacturers (Malik *et al*. 2005) depending upon the perimeter's maximum possible intensity.

1.3.4. Equivalent Decibels (dB) for Apostilbs (asb).

For the current Humphrey perimeters the maximum light intensity is 10,000 asb (Heijl *et al*. 2012, Malik *et al*. 2005) which is the equivalent of 0 dB. Table 1-1 presents the equivalent asb for dB on the Humphrey Visual Field Analyser (HFA).

Decibel (dB)	Log units less than the maximum stimulus.	Apostilbs (asb)	Intensity Luminance units
0	0 log unit	10.000	1000
10	1 log unit	1000	100
20	2 log units	100	10
30	3 log units	10	1
40	4 log units	1	0.1

Table 1-1. dB to asb for the HFA (adapted from Heijl *et al*. 2012. P.24, and Henson. 2001. P.7.). Presenting the equivalent asb for dB. Included are the logarithmic steps and intensity luminance unit equivalents for each stated decibel value.

1.4 . Standard Automated Perimetry (SAP).

SAP was introduced within clinics in the early 1980's (Wall *et al*. 2001). It is a computerised measurement of the visual field and determines the detection of the minimum luminance to invoke a response by using lights of varying luminance. SAP uses white-on-white testing (Houston *et al*. 2010). By presenting the stimuli in various locations of the visual field (Delgado *et al*. 2002, McKendrick *et al*. 2005, Ayala. 2012), for a set period of time, it measures differential light sensitivity across the visual field (Betz-Stablein *et al*. 2016), usually the central 30 degrees, whilst maintaining steady fixation on a designated fixation point for several minutes (Wrobleski e*t al*. 2014). It provides fast and reliable results that are clinically useful when evaluating a person's visual field (Johnson *et al*. 1983). This technique requires the individual being examined to make a conscious decision on whether the visual stimulus was seen. It also requires the individual to make decisions when the stimulus is at near threshold (Wrobleski *et al*. 2014). The individual indicates the seen stimulus by pressing a response button (Rijn. 2002). This technique works due to the fact the human eye will instinctively concentrate on the brightest element within the visual field (Dorosz *et al*. 2002).

SAP is routinely used in optometric practice (Artes *et al*. 2002, Suzuki *et al*. 2001) and it has been the clinical standard of care for over 30 years (Heijl *et al*. 2012). SAP is considered the gold standard for the testing of the visual field (Brusini *et al*. 2005, Nouri-Mahdavi *et al*. 2011) due to its precision (Bengtsson *et al*.1997), especially in those with glaucoma (Ong *et al*. 2014, Wyatt *et al*. 2007). It is also used widely for patients with neurological diseases (Gedik e*t al*. 2007).

Heijl & Patella (2002) state that perimetry, which includes SAP, is fundamental in diagnosing and managing glaucoma (Heijl & Patella. 2002). Most research into

perimetry is with glaucoma patients, due to the test being the standard and most useful tool in clinics to diagnose glaucoma (Cubbidge. 2005) and assess glaucomatous damage along with monitoring progression (Alencar & Mederios. 2011, Wyatt *et al*. 2007)

1.4.1. The Humphrey Visual Field Analyser (HFA).

One perimeter utilising SAP and is used extensively, but not exclusively, in optometric practice is the HFA. There is officially no gold standard perimetry tool or test (McKendrick. 2005). However, the HFA is commonly considered the gold-standard investigative tool (Gedik *et al*. 2007) in the United Kingdom (U.K.) (Tattersall *et al*. 2007), or at the very minimum the accepted standard for automated perimetry (Brouzas e*t al*. 2014), used to aid diagnosis and the monitoring of glaucoma. It possibly holds this gold standard status in perimetry by being the subject to many aspects of perimetry research over a period of more than two decades from the advent of SAP being implemented as the replacement to kinetic perimetry within optometric practice, along with its database of glaucomatous and age matched normal data. The HFA employs STATPAC (Henson. 2001) which is further discussed in section 1.4.2. The HFA has a menu offering various specialised test strategies (Ayala. 2012). In addition to age-matched normal data, the perimeter's software corrects data for diffuse loss. The software performs calculations and presents a summary of the data in the form of global indices (Gedik e*t al*. 2007).

1.4.2. Mean Deviation (MD) Statistic.

The MD is the mean defect value (Viswanathan *et al*. 2010) in the height (Heijl e*t al*. 1986) of the visual field profile. It indicates the arithmetic mean of the deviation measured at all locations from the age matched normal and is recorded as a negative value. MD is an index that is provided with most test strategies (Tattersall *et al*. 2007). The HFA employs STATPAC (Henson. 2001) to calculate MD taking into account the normal degree of variance at each of the 54 test points (Tattersall *et al*. 2007) and hence is a weighted value.

In the HFA this weighted value for MD is calculated from:

$$\mathrm{MD} = \left[\frac{1}{m}.\sum_{i-1}^{m}\frac{(\bar{x}i - zi)}{s_{1i^2}}\right] / \left[\frac{1}{m}.\sum_{i-1}^{m}\frac{1}{s_{1i^2}}\right]$$

Eqn.4.

S_{1i}^2 is the variance at location 1 for normal field measurements. (Cubbidge. 1997) MD provides a negative value when a defect is found. The lower the MD (higher negative numerical value) then the greater the defect found.

When reviewing studies from 1992 to 2000 Ernest e*t al* (2012) established that the MD shows greater reproducibility than pointwise values when assessing glaucomatous progression (Ernest *et al*. 2012).

1.4.3. Pattern Standard Deviation (PSD).

PSD plot adjusts the hill of vision profile by adjusting the sensitivity values for an overall shift in sensitivity. This helps determine focal loss from the diffuse loss determined by the overall reduction in sensitivity of the hill of vision profile. The variance chosen in the HFA is the square root of the variance providing the standard deviation (Henson. 2001).

1.5. The 24-2 Grid.

The 24-2 grid tests 54 locations with 6° spacing (Patel *et al*. 2007) examining the central visual field (Gardiner *et al*. 2006). Each test location receives a score in dB. Average scores would be between 0 dB - 30 dB (Betz-Stablein *et al*. 2016). Figure 1-3 presents the test locations on the 24-2 grid for the right and left eyes and their respective optic disc locations.

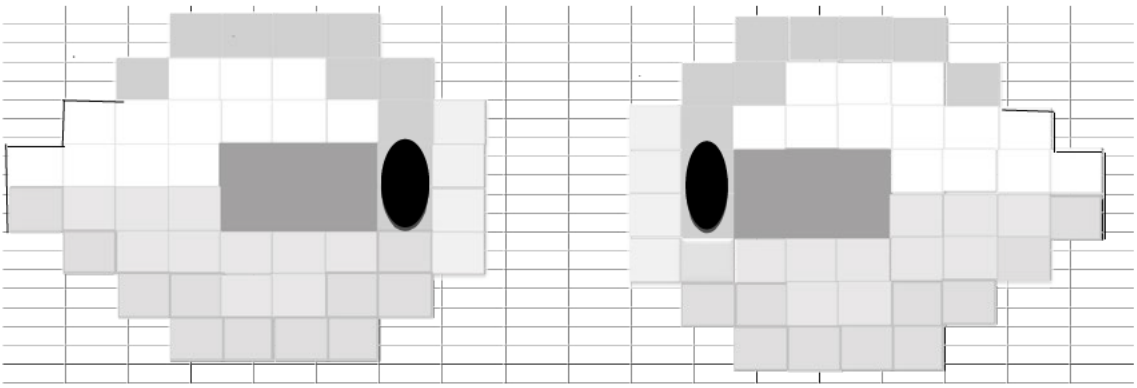

Figure 1-5. The 54 test locations of the 24-2 visual field grid. The right and left eyes are shown along with their respective optic disc locations. Shading represents the nerve fibre arrangement.

1.6. Testing Methodologies in Perimetry.

Ideally, perimetry should not only be reliable, but should also be quick and easy for patients to use. There should be no need to train the patient (Artes *et al*. 2003). There are various strategies available to the clinician, each with their own advantages and disadvantages when considering the ideal.

1.6.1. Suprathreshold (ST) Perimetry

ST tests are used to rule out the presence of disease or to simply detect presence of the disease (Siatkowski *et al*. 1996). As the name ST indicates, this strategy presents the stimulus at a level expected to be seen if the visual field is normal (Heijl *et al*. 2012). If a stimulus is seen it is assumed there is no significant defect at this location (Artes *et al*. 2012, Henson. 2001). If a stimulus is not seen it is presented again. If it is not seen after being re-presented it is then recorded as a defect (Artes *et al*. 2003). It allows for faster assessment of the visual field (Brunn-Jensen. 2011) and is considered less demanding than threshold perimetry, especially for those who are naïve to perimetry (Artes *et al*. 2003). It is considered suitable for screening (Rijn. 2002). However, it is also considered to need a greater change in visual field for detection of the defect (Hitchings. 1994, Brunn-Jensen. 2011). ST perimetry is biased towards specificity and underestimates the extent of VFL (Artes e*t al*. 2001). When a stimulus is seen it is classed as normal, giving rise to false-positive errors and the small sampling provides high levels of variability in the defective visual field (Artes *et al*. 2003). Blinking tends to occur after the presentation of a ST stimulus which has the potential for a patient to miss a stimulus on the following presentation if the blink coincides with the next presentation (Wang *et al*. 2011). Full threshold (FT) perimetry and multisampling ST (whereby 3 points are missed to determine a defect) testing are more sensitive to areas of loss and are able to detect earlier change (Artes *et al*. 2003, Heijl *et al*. 2012).

1.6.2. Full Threshold (FT) Perimetry

FT perimetry is usually considered conventional perimetry (Wall *et al*. 2001). The HFA's FT algorithm has been utilised for most glaucoma clinical trials (McKendrick. 2005, Artes *et al*. 2002) and uses what is termed a 4 dB-2 dB staircase procedure (Conway *et al*. 2014, Wall *et al*. 2001, Bengtsson e*t al*. 1997). The procedure utilises the following method (Figure 1-4).

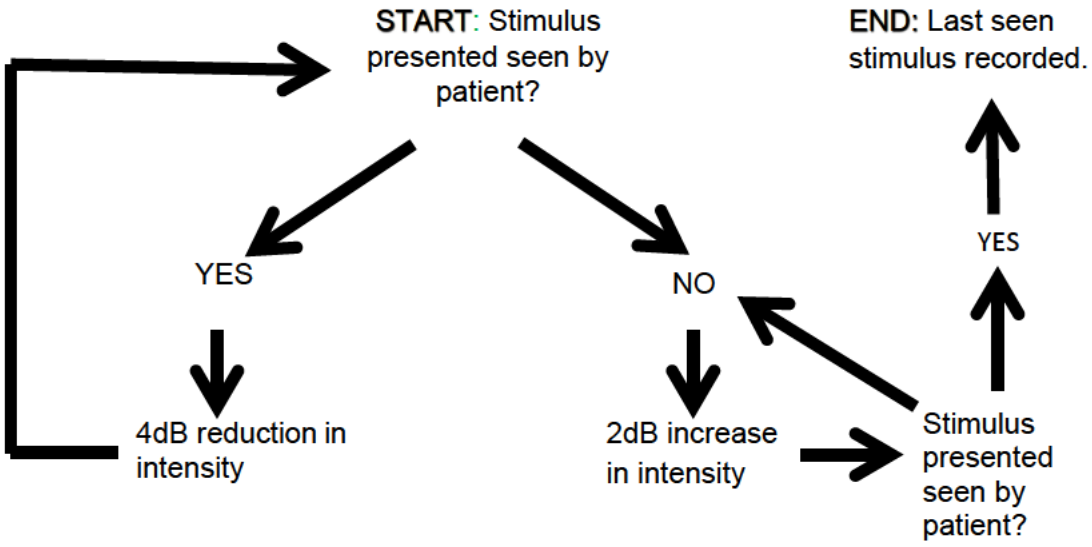

Figure 1-6. The staircase procedure employed by FT perimetry. When the patient cannot see the stimulus after a 4 dB decrease the threshold has been crossed. When the patient sees the stimulus for the first time after a 2 dB increase the patient's threshold has been crossed again (Turpin *et al*. 2007, McKendrick. 2005).

The staircase procedure occurs at all stimulus locations and is not influenced by prior distributions of abnormal or normal results (Conway *et al*. 2014). The stimuli presentation starts from predetermined levels of intensity provided by normative data or from the sensitivity of neighbouring locations (Artes *et al*. 2002). In the HFA the intensity is set as the last seen response (Henson. 2001). FT is a more accurate method of assessing the patient's visual field than ST perimetry (Cubbidge. 2005), however, the test durations can be 15 minutes plus, due to the testing of a point multiple times (Rijn. 2002), this makes it a long and tiring test (Artes *et al*. 2002) making it a source of visual fatigue (Wall *et al*. 2001) and not practical within clinic (Bengtsson *et al*. 1997).

1.6.3. Swedish Interactive Threshold Algorithm (SITA).

The FT algorithm, which was developed in the 1970's (Bengtsson *et al*. 1997), in many cases has been replaced by the SITA algorithms (Artes *et al*. 2002) which were developed over a period of 10 years by Humphrey Instruments (Wall *et al*. 2001) and hence is only available on Humphrey perimeters (Henson. 2001). There are two versions available, SITA Standard and SITA Fast (Shirato *et al*. 1999). The 24-2 SITA is now the most common test in monitoring CFL in the hospital eye services (Rauscher *et al*. 2007). SITA examines the central 30º of the visual field (McKendrick. 2005), with 32 locations being within the central 20º (Rauscher *et al*. 2007), and incorporates population information.

The retest characteristics were designed to be similar to (Shirato *et al*. 2006), and as accurate as, FT testing (Turpin *et al*. 2007. McKendrick. 2005, Wall *et al*. 2001. Bengtsson *et al*. 1997). The global test retest variability has previously been shown to reduce by 15% in participants with glaucoma when compared to FT examination (Artes *et al*. 2002). SITA utilises the 4-2 dB (Shirato *et al*. 1999) staircase procedure but the algorithms are mathematically more complex when compared to the FT strategy (Artes e*t al*. 2002). The algorithm applied methods which took advantage of the available knowledge obtained for both normal and glaucomatous visual fields collected within the 1980's. This allowed estimates of threshold values and threshold errors (Bengtsson e*t al*. 1997) and subsequently also allowed SITA to have the added advantage of being faster (Rijn. 2002. Betz-Stablein *et al*. 2013, Artes *et al*. 2002, Wall *et al*. 2001), reducing test time by up to 50% (McKendrick. 2005, Conway *et al*. 2014, Murray *et al*. 2009, Shirato *et al*. 1999). The 24-2 program is of one of the shortest duration perimetry examinations (Hitchings. 1994). The stimuli presentation increases in speed for those who are able to respond quicker, thereby allowing quicker determination of thresholds (Tattersall *et al*. 2007, Conway *et al*. 2014). It uses the response time to estimate the false positive response rate (Henson. 2001). SITA commences by obtaining the threshold values at four specific points and these values are then used to predict the threshold starting levels at adjacent points (Bengtsson e*t al*. 1997) It has two probability functions, one where it assumes the location tested is normal and the other where it assumes the test location is abnormal (Turpin *et al*. 2007). It uses these two models to determine the commencing staircase values using information from surrounding test areas speeding up test times (Wall *et al*. 2001). The more efficient threshold estimation, which is based on Bayesian principles, reduces the number of stimuli presented (Artes *et al*. 2002). It determines threshold estimates, which compute and update normal and abnormal models after calculation of Bayesian posterior probability distributions (Shirato e*t al*. 1999). 'Abnormal' is based on the glaucomatous visual field (Wall *et al*. 2001) and therefore the inter-point correlations of the threshold values are based on the retinal nerve fibre arrangement. 'Abnormal' is not based on other types of visual field defects. However, the use of the algorithm is not necessarily limited to identifying glaucomatous defects. It has been found to accurately map defects caused by the taking of vigabatrin in epilepsy patients (Conway *et al*. 2014), those with non-glaucomatous optic neuropathies and hemianopia. However, compared to FT, SITA has been shown to overestimate the threshold value (Wall *et al*. 2001) by approximately 1 dB (Henson. 2001, Shirato *et al*. 1999) with values of over estimation ranging from 0.9 dB (Artes *et al*. 2002) to 1.25 dB (Conway e*t al*. 2014, Wall *et al*. 2001) and up to 3 dB at lower sensitivities (Artes *et al*. 2002). An overestimation of

approximately 1 dB has been found in those with optic neuropathies and hemianopia, and a higher mean of 1.3 dB has been demonstrated in those with glaucoma when compared to FT. Although evidence suggests a link to fatigue, by approximately 0.75 dB, with a first SITA test producing higher sensitivity than a second SITA test, it was considered overshadowed by retest variability in these participants. When certain individuals were analysed separately they produced an MD worse on the first test compared to the second test (Wall *et al*. 2001). With sensitivity at approximately 15 dB the maximum difference between SITA Standard and FT is of the order of 1.5 dB. At sensitivities of 15 dB-20 dB it possesses a difference of threshold estimates of approximately 3 dB when compared with FT examination and threshold distributions are considerably different, with FT providing a more symmetrical distribution than SITA Standard. SITA Standard has shown similar test retest variability when compared to FT at sensitivities below 20 dB, but at sensitivities above 25 dB it has been shown to be more repeatable than FT (Artes *et al*. 2002).

1.6.4. Alternative Perimetry Methods.

Novel ways on how to examine visual fields effectively and with ease have been a focus of many researchers (Lowry *et al*. 2016, Aslam. 2011, Brouzas *et al*. 2014. Bruun-Jensen. 2011, Edwards e*t al*. 2005, Ong *et al*. 2014, Bergin. 2011, Houston e*t al*. 2010, Brusini et *al*. 2005, Winther & Frisen. 2015, Gedik e*t al*. 2007, Wroblewski e*t al*. 2014, Hollander e*t al*. 2000, Nazemi e*t al*. 2007), even leading to patents being submitted, not only on computers, but on mobile devices such as phones (Hofeldt. 2013). Ways of reducing the cost of perimetry is desirable. Not only is there the initial outlay to purchase a perimeter there are also maintenance related costs. As well as being expensive for the practice these costs can be passed onto the patient in the form of their eye examination fee. Portable perimetry would allow use in domiciliary settings and at the bedside within hospital settings (Houston *et al*. 2010). Decent laptops and computers are now accessible at reasonable pricing along with available service and maintenance (Brunn-Jensen. 2011).

Peristat is a freely available on-line perimetry tool which allows the user to conduct a ST examination 24º horizontally and 20º vertically from fixation. It can be conducted on a 17” or larger monitor within the patients’ home and takes less than 5 minutes per eye to complete. One advantage of the test is the accessibility to test more frequently. In a study (Lowry *et al*. 2016) comparing it with the HFA 24-2 SITA Standard, the missed points on the Peristat perimeter were highly correlated to those missed on the HFA, The area under the curve (AUC) was found to be similar to other testing methodologies. However, although defective points correlated to the HFA, the Peristat

program missed 46% of early and 14% of moderate to advanced glaucoma cases (Lowry e*t al*. 2016).

Aslam (2011) looked at using a computer game method in examining children. Visual field results for the children with glaucoma (n=5) presented defects in-line with the child's condition (Aslam. 2011). High point-to-point correlation (0.75-0.90) has been provided for a visual field examination utilising a video projector conducting a 30-2 FT examination when compared to the HFA (Brouzas e*t al*. 2014).

A laptop based perimeter studied for development in Denmark demonstrated 100% sensitivity and 78% specificity when examining 173 eyes within a glaucoma clinic and compared against the Octopus 1-2-3 threshold perimetry (Brunn-Jensen. 2011). This examination presents white targets on a background of less intensity and allows for the decreasing sensitivity in the periphery by enlarging the targets presented.

The Useful Field of View (UFOV) test is administered by a computer and this provides the advantage of portability (Edwards e*t al*. 2005). However, the Ring of Sight (ROS) and the UFOV are very different in what they are aiming to examine. The UFOV is aims to measure the useful field of view incorporating processing speed, divided attention and selective attention. The last two of these examinations consist of more than one target (Crabb *et al*. 2004).

The Moorfields Motion Displacement Test (MMDT) utilises moving line stimuli on a laptop display. It is a portable test and relatively affordable compared to stand-alone perimeters. It is a multi-location method based on visuo-spatial principles and has shown to have good diagnostic performance in those with glaucoma. The MMDT ensures the patient is at the correct distance by a chin rest located 30cm from the monitor and is adjustable for height to ensure the test eye is aligned with the central fixation spot. The test is conducted with a room illumination of 85 lux. (Ong e*t al*. 2014). It has been shown to be relatively resilient against the effects of simulated media opacities (Bergin. 2011).

Rarebit is a portable test that can be performed on any personal computer (Brusini e*t al*. 2005) of 15" (Lowry *et al*. 2016), with a liquid crystalline display and presents bright dots of receptive field size against a dark background of luminance 471 asb and 3.14 asb respectively. Two microdots act as the stimuli having a set diameter which is 100th the size of stimulus displayed by SAP. The paired dots are separated by 4º and appear within a series of thirty areas, separated by 10º, within 5º circular diameters at 4 central

locations (1 m test distance) and 26 peripheral locations (0.5 m test distance). Patients utilising this perimeter are corrected for the working distances of 0.5 m and 1 m with the use of a +2.00D and +1.00D respectively (Houston *et al*. 2010). Stimuli are presented at the standard 200 ms. The person being examined indicates if they see zero, one or two stimuli (Lowry e*t al*. 2016) by the clicking of a mouse. Not clicking indicates 'not seen', two clicks indicate 'two dots seen'. It analyses how many responses are made to the microdot presentations and uses this to calculate the integrity of the visual system (Brusini *et al*. 2005) in the form of mean hit rate (MHR) which is the sum of the microdots seen over the microdots presented. The test utilises moving fixation and participants have reported this helps maintain attention (Houston e*t al*. 2010) but omits fixation monitoring (Gedik e*t al*. 2007). This is freely available on the internet and has been shown to be useful in locating macular deficits (Winther & Frisen. 2015). MHR has been shown to be significantly correlated with the MD of the HFA in those with POAG with a trend showing as MHR decreased there was also greater abnormality in the MD. When specificity is chosen as 92.7% and a sensitivity of 97.4% then the AUC when comparing it to the HFA is 0.95 (Brusini *et al*. 2005). The MHR and MD of the HFA have also shown high correlation in those with homonymous hemianopia in all quadrants with Pearson's r ranging from 0.746 to 0.882 (Gedik *et al*. 2007) and defects corresponding in 21 out of 29 visual fields performed on SAP in participants with neurological and neurosurgical diseases (Houston *et al*. 2010). Very elderly patients have been shown to experience problems performing this perimetry test due to not being familiar with the personal computer mouse (Brusini *et al*. 2005), but is concluded in significantly less time than the HFA SITA Standard 30-2 and hence is found to be easier and more comfortable than perimetry on the HFA (Gedik *et al*. 2007). Although performed significantly longer than SITA Fast it was preferred in participants examined at bedside for the convenience (Houston *et al*. 2010).

VirtualEye is a head-mounted perimeter that performs a FT 24-2 using the 4-2 staircase strategy with expected sensitivity having an initial set-up of 30 dB. The background luminance is similar to that of the HFA at 31.4 asb and has a stimulus range of 1.5-45 dB but low dB (0 dB) is limited by the maximum luminance achieved by the display. Test time is reduced by obtaining a weighted average of the already measured sensitivities, which is weighted by inverse distance from the test point being examined. VirtualEye had a shift of -5 dB in sensitivities with respect to the HFA SITA Standard and SITA fast. The reasons for this shift was not clear to the researchers but it was felt it was due to differences between SAP and head-mounted perimetry display, or individual perceived differences (Wroblewski *et al*. 2014).

Another portable head-mounted perimeter designed for bedside perimetry called the Kasha visual field system has produced similar visual field results to the HFA (Hollander *et al*. 2000).

The use of the Amsler grid as a computer automated threshold test exhibits the grid at varying greyscale levels and angular resolution. The result is provided in 3 dimensions. The examination takes 5 minutes and the requirement of the patient is to trace the missing areas by use of a touch screen. Seventy-nine percent of glaucoma suspect participants had a repeatable VFL with this method with all controls demonstrating no visual field defect. The authors concluded that it might provide earlier detection of VFL in participants who have normal SAP results (Nazemi *et al*. 2007).

The ROS (Ibis Vision) is a novel program for visual field testing, which to date has not been validated on patients with established VFL. The ROS has yet to be established in clinical practice and has no known documentation on its performance. To date the ROS has yet to be compared to gold standard visual field testing and is discussed further in chapter 6.

1.6.5. Static Fixation versus Kinetic Fixation in Perimetry.

Static fixation is when the eye is stabilised by viewing a static target whereas kinetic fixation requires the eye to follow a moving target. A limitation of this technique is the target moving over the visual field. Detection can involve the normal field in addition to the damaged areas allowing shallow areas of focal loss to be missed. A moving target is easier for the periphery to detect than a static stimuli (Cubbidge. 2005). A perimeter utilising this kinetic fixation is the Dicon perimeter. This perimeter was compared to the HFA in participants with early VFL due to glaucoma (n=71) and controls (n=45). It found that static perimetry was more accurate for fixation in both those with glaucoma and controls. Controls had significantly more errors with the results from kinetic fixation (27.5%) than static fixation (12.6%). The absolute scotoma at the blind spot was underestimated with kinetic perimetry in both groups. A difference of approximately 10 dB was found between both methods for those with glaucoma and 16 dB for the controls (Asman *et al*. 1999).

1.6.6. Comparisons of Different Testing Methodologies.

There have been no studies to date comparing the ROS with any perimeter. However, the HFA has appeared in many comparative studies (Wall *et al*. 2010. Rauscher *et al*. 2007, Gardiner *et al*. 2006, Cockelburgh e*t al*. 2004, Viswanathan *et al*. 2010, Ayala. 2012, Artes e*t al*. 2002, Ong *et al*. 2014, Lowry *et al*. 2016, Brouzas *et al*. 2014, Brusini

e*t al*. 2005, Nazemi e*t al*. 2007. Gedik *et al*. 2007, Conway *et al*. 2014, Siatkowski *et al*. 1996, Bentley e*t al*. 2012, Spry *et al*. 2003, Owen e*t al*. 2008, Wall *et al*. 2001, Spry e*t al*. 2005, Wroblewski *et al*. 2014, Hollander *et al*. 2000, Houston e*t al*. 2010, Bengtsson e*t al*. 1997, Chauhan & Johnson. 1999, Landers e*t al*. 2007, Patel e*t al*. 2007, Fellman. 1995). Table 1-2 collates results of methodologies compared on or with the HFA.

Study type	Author & year	Sample/ Characteristics	Purpose/aim	Measures/ intervention	Results	Conclusion
Evaluations	Siatkowski *et al*. 1996.	141: Patients being seen at a neuro-ophthalmologic-al clinic who were naive to perimetry.	To devise & evaluate a rapid & cost effective method for detecting neuro-ophthalmic visual field defects.	Tested on: HFA 30-2 FT. HFA amended to present 2dB lower than the estimated median adjusted for age- test A. HFA amended to present 4dB lower than the estimated median level adjusted for age- test B. Fields reviewed by 6 masked reviewers. Measures of: Sensitivity & specificity.	Reviewers classified 70 fields with defects & 71 without. Sensitivity/specificity: 30-2 FT= 99%/71%; Test A=94%/73%. Test B=87%/81%.	The HFA amended to present at 2dB lower than the estimated median adjusted for age, was more rapid than FT, & nearly as effective as FT in detecting VFL due to neuro-ophthalmological disease.
	Bengtsson *et al*. 1997.	Simulations.	To develop a new family of test algorithms for SAP which significantly reduces test time without reduction in accuracy.	Tested on: SITA. FT steps 4-2dB with a 2nd staircase initiated if value departed by 7dB or more. Threshold value based upon threshold values at neighbouring points. Measures of: Detection of defective fields. Duration.	Accuracy greater in SITA than FT. 29% reduction in stimuli presented for normal fields & 26% reduction for glaucomatous fields.	SITA significantly reduces test time whist maintaining accuracy of FT.

Viswanathan *et al*. 1997.	220: Normal tension glaucoma.	To compare performance of PROGRESSOR & STATPAC 2.	Tested on: HFA 30-2 FT in 4-month intervals. Progression= $p<0.05$ at any test location from baseline on 3 consecutive visits. Measure of: Detection time.	Detection time in years: PROGRESSOR=1.077 (SD 0.985). STATPAC 2=2.161 (SD 1.357).	PROGRESSOR detects progression earlier than STATPAC 2.
Shirato *et al*. 1999.	38: Control. 80: Glaucoma.	Clinical comparison of HFA FT & SITA.	Tested on: 30-2 FT. 30-2 SITA. Measures of: Duration. Reproducibility. Threshold sensitivity.	Duration= 56% lower in controls & 45% lower in glaucoma with SITA. Mean sensitivity 1dB higher in SITA in both cohorts.	SITA is faster than FT. Mean sensitivity of SITA 1dB higher than FT.
Wall *et al*. 2001.	28: Control. 18: Hemianopia. 24: Nonglaucomato-us optic neuropathies.	To compare visual sensitivity, fatigue effect & probability plot data between FT & SITA.	Tested on: HFA 24-2 FT (one exam), SITA 24-2 (2 exams). Order of tests: FT, SITA 1, SITA 2. Measures of: Mean sensitivity. Reproducibility.	Mean sensitivities for: Optic neuropathies: SITA 1=1.06dB higher than FT. SITA 2=0.73dB higher than FT. Hemianopia: SITA 1=0.96dB higher than FT. SITA 2=0.11dB higher than FT. -3/4dB difference between SITA 1 & SITA 2. Increased variability with reduced sensitivity.	SITA Standard is as effective as FT for detecting VFL. Mean sensitivities of SITA approximately 1dB higher than FT. Fatigue effects are 3/4dB between SITA tests. Variability increases with reduced sensitivity. Variability increases with eccentricity for all strategies.
Artes *et al*. 2002.	49: Glaucoma.	To investigate the threshold estimates of FT, SITA Standard & SITA Fast & pointwise test-retest variability.	Tested on: FT. SITA Standard. SITA Fast. Measures of: Learning effect. Average sensitivity differences from mean of 3 x FT examinations. Fatigue effect. Pointwise test-retest variability.	No significant learning effect. Sensitivity values compared to FT: SITA Standard=0.9dB higher. SITA Fast=1.6dB higher. More disagreement at lower sensitivities & larger with SITA Fast. 65% reduction in test-retest variability with SITA Fast & 15% reduction with SITA Standard. All strategies increased variability at lower sensitivities.	SITA Standard & FT comparative for monitoring VFL (SITA Standard possibly superior). SITA Standard records sensitivities approximately 0.9dB higher than FT. SITA has reduced test-retest variability.

Artes *et al*. 2003.	Computer simulation. 109: Control (to establish normative data). 190 (342 pairs of data. 152 from both eyes & 38 from one eye): Glaucoma (for test-retest data).	Comparison of multisampling ST with ST & FT in detecting localised VFL & in quantifying the area of loss.	Tested on: ST Multisampling ST (pass criteria: 3/5 seen stimuli at the location). FT. Measures of: Test-retest variability. Defect detection.	Test-retest variability at 30dB could be up to 5dB for FT. FT & multisampling ST, detected defects earlier than ST. FT & ST underestimated area of VFL. Multisampling ST estimates of defect area were less variable. MD learning effect for FT=-0.4dB.	Multisampling ST could be a valid alternative to other strategies. FT provides a learning effect of -0.4dB MD in those with glaucoma. FT test-retest variability at 30dB is 5dB.
Gardiner *et al*. 2006a.	Computer simulation. Test-retest data collected from 63 glaucoma participants.	To present the principle of divergent dysfunction & incorporate it into a model to simulate perimetry.	For test-retest data, tested on FT on HFA. Total deviation taken for each location & converted to sensitivity (+30dB). Measure of: Test-retest variability.	Participant variability=5.91dB.	Variability increased with decreased sensitivity.
Tattersall *et al.* 2007.	68: Control. Glaucoma defect: 71: Mild glaucoma defect. . 34: Moderate glaucoma defect. 17: Severe glaucoma defect. 12: End stage glaucoma.	To describe expected fluctuation in MD.	Tested on: HFA 24-2. Measure of: Variation in MD from five HFA 24-2 examinations classed as stable.	Mean fluctuation in MD (99% CI): Controls=0.3dB; Mild glaucoma=0.4dB; moderate glaucoma=0.8dB; Severe glaucoma=1dB; end stage glaucoma=1.3dB.	Any fluctuation beyond those listed within the results would indicate progression. Fluctuation in MD is small within stable fields.

	Rauscher *et al*. 2007.	60: Central field defect (CFD) within 20º of fixation. 72: Control.	Sub-study: To compare the Esterman Visual Field Test (EVFT) with the integrated visual field (IVF).	Tested on: HFA EVFT. HFA FT- to generate IVF. Measure of: Fitness-to-drive pass/fail frequencies.	Agreement of pass/fail = good (kappa=0.84). 3 participants passed IVF & failed EVFT (defect was peripheral with extension into central field). 1 participant passed EVFT & failed IVF (defect was central).	IVF needs to be supplemented by EVFT if patient is suspected of having a peripheral field defect (PFD).
	Ayala. 2012.	40: Glaucoma.	To compare HFA monocular field test (SITA Fast 24-2) with EVFT.	Tested on: HFA EVFT. HFA 24-2 SITA Fast. Measure of: Fitness-to-drive pass/fail frequencies.	60% passed EVFT. 40% passed with SITA Fast monocular fields. 8 subjects failed with monocular fields but passed EVFT.	Monocular fields are more specific in providing information on location & depth of defect than EVFT. EVFT not as efficient in finding VFL.
	Conway *et al*. 2014.	16: Diagnosed with epilepsy & exposed to vigabatrin therapy. 44% of which were diagnosed with VFL attributed to vigabatrin therapy.	To assess the clinical ability of SITA for accurately mapping vigabatrin attributed VFL.	Tested on: FT. SITA Standard. SITA Fast. Measures of: Mean sensitivity. MD & PSD.	No difference in MD & PSD. Mean sensitivity: SITA Standard=1.25dB higher than FT. SITA Fast=1.51dB higher than FT. All strategies increased in variability with eccentricity. Less agreement with wider CI's across all regions with SITA than FT. Using FT as reference standard, then SITA Standard identified all participants with VFL attributed to vigabatrin.	SITA accurately maps vigabatrin attributed VFL. SITA Fast may benefit those who suffer fatigue, which is common in sufferers of epilepsy. SITA records higher sensitivities & is more variable than FT, & the variability increases with eccentricity.
Comparisons	Chauhan & Johnson. 1999.	64: Glaucoma. 47: Control.	To compare the test-retest variability characteristics of frequency doubling perimetry (FDP) with SAP in glaucoma & normal controls.	Tested on: FDP (prototype- the precursor to the commercially available FDP). HFA FT 30-2. Measures of: Threshold deviations. Variation within zones: Zone 1= central & paracentral. Zone 2= 12 peripheral stimuli.	Strong correlation in average MD for glaucoma participants between methods & also with severity categories. No correlation in average MD for controls. Variability in locations less than 20dB: 120% with SAP & 40% with FDP. Variation increases at reduced sensitivity for all participants.	Strong correlation in MD. Less variability with FDP. Both strategies increase in variability with reduced sensitivity & with increased eccentricity.

Spry *et al*. 2003.	7: Early or moderate glaucoma.	To determine the measurement error of a staircase algorithm similar to FT with SAP & FDP in glaucoma patients.	Tested on: HFA FT. FDP. 3 test locations in each eye examined of varying sensitivity. Measures of: Within test variability.	Within test variability: FDP=1.5dB (SD= 0.42dB) & SAP=6.2dB (SD=5.03dB).	SAP significantly overestimates sensitivity, especially within damaged areas. FDP has less within test variability.
Spry *et al*. 2005.	48: participants referred to a clinical service due to expected glaucoma.	To evaluate the performance of FDP (Humphrey Matrix 24-2).	Tested on: HFA 24-2 SITA Fast. FDP matrix threshold 24-2. Measures of: Duration Visual field abnormality detection. Receiver operating characteristics of MD & PSD.	FDP was faster than SAP. FDP possessed higher sensitivity in detecting glaucoma than SAP. SAP possessed higher specificity.	FDP is faster than SAP. FDP has higher sensitivity in detecting glaucoma than SAP. SAP has higher specificity than FDP. SAP & FDP are comparable when 24-2 grid is used. FDP has similar performance characteristics to SAP.
Brusini *et al*. 2005.	43: Ocular hypertension. 39: Glaucoma. 41: Control.	To compare Rarebit perimetry with SAP in detecting early functional damage in glaucoma.	Tested on: SAP HFA. Rarebit perimetry. Measure of: Comparison of MHR & MD.	Correlation was moderate (Pearson's r=0.38) with MHR & MD.	A moderate correlation exists between MHR & MD.

Gardiner *et al*. 2006b.	100: Normal (aged 20-85).	To compare the rate of age-related decline, learning effects & test-retest variability in FT. short wavelength automated perimetry (SWAP). Temporal modulation perimetry. FDP. Detection acuity perimetry & Resolution acuity perimetry.	Tested on: HFA 24-2 FT. HFA SWAP. Temporal modulation perimetry. FDP. Detection acuity perimetry. Resolution acuity perimetry. Measures of: Dynamic change per year. Change with eccentricity. Learning effect.	Dynamic change per year: Resolution acuity perimetry=<0.25%. Temporal modulation perimetry=<0.25%. SAP:-0.25% for peripheral field, <0.25% for central field. FDP=<0.50>-0.25%. SWAP=>-0.50%. All strategies had more change in the peripheral field compared to the central field. All strategies possessed a learning effect, but this is greater in SWAP. SAP=5% of dynamic change on test-retest & is the least change of all the strategies.	Test-retest variability for SAP=1.65dB. Peripheral fields change more per year than central. Resolution acuity perimetry has less dynamic (<0.25%) change per year than SAP.
Patel *et al*. 2007.	50: VFL on SITA.	To compare visual field defects found by SITA with those found with Matrix perimetry.	Tested on: HFA 24-2 SITA. Matrix 24-2 FT. Measures of: Defect detection. MD & PSD. Duration. Glaucoma hemifield test.	100% of defects found with SITA. 36% of these were not detected on Matrix perimetry. The size of the defect is larger & shallower on SITA. Locations were congruent in 30% of eyes. Matrix MD=-1.25dB lower than SITA. There were no significant differences in PSD. Glaucoma hemifield test agreement was poor. Duration was significantly shorter on Matrix perimetry.	Matrix perimetry did not detect 36% of defects. MD in Matrix perimetry is -1.25dB lower when compared to the MD of SAP. Duration is shorter with Matrix perimetry.
Landers *et al*. 2007.	8: Suspected glaucoma. 8: Ocular hypertension. 32: Glaucoma. 15: Control.	To directly compare global indices of HFA & the Medmont automated perimeter.	Tested on: Medmont automated perimeter. HFA 24-2 FT. Measures of: MD & PSD (HFA). Average defect & pattern defect (Medmont automated perimeter).	There was a highly significant non-linear association between MD & average defect (r^2=0.92) & between PSD & pattern defect (r^2=0.75).	Average defect & pattern defect results from the Medmont automated perimeter may be substituted for the MD & PSD results from HFA after conversion.

Gedik *et al*. 2007.	40: VFL caused by acute occipital lobe infarcts.	To compare rarebit perimetry & HFA in detecting hemianopia in stroke patients.	Tested on: HFA 30-2 SITA Standard. Rarebit. Measures of: MHR, MD & PSD for each quadrant. (Quadrants= superior temporal, superior nasal, inferior temporal, inferior nasal).	MHR & MD were highly correlated (r^2=0.756-0.882) for the four quadrants of the visual field. There was a strong correlation of MHR & PSD.	Rarebit is rapid & detects severe VFL in patients with occipital lobe lesions. MHR on rarebit perimetry is highly correlated with MD on the HFA.
Houston *et al*. 2010.	15 (29 eyes): Participants within a hospital.	To test the feasibility of bedside testing with rarebit perimetry compared to clinic based SAP.	Tested on: Rarebit perimetry at bedside. HFA in clinic. Measures of: Defect detection. Participant preferences.	There was 72% correlation in defects. 5/29 fields had defects on rarebit that were not found with SAP. Participants preferred the convenience of rarebit to SAP.	Rarebit perimetry is convenient for bedside testing & is sensitive to the visual field defects found with SAP.
Wall *et al*. 2010.	Tested once a week for five weeks: 32: Glaucoma. 20: Control. Different participants tested at baseline & at a separate sitting: 120: Glaucoma. 60: Control.	To determine associations between size III on SITA Standard, size V on FT, Matrix & motion perimetry. To compare the effective dynamic ranges.	Tested on: HFA 24-2 SITA Standard with size III. HFA 24-2 FT with size V. Motion perimetry. Matrix perimetry. Measures of: Dynamic range. Discriminable steps.	There was a linear association between size III & size V until 20dB, & with motion & Matrix perimetry up to 25dB. Upper bands were similar for all tests. Size V possessed a lower floor & more discernible steps.	Size V has greater dynamic range & more discernible steps.
Bentley *et al*. 2012.	For the validity study: 77: Control. 53: Glaucoma.	To determine the validity of the UFOV in healthy controls & glaucoma patients (sub-study).	Tested on: UFOV. HFA 24-2 SITA. Measures of: MD from SITA 24-2. UFOV score.	There was a link between MD & UFOV score. The link explained 46% of variability in selective attention.	These examinations test different aspects of the visual field. UFOV & age are associated in controls. MD can explain less than 50% of variability in selective attention.

Wroblewski *et al*. 2014.	80: Including glaucoma, suspect glaucoma, neuro-ophthalmologic-al diseases & control.	To report the development & clinical testing of a compact head-mounted & eye tracking perimeter (VirtualEye).	Tested on: SITA 24-2 or 30-2 Fast. VirtualEye (in two modes- grasp & manual). Measures of: Participant preference. Pointwise comparison.	Mean difference between manual VirtualEye & SAP was approx. 1dB (SD=5.6dB). For the controls there was a 4dB mean shift between VirtualEye (both modes) & SAP. Differences were more pronounced in the upper ranges (28 to 32dB). For comfort & ease, participants preferred VirtualEye to SAP.	Mean difference between SAP & VirtualEye is 4dB in normal participants. Participants prefer VirtualEye for comfort & ease.
Brouzas *et al*. 2014.	7 (9 eyes): Participants with various VFL pathology.	To compare results of a video-projector perimeter with HFA.	Tested on: HFA. Video-projector method. Measure of: Point-to-point correlation.	Point-to-point correlation ranged from 0.91 to 0.75 for the 9 eyes.	Video-projector method had high correlation with HFA.
Lowry *et al*. 2016.	63: Glaucoma. 30: Control.	To determine receiver operating characteristics of Peristat for detecting varying degrees of glaucoma. To determine correlation between Peristat & HFA.	Tested on: HFA SITA Standard. Peristat. (In random order within 3 months). Measures of: Glaucoma detection in three severity groups of glaucoma. (Mild=-16.7dB. Moderate=-21.7dB. Severe=-26.7dB as measured on Peristat).	The Peristat AUC for mild or worse defect=0.81, 0.77, 0.77. & moderate to severe=0.87, 0.85, 0.85 for the mild, moderate & severe categories respectively. Abnormal plot correlation between Peristat & HFA ranged from 0.55 to 0.77.	Peristat has reasonable AUC's & correlates with HFA for abnormal plots, but this varies on severity.

Table. 1-2. Comparative aspects of methodologies compared on or with the HFA. Evaluations on the HFA presented first. Comparisons with different instrumentation presented second. Studies for each section provided in date order. There are no known evaluations or comparisons of the ROS. CI=confidence interval. SD=standard deviation.

1.7. Incidental Factors Influencing the Differential Light Threshold.

1.7.1. Noise

Visual field results are affected by noise. Fluctuations in threshold can impact upon detecting sensitivity loss (Fankhauser & Bebie. 1978) and hence, noise can mask disease and disease progression. Perimetry is reliant on responses that are psychophysical and in essence, variability is inherent (Bergin. 2011). The sensitivity of a test is related to its variability and defects in the visual field can only be established if they exceed the variability that is present within perimetry (Artes *et al*. 2003, Spry *et al*. 2000). Noise can occur across testing sessions (Nouri-Mahdavi *et al*. 2011, Wroblewski *et al*. 2014) and within testing sessions.

1.7.2. Long Term Fluctuation.

This is the variability in threshold sensitivities when testing occurs at different sessions (Nouri-Mahdavi *et al*. 2011, Wroblewski *et al*. 2014) and is further discussed in section 4.1.

1.7.3. Short Term Fluctuation.

This is the variation within the same testing session (Wroblewski e*t al*. 2014, Henson. 2001).

The following factors, along with the variance in the behaviour of the retinal cells (Wyatt e*t al*. 2006), influence the variation of the visual field test result.

1.7.4. Patient's Response, Psychological Status and Fixation.

In any automated visual field test the reliability of the results can be affected by the subjective nature of the patients' response (Delgado *et al*. 2002) giving rise to variability in the test results. The alertness of a patient and hence the reaction to the visual stimulus (Nouri-Mahdevi *et al*. 2011) can be affected by the patients' psychological status (Wroblewski *et al*. 2014). False-positive results can lead to an underestimation of the VFL (Artes *et al*. 2002). Fixational eye movements will also increase retest variability of the sensitivity threshold (Wyatt *et al*. 2007).

1.7.5. Clinician Conduct.

How the test is conducted can also lead to poor reliability of the results (Delgado *et al*. 2002). The conduct of the practitioner can be linked to the cooperation of the patient. Clear instructions and encouragement will have an impact producing a more reliable test (Cubbidge. 2005) as will the attention of the clinician on the monitoring of the test.

1.7.6. Fatigue.

It is currently well known that patients suffer fatigue (Tattersall *et al*. 2007) and find perimetry tiring. The fatigue has been stated to occur 3 minutes into the examination (Cubbidge. 2005) which can lead to depression of the visual field. Longer test duration influences the resulting sensitivity. FT perimetry has been shown to yield lower sensitivities in patients from the age of 20 compared to the faster SITA Standard examination, which may be due to fatigue (Wall *et al*. 2001). Fatigue can be more apparent in older patients which is discussed in section 1.7.9. Older individuals are more likely to have pathology and VFL compared to their younger counterparts. Those with neurological defects can also tire easily due to the underlying illness (Chaudhuri & Behan. 2004).

1.7.7. Attention.

Another factor that can increase variability and reduce sensitivity is lapses in attention. (Miranda & Henson. 2008). Attention is usually ascertained by the amount of false negative results on the perimetry printout. However, the amount of false negative results are also associated with an increase in VFL and in these individuals it does not necessarily make a fair estimation of the patients attention (Bengtsson & Heijl. 2000).

1.7.8. Learning Effect.

Visual field results can suffer from the learning effect (Birch *et al*. 1995). This is a phenomenon where short term fluctuation improves with repeat testing (Tattersall *et al*. 2007). Participants examined on SITA 24-2 have shown to improve in test time, MD and false negative errors upon a second testing session performed on the same day, which were more evident in the peripheral field (Castro *et al*. 2008). Sensitivity has been shown to increase in eccentricities greater than 30º in those with retinitis pigmentosa with practice (Wood. 1987). Participants using the UFOV have been found to be constant in performance after the second test and significant learning effects have been demonstrated by the second visit in those with CFL with a mean of 0.4-0.5 dB (Acton. 2010). It is therefore possible with practice that patients can improve their perimetry result (Hitchings. 1994). It is therefore recommended that the baseline test and possibly a subsequent test is not used to consider progression in VFL (Bentley *et al*. 2012).

1.7.9. Opacities in the Media.

Stray light due to media opacities can lead to false referrals for glaucoma (Bergin. 2011) and thereby impact the specificity of a perimeter. Faunkhauser & Haeberlin (1980) determined that stray light underestimates scotoma depth. The stray light effect

increases at higher luminance levels and is found to spread beyond the geometrical parameters of targets subtending 0.431º. The stray light mostly originates from the optical imaging system as opposed to the perimeter bowl. It impacts by falsifying the level of sensitivity found by a perimetric examination and limiting the useful dynamic range in perimetry (Faunkhauser & Haeberlin. 1980).

1.7.10. Age and Sensitivity Thresholds.

Age causes a decline in functional vision (Wood & Black. 2016) in both the central and peripheral retina (Gardiner *et al*. 2006). Changes include a reduction in cone mediated vision, reduced pupil size, clouding of the crystalline lens and a reduction in rod sensitivity (Neelam e*t al*.2009). These changes result in the elderly possessing a reduction in sensitivity across the entire visual field (Esterman. 1985, Maynard *et al*. 2016). Reduction in rod sensitivity can affect visual performance in low light levels (Reyes *et al*. 2013). The reduction in photoreceptors transmitting a signal also increases variance (Wyatt e*t al*. 2006).

Some models assume a constant decrease across the visual field of approx. 1 dB per decade, with individual variation among the normal population being a constant. A perimeter that decreases linearly by a given amount per decade of life assumes that the reduction in the hill of vision profile reduces in a uniform manner (Cubbidge. 1997). The model constructed by Heijl and colleagues (1987) determined that the sensitivity decreases linearly and continuously, but the rate per change, per location differs. Hence, there are alterations in both the height and the shape of the visual field with age. The model does not assume that the normal variability across the normal population is constant across the visual field, and neither is the inter-test variability, it is allowed to vary with location (Heijl *et al*. 1987). Retinal illumination will be 20x (1.3 log unit) greater in a young member of the population (8mm pupil size) compared to an older member of the population (2mm pupil size) without cataract (Swanson e*t al*. 2014), therefore, due to pupil size and normal lens ageing, there can be a 20-fold variance when administering perimetry to patients. It is reported that there is a reasonable correlation between ageing and sensitivity for SAP (Gardiner e*t al*. 2006).

Narrowing of the vertical visual field has been shown when elderly people utilise compensatory movements descending stairs in lower levels of luminance (Kasahara *et al*. 2007).

In addition, elderly patients find perimetry tiring and this may have a bearing on results. A fatigue effect has been found in patients aged 60 when performing successive SITA Standard examinations, with the second test yielding small decreases in sensitivities

than the first test. Furthermore, the longer duration FT examination, although bearing lower sensitivity for all participants from the age of 20 than the first SITA test, also yielded lower sensitivities compared to the second SITA test only in the 70 year old group (Wall e*t al*. 2001). Thereby the fatigue effect increases with age.

Acquired visual impairments, such as AMD and glaucoma, possess age as a factor (Quigley. 1994, Crabb *et al*. 2010, Rijn. 2002) and hence the patient will have reduced sensitivity across the visual field in addition to any functional visual loss caused by the pathology. Johnson and colleagues (1983) screened 10,000 volunteers and found the incidence of VFL was approximately 3% in those aged 16-60 with an increase between the ages of 61-65yrs and incidence rising to 13% in those >65yrs which is 4x higher than the VFL found in the younger age groups. This was effectively 1 in seven people within this age group (Johnson e*t al*. 1983).

1.7.11. Other Incidental Factors.

Other factors that can affect visual field test results include room lighting, day of test, time of test, inappropriate refractive correction, artefacts, the size and presentation time of the stimulus (Heijl *et al*. 2012). A variance in stimulus size can produce a result of absolute (smaller stimulus) to relative scotoma (larger stimulus) which is discussed in more detail in section 1.15.3. Other artefacts that can provide variable and inaccurate results include angioscotoma whereby the blood vessel is enlarged causing a missed stimulus, variations in retinal topography giving rise to refractive scotoma (Henson. 2001), high plus prescriptions which reduces the field of view, the rim of the spectacle or trial lens, physiological ptosis (Heijl & Paella. 2002) and pupil size variation (Cubbidge. 2005).

1.7.12. Test-retest variability in normal fields.

All of the aforementioned incidental factors that influence the differential light threshold give rise to variability of the recorded sensitivities and MD values within the normal observer. Artes *et al* (2003) when comparing multi-stimulus ST, ST and FT strategies, utilised 109 FT examinations from normal controls to determine the pointwise 90% test-retest intervals of FT perimetry. With an initial sensitivity estimate of 30 dB, the sensitivity at a subsequent test is estimated to fall within the range of 26 dB to 32 dB 90% of the time. This range provides an expected test-retest variability of up to 6 dB within the normal observer. Gardiner *et al* (2006b) looked at test-retest variability amongst normal participants on various methodologies including 24-2 FT testing on the HFA. With 100 normal participants, their data illustrated that test-retest variability in sensitivity, averaged across all locations of both eyes, was approximately 1.65 dB. This

was the equivalent of 5% of the instrument's dynamic range. Their data also showed that test-retest variance increased with eccentricity. The mean sensitivity across all locations increased to 1.98dB (approximately a further 1% of the instruments dynamic range) beyond 12º of fixation. Tattersall e*t al* (2007) looked at the long-term fluctuation in stable visual fields over a period of three years. They assessed the variability of five examinations performed on the HFA using a 24-2 examination. In this study, they had recruited 68 participants who had normal fields. They found that those with no visual field defect possessed an average variation in MD of 0.3dB across the five examinations (Tattersall *et al*. 2007).

Gardiner *et al* (2006b) also plotted data to establish the learning effect. Their data illustrated that participants who were 46 years or below, had a learning effect of 0.33 dB (1% of the dynamic range) for central locations and approximately 0.16 dB within the peripheral field (approximately 0.5% of the dynamic range). The learning effect, in those aged 47 or above, was minimal. This was considered to be due to the experience older participants possess in performing perimetry (Gardiner e*t al*. 2006b). Within the normal observer, age also influences the visual field result. Some models assume a constant decrease across the visual field of 1 dB per decade of life (Cubbidge. 1997).

Therefore, values within the normal observer being examined by SAP on the HFA can be expected to vary upon retest up to 6 dB at individual locations. When averaged across all sensitivities of the visual field, there can be a mean variance on retest of 1.65 dB, and with increasing eccentricity this can be expected to rise to 1.98 dB. The confounding factor of the leaning effect can be expected to account for 0.33 dB in variance of the average values across the normal central visual field and accounts for 0.16 dB within the field beyond 12º from fixation. In the HFA, the MD index, which is a weighted value, rather than the true calculated average across the visual field (Tattersall *et al*. 2007), can be expected to show a change of 0.3 dB on retest in the normal observer. Age can be expected to account for a 1 dB decrease in sensitivity across the visual field per decade of life.

1.8. Perimetry in Cases of Visual Field Loss.

Visual field testing is subjective and considered highly variable (Kim *et al*. 2005). Variability makes determining defects and progression a difficult task (Wyatt *et al*. 2007). Individuals can find perimetry difficult to undertake, particularly if they have VFL (Bengtsson & Heijl. 2000). Increased retest variability increases in areas of reduced sensitivity (Wall e*t al*. 2008, Henson e*t al*. 2000, Turpin *et al*. 2007, Gardiner. 2003)

such as in the case of glaucoma (Gardiner *et al*. 2006, Miranda & Henson. 2008, Artes *et al*. 2003, Heijl e*t al*. 1989) with long term fluctuation found to be more pronounced in those with glaucoma than in patients without the disease (Viswanathan *et al*. 2010, Birch e*t al*. 1995) and reaches higher levels in the more advanced stages of the disease compared to pre-perimetric changes (Kim e*t al*. 2014). The MD in those with glaucoma has been shown to increase in fluctuation when the defect increases (Tattersall *et al*. 2007). Those with glaucoma show more test-retest variability on the UFOV test, having wider limits of agreement than those without the disease (Bentley *et al*. 2012). Fluctuations occur in early glaucomatous field loss (Crabb *et al*. 1995, Haley. 1993, Henson. 2001) and in those with ocular hypertension where there is reduced sensitivity (Henson *et al*. 2000). It follows that a decrease in retest variability is found in areas of higher sensitivity (Artes e*t al*. 2002, Chauhan & Johnson. 1999, Heijl *et al*. 1989). Henson *et al* (2000) equated the variation in visual field to the functional ganglion cell density (Henson *et al*. 2000). Fluctuations in sensitivity can be found even in reliable test participants who have VFL (Henson. 2001). It is considered that this can reach up to 15 dB and therefore makes early detection (Nouri-Mahdavi *et al*. 1997, Swanson *et al*. 2014) and a decision on subsequent progression (Vesti *et al*. 2003) of VFL difficult (Henson. 2001). In areas with moderate sensitivity loss retest variation has produced normal sensitivities to absolute scotomas in glaucomatous individuals (Heijl *et al*. 1989). There are various methods aimed at determining glaucomatous progression and it is thought that each methods ability to determine progression is affected by the intratest and intertest variation to some degree (Vesti *et al*. 2003). Variation therefore remains an obstacle to accurately determining progression (Birch *et al*. 1995).

In pathologies other than glaucoma, ascertaining progression is also complicated. Fluctuations also occur in optic neuritis (Henson *et al*. 2000). Patients with optic neuritis demonstrated varied retest results, providing results of normal one week to hemianopic the following week (Heijl *et al*. 2012) and variation in results for same-day examination has been demonstrated in patients with optic neuritis, which was not limited to the severity but also the pattern of the VFL. Pattern alterations for same day testing ranged from quadrantanopic to hemianopic. (Wall *et al*. 1998). Where stimuli fall within a patient's area of scotoma it gives rise to frustration due to increased difficulty and time establishing the patient's threshold with static perimetry (Schiefer *et al*. 2001)

Retest variability is common to more than one type of testing strategy. FT, SITA Standard (Wall *et al*. 2008) and SITA Fast have all shown increased retest variability

with lower sensitivities (Artes *et al*. 2002). Baseline measurements between 8-10 dB can vary from 4-20 dB (mean 14 dB) when retested on SITA Standard (Gardiner. 2003). Increased variability presents at locations of localised loss and at edges of defects (Henson. 2001). Using FT perimetry when there is an inaccurate starting point, which can occur at the edge of a scotoma, has demonstrated that there is higher variability in glaucoma patients (Turpin *et al*. 2007). SAP when utilising a FT methodology of 4-2-2 dB staircase procedure has shown to overestimate sensitivity value which becomes more pronounced in areas of damage (Spry *et al*. 2003). Retest variability using frequency doubling perimetry (FDP) has been found to be higher than in SAP and Pulsar, and Pulsar has been found to have more stability than SAP using tendency- orientated-perimetry, in early glaucoma and ocular hypertension (Gonzalez-Hernandez e*t al*. 2007).

People with VFL can adapt their visual behaviour to compensate. However, visual field testing does not take into account eccentric viewing which can be adopted by individuals to maximise their visual function. Patients with central scotomas have the issue of the fixation target being within the area of scotoma and hence it can be difficult to maintain fixation and they can even view eccentrically (Esterman. 1985), this can lead to the results showing a large blind spot instead of the central scotoma (Nowakowski. 1994). Those patients with hemianopia can demonstrate larger visual movements and compensatory head rotations in order to provide awareness of the visual environment on the non-functioning side (Esterman. 1985).

1.8.1. The Repeatability of Visual Fields in Those with Visual Field Loss.

Test-retest data has previously been collected in those with glaucoma, with some data collected also including participants with optic neuritis and ocular hypertension. The study conducted by Artes *et al* (2003) utilised 342 pairs of visual fields to compile test-retest data from participants with glaucoma, to determine the pointwise 90% test-retest intervals of FT perimetry. With an initial sensitivity estimate of 10 dB, their results show that the sensitivity at a subsequent test is estimated to fall within the range of 0 dB to 24 dB ninety percent of the time. This range provides an expected test-retest variability of up to 14 dB in participants with glaucoma (Artes *et al*. 2003). Henson *et al* (2000) found a smaller range in test-retest variability in their study. They examined 71 participants with either glaucoma, ocular hypertension, optic neuritis or normal fields using the HFA 24-2 FT program. The chosen examination locations had 20 exposures to a test stimulus. In this study, they plotted the response variability. Their data showed that if a location has an average sensitivity of 35 dB, the test-retest variability was on average 1.5 dB. At locations possessing an average sensitivity of 10 dB, the response

variability increased to approximately 11 dB (Henson *et al*. 2000). Gardiner *et al* (2006a) wished to present the principle of divergent dysfunction as an explanation for variability in those with visual field loss. Within this study, they collected test-retest data from 63 participants with glaucoma using the HFA's FT strategy. Each participant was examined five times over the course of one month. They found that the variability peaked within the best available sensitivity estimates of 8 dB to 12 dB, presenting a test-retest variability average of 5.91 dB (Gardiner *et al*. 2006a). Spry *et al* (2003) collected test-retest data from seven participants with early to moderate glaucoma, also using the HFA's FT strategy. They found that the average test-retest variability was 6.2 dB (Spry e*t al*. 2003).

Artes *et al* (2002a) also plotted the 90% test-retest estimates for SITA Standard from four examinations, across a period of four weeks, conducted on 49 participants with glaucoma. They found that when the initial baseline sensitivities were between 10 dB to approximately 18 dB, the 90% test-retest limits ranged from 0 dB to approximately 25 dB (Artes *et al*. 2002a).

Tattersall e*t al* (2007) looked at the long-term fluctuation in the MD index in stable visual fields over a period of three years. They assessed the variability of five examinations performed on the HFA's 24-2 FT examination. Within this study, they had recruited participants who had glaucomatous fields with field loss of varying degrees. Seventy-one participants were classified as possessing mild defects, 34 participants were classified as possessing moderate defects, 17 were classified as possessing severe defects and 12 participants were classified as having end-stage disease. They found that those with a mild visual field defect possessed an average variation in MD of 0.4 dB across the five examinations. The average variation in MD increased to 0.8 dB, 1 dB and 1.3 dB in those with moderate, severe and end stage defects respectively (Tattersall *et al*. 2007).

Therefore, the expected variability values at individual locations, in areas where the visual field is estimated to have a sensitivity between 8 dB to 12 dB, can be expected to be anywhere between 5.91 dB up to 14 dB in those with glaucoma on FT and up to 15 dB on SITA Standard testing strategies, when the estimated sensitivity is between 10d B to 18 dB. Based on Tattersall and colleagues (2007) study, the MD index can be expected to vary from 0.4 dB in those with mild glaucomatous defects and up to 1.3 dB in those with end stage disease.

1.9. Visual System and Driving.

Vision is a cyclic process of top-down and bottom-up processes (Lim & Liu. 2009) and the act of driving is a complex task not limited to viewing straight ahead and identifying a bright stimulus in the periphery. It is a task that requires hand-eye coordination (Ren *et al*. 2014). Head, eye and body movements are utilised to move items of interest, captured by covert attention, from the periphery to the fovea (Raj *et al*. 2005, Crundall *et al*. 1999). It is a task that also requires attention which is closely linked to eye movements (Hoffman & Subramaniam. 1995) and drivers will move their eyes to the chosen attentional target. Objects exceeding 15-20º from the midline will give rise to a tendency to turn the head in order to re-fixate (Rubenzer *et al*. 2010).

Functional field of view is an area within which a hazard can be seen by the eye when maintaining attention on a target without the use of head or eye movements. This is a dynamic field of view which can change in size and alter its shape dependent upon many factors such as age, anxiety, visual clutter and increasing or decreasing processing demands within the visual system. The size of the functional field of view reduces with increasing processing demands but has also shown to have a learning effect whereby individuals learn to process foveal stimuli prior to peripheral reducing the impact of a reduction in the functional field of view (Crunall *et al*. 1999).

Gaze, smooth pursuit and saccades are the predominant eye movements that occur when driving.

1.9.1. Smooth Pursuit and Saccades.

Scanning of a visual scene has been estimated to utilise gaze and smooth pursuit 80% of the time (Manor & Gordon. 2003, Parkhurst & Niebur. 2003). Smooth pursuit allows a driver to keep a moving object on the fovea and to track it. This allows drivers to view road signs even when the driver is in motion. However, the motion must not be too fast in order for smooth pursuit to occur. Where the driver is moving too fast to track objects with smooth pursuit a saccade will occur.

A saccade is an eye movement that allows change in fixation. These movements are quick, but do need time to prepare and initiate (Rubenzer *et al*. 2010). Large saccades are required where contrast uncertainty has reduced with increased eccentricity (Raj *et al*. 2005). Microsaccades are small magnitude saccades. Drifts are curvy movements, which are slow and occur between saccades and microsaccades (Stasi *et al*. 2015).

1.9.2. Age and Driving.

Increased age has been shown to increase the risk of an at fault motor vehicle collision (MVC). Those aged 78+ have a 2.11x risk of an at fault MVC (Ball *et al*. 2006). It is

considered that a contributing factor other than a reduction in sensory function is the cognitive decline that increases with age (Wood & Black. 2016), that leads to poor driving performance and the subsequent increase in accidents amongst older drivers. Poor scores on a mental status test are linked to a 3-4x increase in MVCs, with those being at junctions increasing to 15x more likely (Owsley *et al*. 2018). This is further compounded by the fact that skills are lost to enable safe driving when self-regulation occurs (Keay *et al*. 2012).

1.10. Fitness-to-drive and Visual Requirements.

Vision is a sense that is important for driving (R.C.O. 2013, Kaleem *et al*. 2012. Racette *et al*. 2005, Coeckelburgh *et al*. 2004) and is considered the most important of all the human senses (Hills. 1980) 90% (Bach *et al*. 2009) of information required for the solution of driving tasks is visual (Rittger *et al*. 2014). Within a rapidly changing environment there is a requirement to assess the threat of these changes efficiently in order to avoid a collision (Rumar 1990). Although many aspects of vision are important for driving, such as VA, contrast sensitivity, depth perception and colour vision it is the persons VA, which should be 0.3 logMAR or better (Coeckelbergh *et al*. 2004) and the visual field (Racette *et al*. 2005) that are deemed important when assessing a person's fitness-to-drive. A deficit of visual field can hinder detection of peripheral objects and impacts on speed and distance judgements (Ayala. 2012).

The Driving Vehicle Licensing Agency (DVLA) is the statutory body in the United Kingdom (U.K.) for vehicle licensing. Utilising recommendations provided by the Royal College of Ophthalmologists (RCO), they set the current visual requirements for driving (Owen *et al*. 2008).

The Esterman Visual Field Test (EVFT), both recommended by the American Medical Association (A.M.A.) and recognised by the International Perimetric Society, is commonly used for testing a patient for visual disability (Heijl *et al*. 2012, Owen *et al*. 2008). The EVFT is currently the visual field test conducted to determine whether drivers have a visual field that complies with the DVLA standards (DVLA. 2014).

In the U.K., the criteria for passing the EVFT are as follows.

> 'There should be no 'significant' loss within the central 20° zone or within a 120° zone along the horizontal meridian' (Owen *et al,* 2008. P. 2449, Muqit *et al*. 2010. P. 1137).

A 'significant' loss centrally is defined as:

> 'A cluster of four or more contiguous points that is either wholly or partly within the central 20° area. Loss consisting of both a single cluster of three contiguous

missed points up to and including the central 20° from fixation and any additional separate missed point(s) within the central 20° area. Central loss of any size that is an extension of a hemianopia or quadrantanopia' (Chisholm. 2008b. P. 41, Chisholm *et al*. 2008a. P. 225, Rauscher *et al*. 2007. P. 22, Crabb *et al*. 2004. P. 1193)

A field that possesses the above is deemed as a failure to meet the requirements (Crabb e*t al*. 2004).

In addition, the extent of the visual field should be at least 50º nasally and temporally which rules out homonymous and bitemporal defects as being classed as fit-to-drive if they are close to the fixation point (DVLA. 2014)

Defects that will be disregarded when assessing the visual field for driving are:

'A cluster of up to three adjoining missed points, unattached to any other area of defect, lying on or across the horizontal meridian. A vertical defect of only single point width but of any length, unattached to any other area of defect, which touches or cuts through the horizontal meridian' (DVLA. 2014. P. 50).

The target required for visual field examination, is to be the equivalent of a white Goldmann III4e (Ayala. 2012) (4mm^2 target (Manji & Plant. 2000) at maximum illuminance and low background luminance) setting (DVLA. 2014).

Additionally, the DVLA provide exceptionality rules for visual fields. Some subjects may be eligible to reapply if a non-progressive defect, caused by an isolated incident, has been present for 12 months, with no other progressive pathology present. There must be also be full functional adaption that is clinically confirmed (RCO. 2013). The applicant must also have binocular vision and no other impairment of functional vision, which includes glare and reduced contrast sensitivity. Uncontrollable diplopia should not be present (DVLA. 2014). Individuals are also allowed to apply for a provisional licence in a dual-controlled vehicle if the visual field defect is static and there is adaption to the defect (DVLA. 2011)

Currently in the U.K. the assessment at licence issue is the number plate test performed by an employee of the Driver and Vehicle Standards Agency. The onus is then positioned on the qualified driver to perform self-assessment (European Council of Optometry and Optics. 2011) and report to the DVLA any diagnosis that can impact on vision (RCO. 2013). Once reported a visual field test may be requested by the DVLA to assess fitness-to-drive (DVLA. 2014, Owen *et al*. 2008), following a completed medical questionnaire and obtainment of medical information from the driver's general practitioner. With the onus being on the driver, perimetry assessment is not an automatic requirement of driving licensure in the U.K. Therefore, there is an opportunity for VFL to go undetected. In 1980 a mass visual field screening project

using the Fieldmaster Model 101-PH found that 5% of 1,027 eyes of people who held driving licenses in California had field loss that was considered significant (Keltner & Johnson. 1980). Manji and Plant (2000) found that out of 24 participants with visual field defects only one participant had VFL symptoms, yet 5 out of the 24 had defects that would fail the visual field driving criteria. (Manji & Plant. 2000).

1.11. The Esterman Visual Field Test.

The binocular (Ayala. 2012) EVFT examines 150º of the bi-temporal visual field. It is a ST test examining each of the 120 (Jampel *et al*. 2002) white test locations (Zeiss. 2014), Ayala. 2012) once (Chisholm. 2008b, Rauscher e*t al*. 2007) with a stimulus of constant size and intensity across the entire visual field (Rijn. 2002). If a patient fails to respond to the presented stimulus in any one location the stimulus is presented again, if the patient fails to respond for the second time this is recorded as a defect (Crabb et al. 2004, Owen *et al*. 2008), which simply informs that the location measures less than 10 dB. The test is in units to score visual fields in percentages (Esterman. 1968). Each unit is represented as a dot (Esterman. 1967). If the dot is unfilled this indicates the observer detected the stimulus at that location. If the dot is blacked out this indicates the observer failed to see the stimulus at that location. The resultant percentage is known as the Esterman efficiency score (EES) and is still the gold standard for binocular visual field examination (Rauscher *et al*. 2007).

The white stimulus presented is Humphrey size III at 10 dB (Heijl *et al*. 2012, Crabb *et al*. 2004, Ayala. 2012) against a background luminance of 31.5 asb. This relates to the Goldman size III4e. On automated perimeters the ½ degree white standard of kinetic perimetry relates to 4mm^2 white at 1000 asb presented with a background luminance of 31.5 asb (Esterman. 1983).

Figure 1-5 presents the visual sensitivity in dB and the location of the 10 dB stimulus intensity within this range.

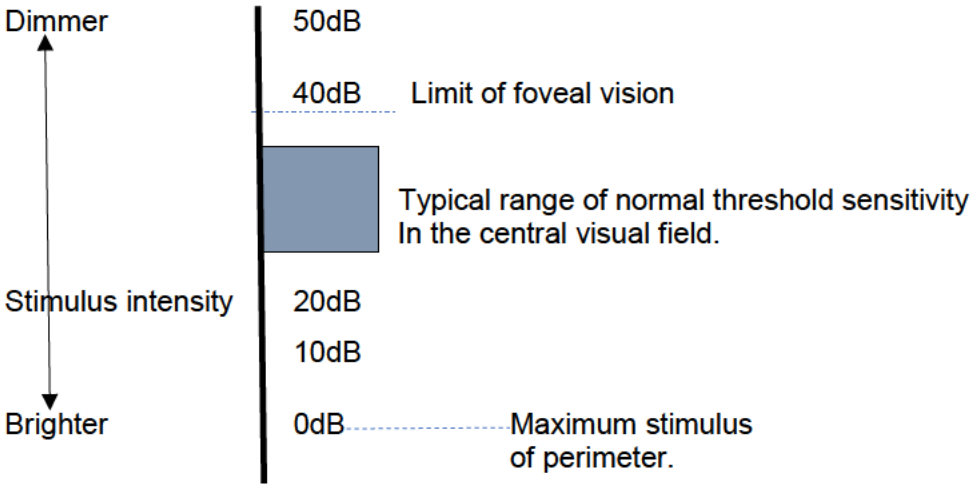

Figure 1-7. Visual sensitivity in decibels (dB). The grey square indicates the typical range of normal threshold sensitivity in the central visual field. (Adapted from Heijl *et al*. 2012. P. 25)

Table 1-3 relates the stimulus size and stimulus terminology between the Goldmann and the HFA perimeter.

Goldmann	HFA	Physical size
1114e	III	4mm^2

Table 1-3. Stimulus size terminology. Equivalents provided for the Goldmann and HFA perimeters.

The locations are not presented in uniform degree spacing but vary dependent upon if they are in the upper or lower field and near the horizontal or vertical meridian. The locations are spread +/- 75° horizontally, 35° superiorly and 55° inferiorly (Chisholm. 2008b). In the central 20º area the EVFT tests 24 points (Crabb *et al*. 2004).

Figure 1-6. presents the plot of the x and y coordinates in degrees. The numerical format for each stimulus location is provided in appendix 1.

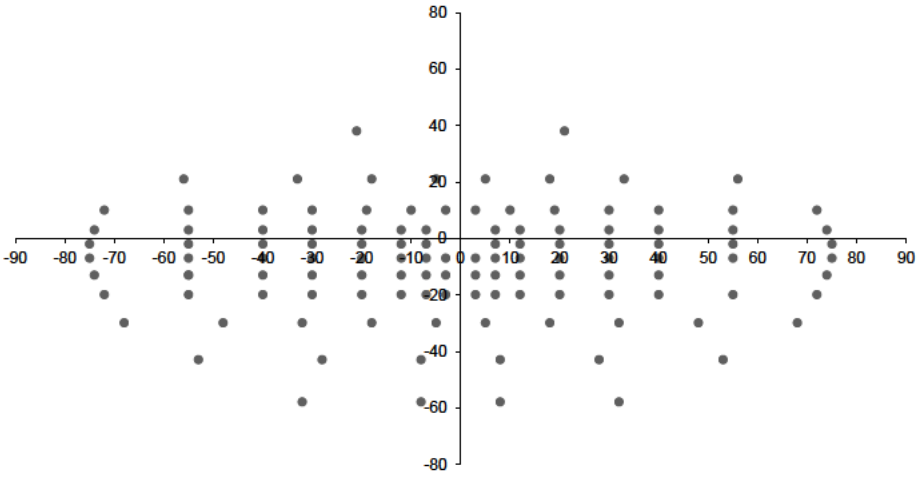

Figure 1-8. Plots of the x and y coordinates (degrees) of the EVFT binocular grid. The test consists of 120 points examining more than 150 degrees.

Esterman's rationale and development of the EVFT grid can be established within his papers (Esterman. 1985, Esterman. 1967, Esterman. 1968, Esterman. 1983, Esterman. 1981, Esterman, 1982) he published on the topic from 1967-1985.

The test was designed to account for the areas considered most useful to the individual, i.e. a measure of functional vision (Esterman. 1967). Although Esterman in his 1967 paper, mentions driving safety as one of the reasons for the design of the grid (Esterman. 1967), it is important to note that this plot was not designed with only driving in mind (Rijn. 2002) but for general mobility. The reason why more stimuli are placed in the lower visual field is to account for activities such as walking, reading and eating. For driving, hunting, sport and combat the periphery of the field was considered important near the horizontal. It was designed to assess function and the usefulness of a patient's field. It is considered that the dominance of the lower field locations crosses over the dashboard and therefore is not useful for locating hazards in the driver's field of view (Rauscher *et al*. 2007). However, support for the lack of dominance of stimuli in superior field locations for driving was found in a study (Vega *et al*. 2013) using a simulator and eye tracker published in 2013. The 6 glaucoma participants and 8 controls rarely looked at the top or the bottom of the simulator screen.

The central 3º of the visual field was deliberately omitted, Esterman (1967) considered its importance more suitably expressed as visual acuity and impractical to express mathematically or graphically (Esterman. 1967).

The relationship of the grid was ascertained from trials, and was sized to fit the criteria set for the peripheral field plotted with a 0.5º white target (equivalent to Goldman size

III) by the A.M.A. on Mental and Physical impairment. It was weighted dependent upon what was considered important to the individuals function (Esterman. 1968), namely the central and inferior field (Jampel *et al*. 2002). Esterman (1981) felt the previous A.M.A. system of scoring could provide identical scores for the same square area of VFL whether present in the upper or the lower field. Although the score was the same, the function would not be identical due to the position of the VFL. Esterman therefore developed a weighting system corresponding to the location of the defect. One unit is a smaller area where it is considered to be a valuable part of the visual field and a larger area where the value of the area was considered less important (Esterman. 1981).

Prior to automation of this grid, kinetic perimetry was used (Jampel *et al*. 2002) and the target used was a 2mm white diameter disc presented at 1m with illumination of 7 foot-candles. However, Esterman in 1967 did consider that the grid would lend itself easily to automation (Esterman. 1967). Figure 1-7 presents the plots following radial coordinates. Figure's 1-8 and 1-9 present the grid which was to be used with a 1 metre tangent screen.

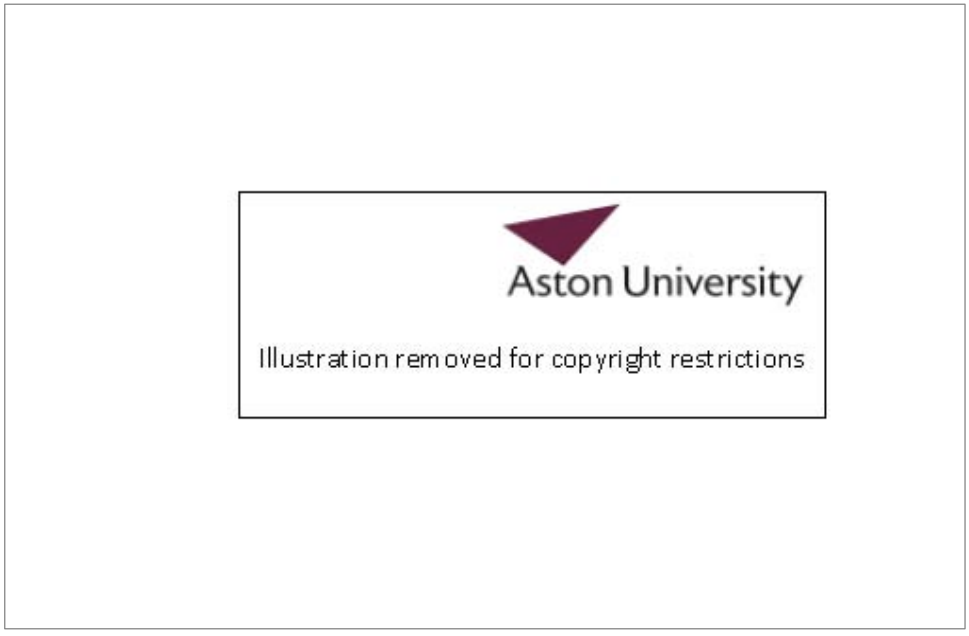

Figure 1-9. **The radial coordinates of the monocular Esterman scale**.(Esterman. 1967. P. 781)

Figure 1-10. The Esterman grid used with a 1m tangent scale (Esterman. 1967. P. 781). Rectangles represent the 1 unit zones.

Figure 1-11. The Esterman grid used with the 1m tangent screen with 1 unit zones removed. The grid utilised with the removal of the 1 unit zones for the 25º field (Esterman. 1967. P. 781)

Figure 1-12. The Esterman grid adapted for the peripheral field (monocular). The weighting of 1 unit has been assigned dependent upon the area and its usefulness to function (Esterman. 1981. P. 377).

This unit of scoring was adapted for the peripheral field with one unit again weighted according to the considered importance of the area. Each dot represents 1 unit. Each unit represents the location a stimulus is presented (figure 1-10).

The final design of the grid was ascertained by evaluating three hundred glaucoma patients over a period of three years. The study was conducted at the Manhattan Eye, Ear and Throat hospital. The final grid chosen was the 35th designed. Trialled and approved by the American Committee on Optics and Visual Physiology, their recommendation to the A.M.A. made it the official standard. It was subsequently taken up by Belgium and France (Esterman. 1981).

Combining monocular fields was considered not to provide accurate results due to the overlap of the fields, with non-seeing areas compensated for by the seeing area in the other field (Esterman. 1985). Therefore, a way of assessing binocular fields was considered. This was achieved by devising a binocular perimetry grid in 1982. The year nineteen eighty-two was the benchmark date set by the International Council of Ophthalmology who required an international standard for the evaluation of binocular peripheral visual fields (Esterman. 1983).

The binocular grid expanded the original monocular 100 unit grid into a 120 unit grid. This still scored the patients functional field in percentage. In figure 1-11 the rectangle

on the combined binocular field has 50 units in total; external to this are 11 units in each quadrant of the superior field and 24 units in each quadrant of the inferior field, hence a total of 70 units in the periphery lying outside the rectangle. The target chosen for the Goldmann-type perimeter was a $4mm^2$ target at maximum illuminance and low background luminance (III4e). This was a size III white stimulus presented at 10 dB (Owen *et al*. 2008), and corresponded to the target originally presented at 7 foot-candles (Esterman. 1982) (75.32Lux).

Figure 1-12 is a print out of an EVFT that fails in accordance with the current DVLA criteria. The EVFT was performed on an automated perimeter, the HFA II model 720 (Humphrey Instruments, Dublin, USA). The horizontal and vertical indicators are separated by 10º. The central circle highlights the central 20º zone. The HFA performs the scoring (Esterman. 1981) and provides it as the EES.

Eventually the use of the EVFT spread to more countries and it became the standard binocular visual field test used by the DVLA for the assessment of fitness-to-drive in the U.K (Chisholm *et al*. 2008a).

Figure 1-13. **The creation of the binocular Esterman grid**. The top two grids show the monocular fields for right and left eyes. The bottom grid shows the final binocular Esterman grid devised from the two monocular fields (Esterman. 1982. P. 1228)

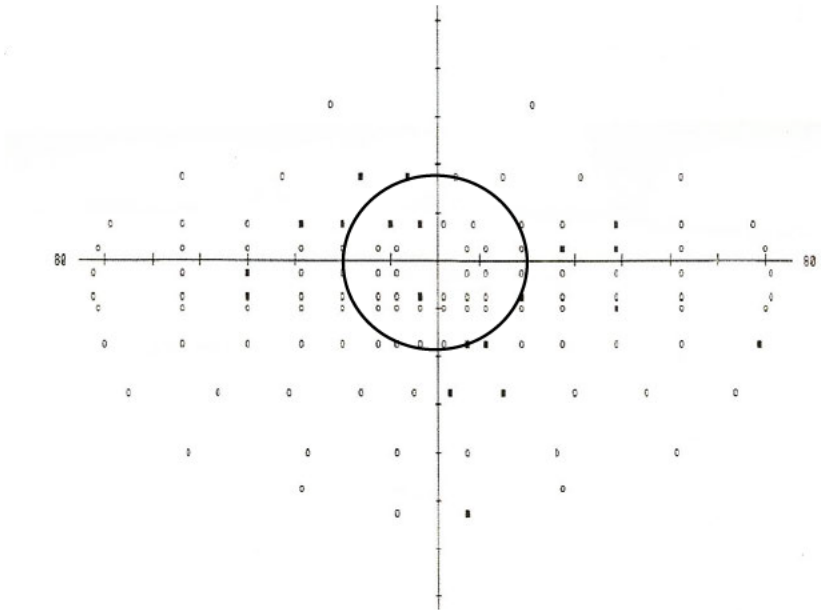

Figure 1-14. The Esterman binocular field print out performed on the HFA II model 720. The central circle indicates the central 20º zone. In this instance the individual will have failed in accordance with the current DVLA criteria.

1.11.1. Evaluations of the EVFT.

Table 1-4 lists studies which have evaluated the EVFT or utilised the EVFT to evaluate alternative test strategies.

Evaluation	Author & year	Sample	Purpose/aim	Measures/ intervention	Results	Conclusion
EVFT vs. Goldmann Perimeter.	Manji &Plant. 2000.	24: Patients who had undergone temporal lobe surgery.	Identification of field defects with Goldmann & EVFT. Comparison of Goldmann & EVFT when determining if DVLA visual field criteria met.	Tested on: HFA EVFT. Goldmann with III4e. Measures of: Field defect present or absent. Fitness-to-drive pass/fail frequencies.	Field defects found: 13/24 with Goldmann. 11/24 with EVFT. Pass/fail frequencies: 10/24 failed on the Goldmann. 7/24 failed on the EVFT.	The EVFT is more lenient than the Goldmann in participants with VFL from temporal lobe surgery for epilepsy.
	Rijn. 2002.	23: Glaucoma.	To investigate the level of agreement between the EVFT & Goldmann.	Tested on: HFA 30-2 SITA Standard. Binocular Goldmann with varying stimuli. HFA EVFT. Measures of: Defect detection & location. Horizontal extent of visual field. Fitness to drive pass/fail frequencies.	Horizontal field extension: Goldmann with III4 stimulus stricter than EVFT. HFA 30-2 central field constriction shown in only 1/3 participants who failed the Goldmann III4. Pass/fail frequencies: Goldmann III4 & EVFT = full agreement. 3 participants passed the Goldmann with V4 & failed both the EVFT & the Goldmann with III4. 9 participants failed the Goldmann with I4 & passed the Goldmann with III4 & the EVFT. Defect location agreement: EVFT & HFA 30-2=70%.	The EVFT can detect peripheral defects found by the Goldmann perimeter. EVFT can detect paracentral defects found by the HFA 30-2 SITA Standard test. Pass/fail frequencies are in full agreement between the EVFT & the Goldmann with III4 stimulus.

Crabb *et al*. 2004.	65: Glaucoma.	To determine the level of agreement between the IVF & the EVFT in classifying fitness-to-drive. To examine the link between the IVF & EVFT with the UFOV.	Tested on: HFA 24-2 SITA Standard. Monocular fields combined to create IVF. HFA EVFT. UFOV. Measure of: Fitness-to-drive pass/fail frequencies.	Good agreement between the IVF & the EVFT (kappa=0.69). 88% agreement in pass/fail frequencies. 12% passed on the EVFT & failed on the IVF. Of these 12%, 6% had a UFOV score of 4 or 5 (very high risk of MVC involvement). 6% had a UFOV score of 3 (high risk of MVC involvement).	The IVF & the EVFT possess good agreement in classifying those with glaucoma as fit-to-drive. The IVF appears better at identifying people who fall in the higher risk categories of having an MVC involvement as measured by the UFOV.
Crabb &Viswanathan. 2005.	48: Glaucoma.	To compare the IVF with the EVFT in identifying those with self-reported visual disability.	Tested on: HFA EVFT. HFA 24-2 FT & combination of the monocular fields combined to create the IVF. Questionnaire utilised to determine perceived visual disability. Measures of: AUC of Receiver operating characteristics to describe diagnostics of scores (EES & IVF score) for individual questions. EES score generated from EVFT & IVF score generated from IVF. (IVF scores: 0 if point was 20dB. 1 if point was 10-19dB. 2 if below 10dB).	AUC of the IVF median=0.79. AUC of the EVFT median=0.70. On individual question analyses the IVF produced greater AUC's than the EVFT.	The IVF score is a better indicator of perceived disability in those with glaucoma than the EES.
Rauscher *et al*. 2007.	60: CFD within 20º of fixation. 72: Control.	Sub-study: To compare the EVFT with the IVF.	Tested on: HFA EVFT. HFA FT & combination of the monocular fields combined to create the IVF. Measures of: Fitness-to-drive pass/fail frequencies.	Agreement of pass/fail = good (kappa=0.84). Three participants passed the IVF & failed the EVFT (defect was peripheral with extension into central field). One participant passed the EVFT & failed the IVF (defect was central).	The IVF needs to be supplemented by the EVFT if the patient is suspected of possessing a PFD.

	Chisholm *et al*. 2008a.	60: Binocular paracentral scotoma.	To determine the level of agreement between the EVFT & the IVF for participants with paracentral scotoma & to compare outcomes with the UFOV.	Tested on: HFA EVFT. HFA SAP & monocular fields combined to create IVF. UFOV. Measures of: Fitness-to-drive pass/fail frequencies. Agreement of pass/fail outcomes with UFOV score.	Agreement of pass/fail between the EVFT & the IVF = good (kappa 0.84). Three participants failed the EVFT & passed the IVF. Agreement on outcome of EVFT & UFOV score = limited (kappa 0.22). Agreement on outcome on IVF & UFOV score = moderate (kappa 0.32).	There is good agreement of the EVFT & the IVF for pass/fail frequencies. The IVF passes some participants with paracentral scotoma that the EVFT classifies as unfit-to-drive. The UFOV has limited to moderate agreement with the IVF & the EVFT.
	Ayala. 2012.	40: Glaucoma.	To compare the HFA monocular field test (SITA Fast 24-2) with the EVFT.	Tested on: HFA EVFT. HFA 24-2 SITA Fast. Measure of: Fitness-to-drive pass/fail frequencies.	60% of participants passed the EVFT. 40% of participants passed with SITA Fast monocular fields. Eight participants failed with monocular fields but passed the EVFT.	Monocular fields are more specific in providing information on location & depth of defect than the EVFT. The EVFT is not as efficient in finding VFL.
EVFT vs. Perception of Visual Field Loss.	Jampel *et al*. 2002a.	191: Glaucoma. 46: Suspected glaucoma. To estimate floor of scales: 12: VFL with VA of count fingers in the better eye. 12: Control.	To determine how glaucoma & glaucoma suspect patients rating of their own vision correlates with the EVFT & other visual functions.	Tested on: HFA EVFT. Scores generated from participants responses to VFQ-25 & the short form-36 medical outcomes questionnaire at face-to-face interviews & indications of vision on two feeling thermometers. Thermometer 1 range=0 (blind) to 100 (ideal vision). Thermometer 2 range=0 (death) to 100 (ideal health & vision). Time trade off decided by the proportion of remaining life the participant would sacrifice to have ideal vision. Measures of: EES correlation with perception of VFL rating scales.	Mean EVFT EES=88.2 (SD 17.4) for the glaucoma participants. Rating scale floor estimates: Count finger participants=15.6. Normals=90. Time-trade off for ‘any life’ to live with ideal vision: 11% in those with glaucoma. 22% in glaucoma suspects. 0% in normal fields. 50% in those who had VA of count fingers. The EES correlation with VFL perception rating scale=0.17 & correlation with time-trade off=0.14. The EES correlations classed as poor.	The Correlation of utility values that glaucoma & glaucoma suspect participants assign to their level of vision with the EVFT EES is poor.

Jampel *et al*. 2002b.	101: Suspected glaucoma & glaucoma.	To determine which measures of the binocular visual field correlate best with a patients' own assessment of vision.	Tested on: HFA EVFT. HFA 24-2 SITA Fast (right & left fields). Custom central 24dB. Custom central 26dB. Custom peripheral 20dB. Custom peripheral 22dB. Scores generated from participant's Visual Function Questionnaire-25 (VFQ-25) & the short form-36 medical outcomes questionnaire responses at face-to-face interviews & indications of vision on a feeling thermometer. Thermometer range: 0 (blind) to 100 (ideal vision). Measures of: EES correlation with perception of VFL rating scales. EES correlation with other visual field tests.	Mean of the EES=87.4% & distribution skewed towards higher scores (high 90s). The EVFT correlation with custom tests ranged from 0.24 to 0.28. The EES correlation with rating scales=0.4 to 0.48. HFA 24-2 SITA Fast correlation with rating scales=0.48 to 0.51.	The EES mean is skewed towards the higher range in those with glaucoma or suspected glaucoma. Two monocular visual fields have better correlation with an individuals perception of their VFL, than the EVFT & other custom tests used in this study.

Table 1-4. Previous studies evaluating the EVFT or utilising the EVFT to evaluate alternate test strategies to determine fitness-to-drive. Studies presented grouped into similar comparisons followed by date order. IVF=integrated visual field. CFD= central field defect. PFD=peripheral field defect. VFQ-25=visual function questionnaire-25.

1.11.2. Advantages and Limitations of the EVFT.

The EVFT is a readily available test (Crabb *et al*. 2004). Other advantages are the speed of the test and ease of use for both the examiner and the person under examination (Ayala. 2012) to determine binocular visual field defects. The test time is approximately 4-5 minutes (Rauscher *et al*. 2007) which will vary dependent upon the severity of the VFL. It should be noted that the EVFT allows for binocular enhancement (Rijn. 2002), which occurs naturally in the binocular visual field, whereby a defect in one eye can be compensated for by the other eye. It is considered a useful method for those with later stage glaucomatous visual field defects when establishing their remaining visual ability (Ayala. 2012) and has been used in research to assess visual disability in those with glaucoma (Jampel *et al*. 2002), but is also considered to have limitations (Owen *et al*. 2008).

1.11.2.1. Sampling Density.

The lack of central testing locations provides the ability to miss central field defects (CFD) (Owen *et al*. 2008). The EVFT, devised more than 30 years ago, was originally designed as a manual test to assess mobility (Crabb *et al*. 2004). For the purpose of driving it has poor sampling density that is considered relevant for the function of a driver's field of view. The test locations are sparse, with only 34 locations examined within the central 20°, 12 of which are above the midline and 22 below. There are no stimuli for the central 7.5°. It is possible that large scotomas may only be represented by one missed point with lower sensitivity in the upper field to detect a paracentral scotoma close to fixation, the EVFT is therefore not useful in determining size of defects (Rijn. 2002). The Road Safety Research Report No. 79 (Rauscher *et al*. 2007. P. 25) stated that 3 missed points in the upper field, although representing a paracentral scotoma of substantial size, would not prevent a patient from retaining their licence. In addition, they found only 25% of the EVFT locations relevant to the field of view required by a driver when superimposing the array of stimuli over the driver's visual field. The EVFT provides more weighting to the inferior field than the superior field. The visual field lower than the dashboard is not considered useful to determine movement and the lower 10-15° is overlaid by the dashboard. The superior visual field will be interfered with by the rear view mirror, but both areas are included within the EES. In addition the left visual field at 20-35° is obscured by the cars A-bar (Rauscher *et al*. 2007). However, Krader (2014) used software to simulate inferior and superior visual field defects using 30 healthy participants. The participants undertook a hazard perception test and this determined that both defects impaired driving performance.

However, the inferior defect appeared to have more impact with a reduction of 12% in the hazard perception score compared to a reduction of 8% in hazard perception score for superior visual field defects. As the test is binocular, temporal defects would have more impact on results than nasal defects (Krader. 2014). Nasal defects are within the overlap of the binocular field of view and can be compensated for by the fellow eye (Ayala. 2012). The EVFT has been compared with the Goldmann and the HFA, and found comparable to the Goldmann in detecting peripheral field defects (PFD) and comparable to the HFA for paracentral defect detection, although the size of defect differed, which would relate to the sampling differences. However, this did not impact upon outcome of driving status between perimeters (Rijn. 2002).

The EVFT measures 150º of visual field, however, when navigating a curve drivers have been shown to use a small region in the visual field. Visual flow models determine that when driving towards an object the visual field expands uniformly and symmetrically about the focus of expansion, whereas moving away will cause a contraction of the visual field (Lappi. 2014).

1.11.2.2. Lack of Range in the Esterman Efficiency Score (EES).

In those with glaucoma and suspected glaucoma it has been found to provide a limited range of EES results, averaging in the high 80% range and skewed around the higher score area (Jampel e*t al*. 2002).

1.11.2.3. Uniform 10 dB Stimulus.

The stimulus is presented at 10 dB on the HFA. This is considered a bright stimulus (Chisholm. 2008b) and provides limited breadth for the measurement of any VFL (Owen *et al*. 2008). This static and bright stimulus level potentially means that only deep scotomas will be found (Rauscher *et al*. 2007) and hence cannot assess whether a scotoma is absolute or relative (Ayala. 2012). It is presented at a uniform brightness across the entire visual field. In essence, the EVFT does not measure the hill of vision profile (Cubbidge. 2005). For the central retina, 10 dB is over the threshold of normality for this area and hence it would require a particularly deep scotoma within this area in order for it not to be seen (Rijn. 2002). It is a uniform brightness regardless of the observer's age. A young adult has higher sensitivity than an older adult with the elderly having a reduced sensitivity across the entire visual field (Esterman. 1985). It is less sensitive than the Goldmann perimeter providing more leniency by passing more patients as fit-to-drive with VFL resulting from epilepsy surgery (Manji & Plant. 2000). It can however be noted that this ST nature does allow the test to be completed

comparatively quicker than if the test was conducted as a FT examination. FT examinations are considerably longer in duration (Siatkowski *et al*.1996).

1.11.2.4. Lack of Fixation Monitoring.

Used binocularly, without any occlusion (Jampel et al. 2002) means that the physiological blind spots are eliminated and hence cannot be used to assess fixation stability (Chisholm. 2008b, Crabb et al. 2016, Ayala. 2012). It is only possible to monitor fixation by indirect observation (Crabb et al. 2004) which relies on the clinician maintaining concentration and is reliant on their subjective judgement which has the potential to cause retest variation (Wyatt et al. 2007).

1.11.2.5. Viewing Distance of Stimuli.

Presbyopes will not necessarily see a 33cm/25cm object clearly without an optical correction for the specified near working distance. Optical defocus is known to reduce visual field sensitivity, which has a negative impact on driving (Wood et al. 2009, 2010 & 2014). The EVFT is performed with distance refractive correction in the form of spectacles or contact lenses. Further, the habitual correction is used to carry out the test, which may take the form of progressive power lenses (varying corrective power and surface aberrational astigmatism) or bifocal lenses (variable power across the visual field and prismatic jump at the segment boundary). The influence of under correction and lens type worn by presbyopes on the EVFT is unknown.

1.11.2.6. Binocular Fusion.

Many patients have been found to have difficulty fusing the images binocularly at the HFA fixation distance of 1/3m (33cm) (Rauscher et al. 2007. Chisholm et al. 2008a). The visual axes need to converge to the central fixation point 1/3m away when undertaking the test with the HFA and to a point 25cm away for the Henson perimeter. If a hypermetrope is wearing their distance spectacles and are converging for near, the visual axes will move inwards from the optical centre of their lenses. This will give rise to base out prism when fixating at 1/3m or 25cm. Prentices rule informs that the amount of base out prism induced is dependent upon both the power of the lens and the distance from the optical centre of the lens to the near centration distance (Jalie. 1988). A hypermetrope wearing a distance correction of +6.00D lenses for both right and left eyes, which are centred at 64mm for distance viewing, and fitted with a back vertex distance of 12mm can experience 1.82Δ base out prism binocularly when viewing a near target at 25cm.

1.11.2.7. Regression Towards the Mean.

If an abnormal point that is close to threshold is retested using a suprathreshold method, it obtains a second chance to be classed as normal, because close to threshold the probability of detection is near 50%. Smith (1989) demonstrated that local retesting, which occurs when a point is not seen on the EVFT, allowed participants to see on average a further twenty out of one-hundred test points. This underestimated the VFL by 20% compared to no retest at any location or retesting at all locations. The average amount of seen points for the latter two strategies, in 10 participants with glaucoma, were 45.4 and 43.4 respectively. Whereas, with local retesting the amount of seen points increased to an average of 64.9 (Smith. 1989).

1.11.2.8. Noise Reduction.

The HFA has a double determination of sensitivity, which as well as reducing retest variability acts as a basic noise filter (Gardiner. 2003). As the EVFT is not locating threshold values but seen/not seen information at one set level of brightness, then there is no strategy to overcome noise.

1.11.2.9. Correlation with Perceived Vision Loss.

There is low correlation (0.44) with the EES and an individuals perceived difficulty measured on the Visual Function Questionnaire-25 (VFQ-25) (Jampel *et al*. 2002a, *Jampel et al*. 2002b).

1.11.2.10. Realistic Driving and the EVFT.

The EVFT, although utilised to determine fitness-to-drive, only examines visual field and hence cannot determine many of the visual aspects that are utilised when a person drives.

1.11.2.11. Dynamic Environment.

Ninety-five percent of the drivers visual world is dynamic and this dynamic visual information is related to MVCs (Underwood *et al*. 2002, Salvucci *et al*. 2002). The EVFT does not allow for assessment of dynamic stimuli nor does the EVFT show how the eyes will perform in a moving environment. Optokinetic nystagmus, which is considered a mechanism to prevent retinal slip of the image occurs during self-motion. Here the saccadic movement resets gaze following optokinetic slow phase (Lappi. 2014). A complex visual task is leaving a multi-storey car park which requires scanning of many vehicles moving, parked, about to drive forward, about to reverse, coming from around a corner of parked vehicles (MacDougall *et al*. 2005). The EVFT will examine the field available but not the scanning ability.

1.11.2.12. Determining Important Visual Information.

The EVFT does not represent how information is determined whilst driving nor does it assess an individuals' perception of a hazard. When driving in a demanding situation, drivers fixate less on the peripheral stimuli than when in less demanding driving situations. Moving stimuli can be detected correctly and quickly without fixation (Falkmer *et al*. 2000). Hazard processing is effective in the peripheral vision and peripheral vision is necessary for this task, however, this is then used to direct the eyes towards potential hazards. How far into the periphery information can be processed is still a question to be answered as this will vary on many factors such as flanking, cognitive load, task demand, contrast and VA at each point and saliency (Huestegge & Böckler. 2016).

1.11.2.13 . Driving Fixation.

Examining binocularly would realistically require a patient to converge both eyes on the one central fixation point. The convergence required is dependent upon the observer's pupillary distance and the object position. When driving, patients would not usually converge to fixate on such a point. People steer their vehicle in the direction of gaze (Robertshaw & Wilkie. 2008). When a driver inspects a visual scene for change (such as a pedestrian stepping out into the road) a driver will focus initially on the areas of higher interest (Rensink *et al*. 1997). This top-down system of attention allocation when change occurs is influenced by previous experience (Werner & Thies. 2000). The EVFT requires the patient to maintain steady fixation on a central target, so it can only examine for this sole fixation. There are no eye movements made by the participant that would usually assist a person steer their vehicle, these eye movements have shown to produce more accurate steering even when visibility is reduced for the area being viewed (Wilson *et al*. 2007).

1.11.2.14. Gaze strategies.

There are differing models of where a person looks when they drive. One is the Tangent Point and is considered the area of interest on curved roads to determine steering. It is the point where direction reversal of the movement of the inside edge of the curve (Ren *et al*. 2016) occurs to the observer (Land & Lee. 1994). For some researchers they consider there is a high reliance on the tangent point and it is of interest in bends that are close, whereas in open bends then segments of straight-road adjacent to the bend appears to be of interest for steering (Kandil *et al*. 2010). Or areas in close vicinity of the tangent point (Authie & Mestre. 2011) near the inside edge line to determine a safe trajectory (Mars & Navarro. 2012) and the starting point of which having a salient influence on this trajectory (Ren *et al*. 2014).

Varying evidence exists for the tangent point, including that there is no evidence to favour it over future path models with limitations in the existing data that do not enable clear interpretation (Lappi. 2014). Evidence has also been collated against it (Itkonen *et al*. 2015) and some models have been presented used in conjunction with the tangent point or instead of it. Evidence for drivers steering in the direction of their gaze has been found, indicating that if drivers do look at the tangent point then they will steer towards it (Robertshaw & Wilkie. 2008).

Another model suggests drivers look at waypoints on the future path (Itkonen *et al*. 2015) with no evidence for favouring the tangent point model over the future path model (Lappi *et al*. 2013) or looking ahead at fixations at a bend to assist the driver to create their driving line and consider on-coming vehicles (Lehton *et al*. 2016).

Drivers tend to direct their gaze in the direction of motion, but will shift their gaze toward a potential collision point (Roger *et al*. 2016). Gaze strategies will also vary dependant upon the environment being considered. Tunnels lead to increased fixation duration but reduced fixation number at 100 metres prior to entry with a reduction in fixation duration followed by an increase in fixation duration at 100 metres after entry with the pattern being scatter, focus, scatter relating to entry, within tunnel and exiting (Yan *et al*. 2014).

The EVFT does not account for active search or any of the proposed models of where a driver views whilst driving.

1.11.2.15. Experience.

The EVFT does not take into account previously learnt information from the experience of the driver. Driving can be driven top-down, bottom-up or a mixture of both. There is also a possibility of a bi-directional link, which means it is not necessarily the eyes that lead the hands when driving (Mars & Navarro. 2012). However, biases have been found in steering when road edges are removed or degraded (Kountouriotis *et al*. 2012). Although it has also been found that if drivers make coordinated eye movements to the inside edge of a curve even when the information has been removed, they still perform better than drivers who did not make coordinated eye movements (Wilson *et al*. 2007). It is in the best interest of a driver to focus on locations that will provide the most required information (MacInnes *et al*. 2014) and these eye movements are affected by expectation within the visual scene (top-down process) (Wickens e*t al*. 2004).

Experienced drivers utilise differing search strategies to their inexperienced counterparts (Crundall *et al*. 1999). A lack of experience is a major contributing factor to MVCs (Konstantopolos. 2009). Drivers may use learnt knowledge in a top-down system when there is uncertainty in their environment (Shinoda *et al*. 2001). The selection of task specific information has been shown to be an effective strategy (Ullman. 1984). One proposition is that hand-movements are stored within, and these are then considered by the eye (Vercher *et al*. 1997). Associated learning enhances top-down modulation and reduces bottom-up (Lin *et al*. 2016). To see signs active search is employed and governed by previously learnt knowledge (Shinoda *et al*. 2001). It has been shown that attention will shift with the anticipated predicted movement of an object being tracked, attention is removed from the current path of a tracked object and drawn to the retinal location that the object would appear after a saccadic eye movement (Szinte *et al*. 2015). Driving experience provides learning, such as identification of contextual cues that is associated with increased skill in distributing visual attention efficiently (Zhao *et al*. 2014) directing attention towards positions where a relevant visual target is most likely to appear (Chun & Jiang. 1999). Rockwell did much research on where drivers look to obtain information and established that experience and skill will lead to a change in fixations (Stunar. 2016). Experienced drivers spend more time fixating on look-ahead at curves rather than the road-ahead (Lehtonen *et al*. 2014) whilst driving straight ahead the gaze was directed directly below the vanishing point (Land & Lee. 1994). The front visual field was segmented into nine areas by Underwood *et al* (2003) and found that the middle distance area (defined as 2 seconds ahead) received the majority of fixations regardless of road type. Negative findings have been found in experienced drivers where there was a lower duration of glances away, which may increase risk of 'look but failed to see' collisions (Taylor *et al*. 2013). Experience of previously learnt visual skill and how this impacts upon driving is not considered within the design of the EVFT.

1.11.2.16. Saliency.

Although it could be argued that the EVFT does provide salient stimuli to the person undertaking the test, it does not show what a person would consider salient in a busy social scene. Saliency is driven by objects and features that grab the attention. This would include, high contrast objects and those that move suddenly. They can be unique in colour and size (Wolfe & Horowitz. 2004). Saliency appears to be more prevalent during passive viewing than in active search (Sakai *et al*. 2012). Drivers decisions are influenced by saliency with high saliency causing an early fixation and low saliency giving rise to more risky decisions (Underwood *et al*. 2011). Saliency has

not always been supported, a driver's fixation can be driven by their default interest in a scene (Birmingham *et al*. 2009).

1.11.2.17. Attention.

The EVFT does not analyse for attention. "Failed to look properly" was the main contributing factor for accidents within Great Britain during 2014 (Department of Transport. 2014) and remained the top factor in 2016, accounting for 44% of reported road accidents (Department of Transport. 2017). The commonly reported statement is "looked but failed to see". Therefore "looking" and "seeing" are two separate functions. Within a driving scene, certain elements will have an implication upon action and to respond to this attention needs to be directed to that element (Rittger *et al*. 2014).

Eye movements are closely linked to attention (Shinar *et al*. 2008) in the sense that it is considered that eye movements follow attentional movements. Before a saccadic eye movement occurs attention is directed towards the object of interest (Palmer. 1999). However fixations themselves do not necessarily indicate attention if 'look-but-failed-to see' phenomenon is considered (Rittger *et al*. 2014). It also therefore does not account for inattentional blindness. A low percentage of 25.06% of 75 vertical signs were looked at within a 2014 study (Costa e*t al*. 2014) monitoring drivers gaze behaviour. Highly salient stimuli such as traffic light signals may receive attention within the peripheral visual field without being fixated (Rittger *et al*. 2014). Poor attention allocation will increase accident rate (Werneke & Volliath. 2011) and absence of attention will cause an increased concentration of irrelevant salient loci within a traffic scene (Sakai *et al*. 2012). Experienced drivers place more of their visual attention on trajectory planning (Lehtonen *et al*. 2014). There is always the possibility that visually impaired drivers suffer from inattentional blindness as much as someone who has full use of visual senses. However, they are driving with a disadvantage and this may lead to visually impaired individuals providing full attention to the task.

1.11.2.18. Compensatory Behaviour.

The EVFT does not allow a person to demonstrate compensatory strategies, such as reducing speed or scanning of the visual field that can be utilised by those who have VFL (Coekelburgh *et al*. 2002). Scanning involves both head and eye movements. Visual field testing requires the head and eyes to remain stationary (Gruber *et al*. 2012). Scanning the visual field can reduce the impact of a scotoma (Coeckelburgh *et al*. 2004). Compensating behaviour in those with homonymous hemianopia has been found to allow safe driving comparable with those who do not have VFL (Hamel *et al*. 2012).

1.11.2.19. Distractions/fatigue.

The EVFT does not take in to account driving performance in the presence of distractions, which has shown to reduce hazard perception times to nearly 1 second (Lee *et al*. 2016). Cognitive load increase leads to a shorter 'look-ahead' distance (Lehton *et al*. 2016) and provides a general interference with the UFOV (Gasper *et al*. 2016). Neither does the EVFT demonstrate what occurs to a driver during extensive driving time. Microsaccade velocities decrease with driving time (Stass *et al*. 2014). Increased clutter (along with ageing) reduces the efficiency of road sign searching with more fixations being required to view road signs in a cluttered visual field (Adams. 1988), with the UFOV reducing (Muira. 1990, Ball *et al*. 1991) and more time being required to process the information required (Ho *et al*. 2001).

1.11.2.20. Weather Conditions and Glare.

The EVFT does also not indicate how people will perform in differing weather conditions or for varying levels of glare that a driver can experience. A drivers visual search is reduced in conditions of poor visibility, particularly in rain (Konstantopoulos. 2009).

1.11.2.21. Night Time Visual Field.

Seeing an item requires a minimum luminance contrast against the target background in order to identify it. Recognition requires perception of fine details (Eloholma *et al*. 2005) and reaction times need to be speedy in order to identify a target quickly, however, the EVFT may account for this due to the 200 ms presentation time of the target inevitably requiring a quick reaction. Accidents resulting in injury increase in darkness (Wanvik. 2009). Under mesopic lighting conditions such as driving at night, impairment to the rod system will impair contrast sensitivity and also by definition the differential light sensitivity because it is a measure of luminance contrast (Freeman *et al*. 2006).

Compared to photopic testing, mesopic vision testing shows higher sensitivity to vision loss (Maynard *et al*. 2016). Saturation of colours is also reduced as rods begin to take precedence (Stabell & Stabell. 2003) and spectral sensitivity is shifted to shorter wavelengths in scotopic vision (Eloholma *et al*. 2005).

Those with VFL are less likely to be driving at night due to the loss in scotopic vision potentially making it difficult to recognise obstacles and pedestrians within the peripheral vision (Kaleem *et al*. 2012). The EVFT does not consider the variance in luminance and hence the possible change in visual field.

1.11.2.22. Contrast, Motion and Colour.

The EVFT does not assess for factors such as contrast acuity, colour vision and the detection of moving objects. These have been considered potentially important in driving performance (Rauscher *et al*. 2007).

1.11.2.23. Resources

The EVFT is a test not usually conducted in the standard eye examination. It therefore requires additional examination.

1.12. Alternative Visual Field Assessment Methodologies for Driving.

The limitations of the EVFT are well known. This has led to alternative visual field tests for driving to be considered. Including the UFOV test which also examines for cognitive skills (Racette *et al.* 2005), The Hazard Perception Test (HPT) which examines a person's ability to identify hazards and the speed at which a person can identify these hazards. It is currently used in the theory tests for the U.K. driving licence examination (Crabb *et al*. 2010). Another examination is the Attended Field of View Test (AFOV), which is a binocular peripheral location examination, delivered on a computer monitor, that allows the individual to move their head whilst visually searching (Coekelburgh *et al*. 2002). Another method developed by Crabb and Viswanathan (Crabb & Viswanathan. 2005) is the Integrated Visual Field (IVF) examination which merges two monocular fields to assess the binocular visual field. The sensitivity value chosen is the highest sensitivity value between the corresponding locations of the right and left visual fields (Ayala. 2012, Viswanathan e*t al*. 2003).

1.13. Driving and Visual Field Loss.

1.13.1. Implications of Not Meeting the Fitness-to-drive Criteria.

A driver found to have reduced visual fields, in as much as not meeting the DVLA criteria, can have their licence revoked. The figures for a licence being refused or revoked due to a vision related disability accounts for a very small percentage of drivers in Great Britain (G.B.). From 2010 up until March 2016 this has never exceeded more than 1%. This appears to be very small. The actual figures of licences revoked or refused for a vision related disability has ranges between 4,400 and 7,500 drivers or aspiring drivers annually between the years 2010 and 2016 (table 1-5) (Morgan. 2016). Impact on not meeting the DVLA criteria can therefore impact on just under 8,000 people annually.

Year	2010	2011	2012	2013	2014	2015	2016
Amount of full Group 1 licences revoked/refused due to a vision related disability in GB	4540	4816	6467	7132	7341	7605	6400
Amount of full Group 1 licences held in GB			37,567,461	37,841,993	37,894,054	38,427,666	38,558,731
Percentage of full Group 1 licences revoked/refused due to a vision related disability in GB.			0.172	0.189	0.194	0.198	0.166

Table 1-5. Group 1 (Ordinary driving licence) drivers refused/revoked a driving licence due to a disability linked with vision within Great Britain (G.B). (Adapted from driving-licence-data-2010-Mar2016). Included are Group 1 licences held in G.B. Calculated percentages shown are licences revoked/refused in G.B. due to a disability linked with vision from all licenses currently held in G.B.

However, although values of those affected are small, it can impact on any one of these individuals lives. Up to 30% of patients who have undergone panretinal photocoagulation for proliferative diabetic retinopathy, can possibly fail the DVLA criteria after having their binocular visual field examined (Muqit *et al*. 2010).

The loss of a driving licence can have a major impact on the practicalities for the visually impaired such as travelling to work, freedom to go shopping, attend appointments and socialise and can be considered to be a significant life event (Owen *et al*. 2008). It can be particularly important for the retired person especially if they have retired to an isolated area where local travel services are scarce. Driving provides a person with a sense of independence and is a mode of transport for work. Reducing travel confines a person's space to around the home (Ramulu *et al*. 2014) resulting in social isolation (Racette e*t al*. 2005) and work restrictions (Manji & Plant, 2000). In a review of the literature aiming to establish the quality of life in those with AMD, Bradley and Mitchell (2006) reported on the findings of an Australian study, which found that losing the ability to drive was a major factor leading to the loss of a person's independence. The loss of independence to drive adds to isolation. Isolation itself is also a contributing factor to depression (Bradley & Mitchell. 2006).

Losing a driving licence can be psychologically traumatic resulting in feelings of inadequacy and low self-esteem as a result of the loss of independence (Owen e*t al*.

2008) and reduces quality of life (Medeiros *et al*. 2012, Ramulu *et al*. 2014) resulting in depression (Racette *et al*. 2005). Driving is an important sub-category on the National Eye Institute Questionnaire- 25 item version (Matza *et al*. 2008. Betlemann *et al*. 2016) and hence, the lack of ability to drive impacts an individuals quality of life score (Alqudah *et al*. 2016).

Cessation of driving increases the risk of depressive symptoms (Fonda *et al*. 2001). Ragland *et al* (2005) interviewed 1953 drivers at baseline in order to compare depressive symptoms in those who were current drivers and former drivers. They followed up 1772 (minus 311 participants lost to follow-up) participants who had been current drivers at baseline 3 years later. They reported that those who had ceased driving reported higher levels of depression than those who continued to have the freedom to drive. However, the sample of those who ceased driving during this period amounted to only 3% of the current drivers followed up. To obtain the data for this study they utilised the Center for Epidemiological Studies Depression Scale and data were controlled for age, sex, health, martial and cognitive status. All participants were 55 and above and lived within the state of California. These participants did not necessarily have licenses revoked due to visual impairment, but the study demonstrates the impact driving cessation has on older adults (Ragland *et al*. 2005).

The risk of VFL and subsequent loss of a driving licence is an important factor for the glaucomatous patient (Bhargava *et al*. 2006) and being unable to drive at night is associated with depressive symptoms in females (Kaleem *et al*. 2012). The RCO (Elliot & Newman. 2016) acknowledge in their Vision Standards for Driving document that adolescents can also be significantly upset, along with their parents if the current driving standards have not been met (Elliot & Newman. 2016).

The lack of ability to perform the task of driving also reduces scores measured on a validated Italian version of the National Eye Institute Visual Functioning Questionnaire (a self-administered questionnaire that was presented to 196 diabetic patients) in those with reduced VA due to diabetes. These results demonstrated that reduced vision, that hindered the ability to drive, reduced quality of life (Trento *et al*. 2013).

It is imperative therefore, that the visual field test to establish fitness-to-drive is reliable and repeatable to avoid a licence revocation from a person who may be safe to drive. It should also provide the same consistent result regardless of which machine is utilised to examine the visual field.

At the other end of the argument, there is also a need to ensure it is a stringent enough test to avoid people continuing to drive when they could be considered unfit-to-drive

due to VFL. This scenario may not only have a negative impact on the unfit driver but also on other road users and pedestrians. An unfit driver may be the cause of an MVC.

1.13.2. Motor Vehicle Accidents Related to Vision.

At the end of September 2016 road casualties in G.B. were as follows: 1,730 fatalities, 22,144 serious injuries and 162,315 minor injuries. Fatalities equated to approx. 0.0000055% for every mile travelled within 2016 (Department for Transport. 2016). The reason for this is not solely due to visual impairment, but vision itself appears to be the main reason being reported as “looked but failed to see”. This could be argued to relate more to attention applied than any impairment within the anatomical visual system itself.

There are many papers that have researched VFL and driving but it is recognised that it is a difficult area to study as each participant will vary in exact scotoma size and location. There can also be variance in depth of the scotoma (Rauscher e*t al*. 2007). A review of papers covering various conditions found the results suggested that different pathologies lead to differing difficulties for the driver (Wood & Black. 2016) and hence there is no uniformity between different people. It should be noted that many eye pathologies such as glaucoma and macular degeneration have age as a risk factor. Age itself for some people, but not all, can be linked to MVCs (Roenker *et al*. 2003) due to deterioration in cognitive and motor function along with the deterioration in vision (Molner *et al*. 2007).

1.13.3. Evidence for Motor Vehicle Collisions and Visual Field Loss.

Table 1-6 collates evidence for a link between VFL and MVCs.

There has been much research on VFL and driving. When establishing MVC prevalence, studies have used methods of self-report (Tanabe *et al*. 2011, Szlyk e*t al*. 2005, Szlyk e*t al*. 2002, Yuki e*t al*. 2014) or evaluation of police records (McGwin *et al*. 2013, Dow. 2011, Kwon *et al*. 2016, Gracitelli *et al*. 2015, Rubin *et al*. 2007, Cross e*t al*. 2008, Johnson *et al*. 1983). Both methods have limitations. A limitation of using police data is that not all MVCs are likely to be reported (Rauscher *et al*. 2007, Roenkar e*t al*. 2003), and self-reported MVCs have been questioned on their reliability and therefore may not be actual representations of real-life accidents (Wood & Black. 2016). Many of those that have utilised police records demonstrate an increase in MVCs due to VFL (McGwin *et al*. 2013, Kwon *et al*. 2016, Rubin *et al*. 2007). Some studies that have utilised self-report questionnaires also support an increase in MVCs due to VFL (Tanabe *et al*. 2011, Szlyk *et al*. 2005), whilst one study did not find a link (Szlyk *et al*. 2002). A further study using questionnaires, did not compare the

prevalence of MVCs with any other cohort (Yuki *et al*. 2014), hence, a link cannot be determined if the prevalence of MVCs would be considered an increase in those with VFL.

Most studies investigating the link between VFL and MVCs have been limited to participants with glaucoma (McGwin *et al*. 2013, Tanabe *et al*. 2011, Szlyk *et al*. 2005, Kwon e*t al*. 2016, Blane e*t al*. 2016, Szlyk *et al*. 2002, Gracitelli *et al*. 2015, Yuki *et al*. 2014, Sotimehin & Ramulu. 2018). Szlyk *et al* (2005) found that 32.5% of those with glaucoma had a self-reported MVC, compared to no reported MVCs for the controls, when looking back over a five-year period. However, not all participants had visual field data available (Szlyk *et al*. 2005), and the severity of the VFL was not reported. There is evidence to suggest that the increased risk is linked to the severity of the glaucomatous VFL. An earlier study by Szlyk e*t al* (2002) only included those with mild to moderate glaucoma and found that these participants did not have any more self-reported accidents, over a 5 year period, compared to the controls (Szlyk *et al*. 2002). Kwon e*t al* (2016) found that those with glaucoma have a 1.65x higher risk of a MVC compared to those without glaucoma, which rises to 2.11x when the mean visual field sensitivity is ≤22.5 dB (Kwon *et al*. 2016). McGwin *et al* (2015) found that there was an increased risk of 2.13x of having a MVC for participants with glaucoma who had a PSD less than -3.97 dB, compared to those with a PSD of -3.97 dB and better (McGwin *et al*. 2015). Tanabe *et al* (2011) found that there was no significant difference between driving licence holders with glaucoma compared to controls in those who had mild to moderate VFL (MD=-10 dB or better), however, those with MD of -10 dB or worse, had a 7.14x increase of having a MVC compared to the controls (Tanabe e*t al*. 2011). Gracitelli *et al* (2015) reported that those with a PSD recording falling within <0.05% of the normal population, had a prevalence of 9.4% of MVCs (Gracitelli e*t al*. 2015). However, this value was not compared to those who did not have a PSD recording falling within <0.05% of the normal population, and hence it is not known if 9.4% is an increase in prevalence. One study (Yuki *et al*. 2014) concluded that they did not find any relationship with MD and central visual field damage with increased MVC occurrence. However, 20.65% of participants with glaucoma had reported having a MVC (Yuki e*t al*. 2014). There was however, no control group to compare this prevalence. Sotimehin & Ramulu (2018) reviewed literature on measuring disability in glaucoma. Most studies they found provided a link to MVCs and glaucomatous VFL. Finding figures of 65% increase in MVC in those with glaucoma, increasing to 111% increase in risk for those individuals with severe VFL. However, one study they reviewed found MVCs were lower, which may be linked to cessation (Sotimehin &

Ramulu. 2018). Another review (Blane. 2016) concluded that there was an overall lack of consensus whether glaucoma increases the risk of MVCs with poor methodologies been blamed in part for the lack of certainty. However, they acknowledged that there was evidence that glaucoma has a negative impact on driving and reported on findings demonstrating those with glaucoma have a 10x more likely risk of an at-fault MVC compared to those without VFL, and that those who have had an MVC are 3x more likely to have glaucoma (Blane. 2016). Wood & Black (2016) conducted a literature review aiming to establish the evidence between ocular disease and MVC. They found variable values of the likely risk for a MVC occurrence for participants with glaucoma. These values ranged from 1.65x to 6x more likely for those with glaucoma to have a MVC compared to those without impairment. In this review, they found studies to support that the increased risk of a MVC only occurred when VFL was moderate to severe (Wood & Black. 2016).

There is limited information available looking at MVC rates for other ocular conditions independently. One study by Cross *et al* (2008) did evaluate cataract, glaucoma, macular degeneration and diabetic retinopathy independently and found none of the diseases themselves were associated with an increase in the MVCs recorded on the state agency records across a seven-year period (Cross *et al*. 2008). The lack of MVC increase could possibly be due to driving cessation (Wood & Black. 2016) and may not have been evidenced within the very small samples that were within some of the disease categories. Some studies have evaluated cohorts with differing VFL collectively (Dow. 2011, Wood & Black. 2016, Johnson & Keltner. 1983. Rubin *et al*. 2007). Dow (2001) included participants with hemianopia, quadrantanopia, CFL, PFL and one monocular participant. All participants had previously had their licences revoked due to not meeting the visual field standards for driving in Quebec. They found that many of these drivers passed the on-road driving test to enable exemption from the visual field standards. The driving records found the crash rate to be 6.79% in this cohort of participants compared to the overall crash rate in Quebec of 5.5% (Dow. 2011). Johnson & Keltner (1983) conducted a study including participants with glaucoma, other retinal disorders and cataracts. They found that binocular VFL increased crash risk by 2x compared to those without binocular VFL (Johnson & Keltner. 1983). Rubin *et al* (2007) examined visual fields on 1801 drivers and after examining police records found that MVCs were associated with participants who had missed 15 visual field test stimuli, set at 24dB, over a visual field extent of 60º. They concluded that binocular VFL was associated with MVCs (Rubin e*t al*. 2007). Wood & Black (2016) in their review of the literature found a lack of studies evaluating MVC risk

in those with AMD and diabetic retinopathy. Those that were conducted found no evidence to determine an increase in MVCs due to AMD and diabetic retinopathy. They found no studies evaluating MVC risk on participants with hemianopia and this may be due to licensing authorities not permitting a sufferer to hold a driving licence (Wood & Black. 2016).

Field loss/Source of MVC data.	Author	Year	Sample size	Participant characteristics	Controls	VFL & MVC link	MVC risk.	Evaluation method.
Glaucoma/ police records	McGwin *et al*	2013	438	Glaucoma	No	Yes	2.13x for those with PSD of <-3.97dB	IVF
	Gracitelli *et al*	2015	117	Glaucoma	No	Inconclusive	Risk not determined.	SAP. UFOV. Simulator.
	Kwon *et al*	2016	2000	Glaucoma	Yes	Yes	1.65x increasing to 2.11x when mean sensitivity is ≤22.5dB	IVF
Glaucoma/ Questionnaires	Szlyk *et al*	2002	51	Glaucoma	Yes	No	No risk found.	Simulator. Goldmann Visual Field. HFA.
	Szlyk *et al*	2005	57	Glaucoma	Yes	Yes	32.5x	Simulator. Goldmann Visual Field
	Tanabe et al	2011	121	Glaucoma	Yes	Yes	7.14x for those with MD of -10dB or worse.	Self-report vs diagnosis
	Yuki *et al*	2014	247	Glaucoma (focussing on CFD)	No	Inconclusive.	No risk determined.	IVF and total deviation.
Glaucoma/ reviews.	Blane	2016	Literature review	Glaucoma	N/A	Overall inconclusive. However, evidence that glaucoma impacts negatively on driving.	10x.	Various- literature review
	Sotimehin & Ramulu	2018	Review	Glaucoma	Not indicated for all studies.	Yes- most	65% higher risk in those with glaucoma. 111% higher risk in individuals with severe VFL.	Review.

Various VFL/ Police records.	Dow	2011	103	Hemianopia. CFD. PFD. Monocular vision	No	No	No risk found.	On-road.
Various/ review.	Wood & Black	2016	Review	Cataract, glaucoma, AMD, Diabetic retinopathy, Hemianopia.	Yes	Yes- some	1.65x to 6x for glaucoma participants when VFL is moderate to severe. No risk evidenced for AMD, diabetic retinopathy, hemianopia & quadrantanopia.	Review
Current/prospective drivers./Police records.	Johnson *et al*	1983	10,000	Any who had applied for a driving licence.	Yes	Yes	2x with binocular VFL.	Fieldmaster modified: target luminance 1,270 asb. Background 31.5 asb. Elimination of 60º temporal targets and 40º degree nasal targets.
	Rubin *et al*	2007	1801	Drivers.	Yes	Yes	MVC risk in those who have a loss of 15 points examined at 24 dB in a 60º visual field.	HFA.
	Cross *et al*	2008	3158	Drivers	Yes	No	No risk found.	UFOV.

Table 1-6. Evidence for a link between VFL and MVCs. Studies collated by condition and the method of obtaining MVC information.

A limitation of using police data is that not all MVCs are likely to be reported (Rauscher *et al*. 2007, Roenkar e*t al*. 2003) and therefore, self-report MVCs may not be actual representations of real-life accidents (Wood & Black. 2016).

1.13.4. Driving Cessation.

One difficulty in establishing a link or no link between VFL and MVCs is that drivers with a VFL, having an insight into their own driving ability, may self-restrict or choose to cease driving and therefore be less likely to be involved in an MVC. This subsequently adds to driving safety (Wood & Black. 2016).

The literature (table 1-7) establishes a tendency for individuals with glaucoma to self-regulate or cease driving (Blane. 2015). Individuals with glaucoma have been found to be 2x more likely not to leave home on any given day (Ramulu *et al*. 2014) and 3x more likely to cease driving when compared to those without the condition (Black & Wood. 2013). This tendency increases with the severity of the VFL with the likelihood of driving cessation increasing with every 5 dB of visual field restriction in the better eye (Ramulu *et al*. 2009, Ono *et al*. 2015). Use of topical alpha agonists also increased the likelihood of an individual not leaving home (Ramulu *et al*. 2014).

Poor depth perception is found within glaucoma suspects (Gupta *et al*. 2009) and poor depth perception is linked to driving cessation (West *et al*. 2003). Drivers who suffer reduced contrast sensitivity reduce their driving exposure (Sandlin *et al*. 2014). Drivers with POAG who do not self restrict did show an increase in MVCs when compared to those who do (Ono *et al*. 2015).

However, cessation only occurs when there is insight in to one's own VFL. Where drivers have no knowledge of their own VFL, then cessation is unlikely to occur. This has previously been found by Keltner & Johnson (1980). In their study they found that 5% of 1,027 eyes, of people who held driving licenses in California, had field loss that was considered significant (Keltner & Johnson. 1980). In addition, Manji and Plant (2000) found that out of 24 participants with visual field defects only one participant had VFL symptoms, yet 5 out of the 24 had defects that would fail the visual field driving criteria (Manji & Plant. 2000).

Field loss/visual symptom	Author	Year	Characteristic	Cessation/self-regulation
Glaucoma	Ramulu *et al*	2009	Glaucoma	Cessation doubles for every 5 dB reduction in visual field.
	Wood and Black	2013	Glaucoma	Cessation 3x more likely.
	Ramulu *et al*	2014	Glaucoma	Increase in VFL due to glaucoma is linked to less travel from home compared to those with no VFL (not necessarily driving). Use of topical alpha antagonists is also linked to less travel from home.
	Ono e*t al*	2015	Glaucoma	Cessation doubles for every 5 dB reduction in visual field.
	Blane	2016	Glaucoma	Tendency found for self-regulation and cessation within literature review.
Hemianopia/ Quadrantanopia	Parker *et al*	2011	Hemianopia and quadrantanopia	Limited driving in terms of fewer trips, limit on how many places visited and reduction in miles driven.
Reduced Contrast Sensitivity	Sandlin *et al.*	2014	Reduced contrast sensitivity	Self-regulated.

Table 1-7. Likelihood of cessation/self-regulation of driving in those with VFL.
Studies grouped into pathology or visual symptom of participants.

1.13.5. Safe or Unsafe to Drive with Visual Field Loss?

Although not many papers actually measure the prevalence of MVCs many do consider if those with a VFL are considered safe or unsafe to drive.
Table 1-8 Collates evidence to determine if those with a VFL are safe or unsafe to drive.

Assessing a link between driving safety can be difficult due to the difficulty in assessing people who do not hold a licence to legally drive (Rauscher *et al*. 2007). A review (Wood & Black. 2016) was performed in 2016 looking at the evidence of the impact on driving with cataract, glaucoma, AMD, diabetic retinopathy and homonymous hemianopia (Wood & Black. 2016) within which they ascertained that MVC risk in those with glaucoma was similar to controls until the loss was classed as moderate to severe. For AMD they determined that too few studies had been conducted to enable a conclusive decision on the extent this condition impacts upon driving. Studies covering diabetic retinopathy had conflicting results and no reports were available for a direct

link on MVC risk and hemianopia (Wood & Black. 2016). Many studies have been conducted on participants with hemianopia or quadrantanopia (Hamel *et al*. 2012, Papageorgiou *et al*. 2012, Wood *et al*. 2009, Haan *et al*. 2014, Bowers *et al*. 2007, Alberti *et al*. 2014, Kasneci, 2014, Parker e*t al*. 2010, Racette *et al*. 2005) and glaucoma (Bhorade e*t al*. 2016, Kasneci e*t al*. 2014, Kubler e*t al*. 2015, Szylk *et al*. 2002, Blane. 2016, Szylk *et al*. 2005, Gracitelli e*t al*. 2015, Kunimatsu-Sanuki *et al*. 2017, Smith. 2011, Racette *et al*. 2005, Coeckelburgh *et al*. 2004, Coeckelburgh e*t al*. 2002a, Coeckelburgh e*t al*. 2002b) one of which included retinitis pigmentosa along with glaucoma (Bowers *et al*. 2005). Few appear to have been conducted looking at central VFL (Bronstad e*t al*. 2013, Bronstad *et al*. 2015, Lamble *et al*. 2002, Alberti *et al*. 2014, Coeckelburgh *et al*. 2004, Coeckelburgh *et al*. 2002a. Coeckelburgh *et al*. 2002b). One study has looked at the association of retinal nerve fibre thickness and fitness-to-drive with HIV positive patients (cheung *et al*. 2011), which may have relevance to retinal nerve fibre thickness that can alter in glaucomatous individuals. Simulated inferior and superior VFL have also been studied (Krader *et al*. 2014, Glen *et al*. 2015).

Field loss	Author	Year	Sample size	Characteristics	Controls	Simulator/ on-road	Fit-to-drive	Result considered to be due to
Hemianopia	Haan e*t al*	2014	26	Hemianopia	No	On-road	YES	N/A
	Hamel *et al*	2012	91	Hemianopia	Yes	Simulator	YES	Compensatory gaze behaviour
	Papageorgiou e*t al*	2012	30	Hemianopia	Yes	Simulator	Some participants/ inconclusive	N/A
	Bowers *et al*	2009	36	Hemianopia	Yes	Simulator	NO	N/A
	Alberti e*t al*	2013	12	Hemianopia	No	Simulator	NO	N/A
Hemianopia & quadrantanopia	Wood e*t al*	2009	60	Hemianopia (n=22) Quadrantanopia (n=8)	Yes	On-road	YES	N/A
	Parker e*t al*	2010	48	Hemianopia. Quadrantanopia	Yes	On-road	YES	_____
	Wood e*t al*	2011	60	Hemianopia (n=22) Quadrantanopia (n=8)	Yes	On-road	Some participants	Fit-to-drive: Increased head movement
Hemianopia & glaucoma	Kasneci e*t al*	2014	40	Hemianopia & glaucoma	Yes	On-road	YES	Right hemianopia (German study-drive on the right)
Glaucoma	Bhorade e*t al*	2016	59	Glaucoma	Yes	On-road	NO	N/A
	Szlyk *et al*	2002	51	Glaucoma	Yes	Simulator	YES	No significant increase in simulator or real-world accidents between study and control group.

	Kubler e*t al*	2015	14	Glaucoma	Yes	Simulator	YES	Increased head/eye movements.
	Szlyk *et al*	2005	57	Glaucoma	Yes	Simulator	NO	Visual field <100˚ horizontally
	Kunimatsu-Sanuki e*t al*	2017	72	Glaucoma	Yes	Simulator	NO	Decreased IVF sensitivity.
	Smith	2011	30	Glaucoma	Yes	Simulator (HPT).	Inconclusive	Glaucoma participants required increased target detection time and reduced saccades. Not linked to if this will increase MVC.
	Gracitelli *et al*	2015	117	Glaucoma	No	Simulator	Inconclusive	9.4% of Study group had MVC at follow-up. No control group.
	Blane	2016	Literature review	Glaucoma	N/A	Various-review	Inconclusive	Varied methodology and results across studies.
Glaucoma & retinitis pigmentosa	Bowers *et al*	2005	28	Glaucoma & retinitis pigmentosa	No	On-road	YES. Although peripheral field restrictions (both mild and moderate) affected driving skills.	Not investigated.
Reduced retinal nerve fibre layer thickness	Cheung *et al*	2011	38	Reduced retinal nerve fibre layer thickness	Yes	Simulator	NO	Reduced retinal nerve fibre layer thickness

CFD	Lamble *et al*	2002	10	CFD	Yes	On-road	YES	No significant difference between study and control group.
	Bronstad e*t al*	2013	22	CFD	Yes	Simulator	NO	Scotoma size.
	Alberti *et al*	2014	22	CFD (AMD, Stargardt's, optic atrophy)	Yes	Simulator	NO	Decreased multiple object tracking, decreased divided and selective attention, decreased contrast sensitivity. Increase in scotoma size.
	Bronstad *et al*	2015	14	CFD	Yes	Simulator	NO	Any binocular CFD affects hazard detection.
CFD & PFD	Coeckelburgh e*t al*	2002b	87	CFD. PFD.	No	Both	Some participants	In those participants who passed: Slower driving speed for CFD and more and earlier scanning for PFD.
	Coeckelburgh *et al.*	2004	100	CFD. PFD.	No	On-road	Some participants. Peripheral and mild defects fared better than central defects.	Location of VFL and compensatory viewing strategies.
Various VFL	Racette and Casson	2005	131	Hemianopia. Quadrantanopia Monocular. Moderate & mild PFD.	No	Retrospecti ve on-road.	Some participants. Monocular. Quadrantan-opia. Right hemianopia.	Extent of VFL, but differences in individual results. Overall: Inconclusive.

	Tanja *et al*	2002	87	CFD, PFD, mild field defects.	No	On-road and simulator	22% of CFD. 43% of PFD participants and 43% and 57% with mild field defects.	Reduction in driving speed and increased scanning,
	Wood and Black	2016	Review	Cataract, glaucoma, AMD, Diabetic retinopathy, Hemianopia.	Yes	Both	Cataract- no. Glaucoma- conflicting. AMD – still to be determined. Diabetic retinopathy- conflicting. Hemianopia- conflicting.	Cataract- reduced contrast sensitivity increases risk. Glaucoma- extent of field loss. Early loss provides driving similar to that of controls. AMD – possible cessation reduces risk? Uncertain. Hemianopia- on-road possibly safe due to compensatory eye movements.
Simulated VFL	Krader	2014	30	Simulated visual field defects	Yes	Simulator	NO	Location of VFL.
	Glen *et al*	2015	30	Simulated superior and inferior VFL	No	Simulator (HPT)	NO	Both defects. But superior > inferior.

Table 1-8. Evidence for safe/unsafe driving with VFL. Order of studies provided firstly by defect, secondly by driving method (on-road/simulator), thirdly whether participants deemed safe/unsafe, and finally, by date of study.

The extent of the VFL has been found to be related to driving performance. As constriction of the vertical and horizontal field occurs, ability at maintaining lane position, changing lanes, following a curve and maintaining speed have been found to deteriorate (Coekelburgh *et al*. 2002b). However, extent of the VFL cannot solely be relied upon when determining whether an individual is safe to drive, with many individual differences observed. Bowers *et al* (2005) reported that most drivers who demonstrated these deficiencies were considered safe to drive when assessed on an on-road 14 mile long route. Bowers *et al* (2005) also stated that the location of VFL did not have a significant effect, again differences within each individual presenting with VFL were observed (Bowers *et al*. 2005).

The type of VFL may have some relationship with classification as fit-to-drive or not-fit-to-drive, with 25% of participants with CFL passing the Dutch on-road test compared to 42% of those with PFL and 64% of those with mild VFL (Coeckelburgh *et al*. 2004). Individuals with CFL have shorter reaction times in response to a collision than peripheral defects. In a cohort of 23 CFL, 35 PFL and 23 mild defect participants, 35% caused a collision using a simulator. This amounted to 23% of those with PFL and 9% of those with mild visual field defects. In the same cohort 22% of participants with CFL passed an on-road test, 43% with peripheral field loss and 57% with mild field defects. This study also observed individual differences (Coeckelburgh *et al*. 2002b). Those with monocular vision have been found to be safe to drive (Racette et al. 2005). For those with VFL, compensatory gaze behaviour has shown to provide driving performances similar to that of controls (Hamel *et al*. 2012). Participants with VFL exhibiting compensatory gaze behaviour have been considered as safe (Wood *et al*. 2009, Haan *et al*. 2012) and fit-to-drive (Wood *et al*. 2009). Hemianopic patients have been noted to make more head movements into their blind side (Wood *et al*. 2011). Kasneci *et al* (2014) conducted a study assessing driving safety on participants with homonymous hemianopia or glaucoma. A driving instructor, blinded to the participants diagnosis, passed 60% of the participants with hemianopia on a 40 minute on-road driving test, as well as 40% of those with glaucoma. The hemianopic participants that passed the test had a right homonymous visual field defect. All those who failed, possessed a left homonymous visual field defect (Kasneci *et al*. 2014). This study was conducted in Germany whereby the driving occurs on the right. In the U.K. where driving occurs on the left, it could be considered that the opposite would be true. However, opposite findings have been reported where driving also occurs on the right. Racette *et al* (2005) found that those with left hemianopia were classed as ‘safe’ and those with ‘right’ hemianopia were classed as ‘unsafe’. The findings of Kasneci *et al*

(2014) and Racette *et al* (2005) may therefore have more to do with the area of the brain that is affected as opposed to the resultant VFL. In a simulator, 50% of participants with glaucoma were rated as passed by a blind assessor and demonstrated adaption with more head and eye movements towards eccentric regions being observed (Kubler et al. 2015). Szylk et al (2002) found that people with glaucoma can be considered safe to drive finding no significant difference in the study or the control group when looking at real world accidents (Szylk e*t al*. 2002). However, the same author conducted a study in 2005 and concluded that those with visual fields less than 100˚ horizontally were not considered safe to drive (Szylk *et al*. 2005). Detection rate has been shown to be lower in the blind side for hemianopic patients, albeit within a timed guideline, the researchers concluded this detection rate was not compatible with safe driving (Bowers *et al*. 2009). However, it can be noted here that those who had lower detection rates were just over 50%. It could therefore be argued that just under 50% were deemed as safe to drive. Detection rates of stationary or approaching pedestrians have been found to be too late to avoid collision (Alberti *et al*. 2013). In an on-road study (Bhorade e*t al*. 2016) 52% of glaucoma participants failed or were rated as marginal after assessment by a masked driving rehabilitation specialist and possessed an increased risk of 4.1x of being unsafe to drive (Bhorade e*t al*. 2016). Decreased IVF sensitivity has found to relate to unsafe driving in glaucoma (Kunimatsu-Sanuki *et al*. 2017). One study (Gracitelli *et al*. 2015) found that 9.4% of glaucoma participants had experienced an MVC on follow-up (Gracitelli e*t al*. 2013), but as there were no controls in this study it is uncertain if this is an increased risk compared to those without eye pathology. Another study (Smith. 2011) found that glaucoma patients require increased time to locate targets, but they did not conclude if this would relate to being unfit-to-drive (Smith. 2011). In essence there is varied results as found by Blane (2016) in doing a literature review on whether glaucoma patients are safe to drive. The methodologies were varied which is a possible reason for the varied results (Blane. 2016). Retinal nerve fibre layer thickness has been correlated to driving errors and thereby impairs driving ability (Cheung *et al.* 2011). Those with CFL have been shown to have a delayed hazard detection rate and can fail to detect pedestrians (Bronstad *et al*. 2013) and this is dependent upon scotoma size (Alberti *et al*. 2014) and if the CFL is binocular (Bronstad *et al*. 2015). One on-road study (Lamble e*t al*. 2002) did find that there was no significant difference in those with CFL and those without VFL (Lamble *et al*. 2002). The three studies finding that CFL provided a scenario to be unfit-to-drive was conducted with a simulator. Simulating VFL (superior and inferior VFL) shows a reduction in hazard perception (Krader. 2014) and hence

both defects impair driving performance with superior defects demonstrating poorer driving performance than inferior (Glen e*t al*. 2015).

Sample sizes varied between studies ranging from 10 to 131 participants. Many studies were performed using a simulator (Hamel *et al*. 2012, Papageorgiou e*t al*. 2012, Bowers e*t al*. 2009, Alberti *et al*. 2013, Bronstad *et al*. 2013, Kubler *et al*. 2015, Krader *et al*. 2014, Cheung *et al*. 2011, Szlyk e*t al*. 2005, Glen e*t al*. 2015, Bronstad e*t al*. 2015, Szlyk *et al*. 2002, Gracitelli e*t al*. 2015, Alberti *et al*. 2014, Kunimatsu-Sanuki e*t al*. 2017, Tanja *et al*. 2002, Coeckelburgh *et al*. 2002b). This could be argued as not a true representation of driving as they do not possess high fidelity (Roenkar *et al*. 2003) and the unpredictability of a real-life situation is standardised. Simulator tasks can be conducted with the task of simply identifying a stationary hazard, which does not reflect real life driving. They do not allow individuals to use adaption strategies such as slowing down (Wood & Black. 2016). Participants can also suffer simulator sickness (Kubler *et al*. 2015, Roenkar *et al*. 2003). On-road studies were also conducted (Wood *et al*. 2009, Wood *et al*. 2011, Haan *et al*. 2014, Kasneci *et al*. 2014, Bhorade *et al*. 2016, Parker *et al*. 2010, Lamble e*t al*. 2002, Racette & Casson. 2005, Coeckelburgh e*t al*. 2004, Tanja *et al*. 2002, Bowers e*t al*. 2005, Coeckelburgh *et al*. 2002b). Although real-life, they possess their own limitations, particularly for research where the scenario cannot be standardised between participants to ensure each driver has the same experience. There can also be differences in assessment scoring (Roenkar *et al*. 2003). When assessing driving safety with CFL, the participants used their preferred retinal locus with no clear statement how it was located or if habitually used. It can be argued that the preferred retinal locus is not a particularly good strategy for use in a moving environment. For reading it would be usual to teach a low vision patient how to use steady eye strategy in conjunction with eccentric viewing. This is unlikely to be able to be used within a dynamic environment that requires people to alter fixation on numerous occasions. Another limitation can arise from simulating VFL, this does not enable participants the opportunity to adapt to the VFL and impairment which may occur in those who have had the VFL for a longer duration.

1.13.6. Adaption and Safe Driving.

There are many studies (Sandlin *et al*. 2014, Haan *et al*. 2014, Kanesci *et al*. 2014, Bowers *et al*. 2010, Papageorgiou e*t al*. 2012, Vega *et al*. 2013, Legge. 2013, Smith. 2011, Rauscher e*t al*. 2007, Crundall *et al*. 1999, Hamel *et al*. 2012, Coeckelburgh *et al*, 2004, Coeckelburgh *et al*, 2002a, Crabb *et al*, 2010) that have investigated whether or not adaption has the potential to allow those with VFL to drive safely including

investigating hazard perception and response times when vision is blurred (Lee *et al*. 2016)

Table 1-9 collates evidence to link adaption to safe driving.

Field loss	Author	Year	Sample	Characteristics	Controls	Adaption leading to safe driving	Simulator/ On-road	Adaption characteristic
Hemianopia	Haan *et al*	2014	26	Hemianopia	No	Yes	On-road	Visual scanning
	Bowers *et al*	2010	32	Hemianopia	Yes	Yes	Simulator	Lane positioning on opposite side of defect.
	Papageorgiou *et al*	2012	60	Hemianopia	Yes	Yes	Simulator	Made longer scans into both affected and unaffected side.
	Hamel *et al*	2012	91	Hemianopia (n=6)	Yes (n=85)	Yes	Simulator	Compensatory gaze behaviour.
	Sandlin e*t al*	2014	2000	Hemianopia	No	Yes	N/A- driving habits questionnaire	Head/eye movements
Hemianopia & glaucoma	Kanesci *et al*	2014	20	Hemianopia, glaucoma	No	Yes	On-road	Longer central field focus. More glances to blind side.
Glaucoma	Crabb *et al*	2010	19	Glaucoma	Yes (10)	Not evaluated	Simulator (HPT)	On average, the glaucoma participants viewed the same driving field, although this varied with individual cases. Glaucoma participants made more saccades, smooth pursuits and fixations per second. Smooth pursuits and fixations were shorter than controls.
	Smith	2011	36	Glaucoma	Yes	Inconclusive	Simulator	Saccadic rate correlated with driving performance. 6% decrease in saccadic rate found in glaucoma group.

	Vega *et al*	2013	35	Glaucoma	Yes	Some	Simulator	Unknown
CFD	Rauscher *et al*	2007	For HPT analysis: 40	Various binocular defects affecting the central 20°	No	Yes	Simulator (HPT)	Eye movement analysis suggested scanning to compensate for VFL.
	Legge	2013	22	CFD	Yes	No	Simulator	Smaller scotoma size.
	Coeckelburgh *et al*	2002a	50	CFD. Previously informed unfit-to-drive.	No	No	Dot counting task	N/A- looking to see if eye movements were predictive of viewing behaviour.
CFD & PFD	Coekelbergh *et al*	2002b	87	CFD. PFD.	No	Yes	Both	Compensatory speed (CFD), Compensatory gaze behaviour (PFD)
	Coekelbergh *et al*	2004	100	CFD. PFD.	No	Yes	On-road.	Compensatory viewing strategies.
Normals	Crundall *et al*	1999	60. 20 experienced drivers. 20 novice drivers. 20 non-drivers.	Normal fields. Differing levels of driving experience	Yes- non-drivers	Yes- the effect of experience	Simulator (Moving drivers perspective video clips)	Experience.

Table 1-9. Evidence linking adaption to safe or unsafe driving. Order of studies provided firstly by defect, secondly by driving method (on-road/simulator), thirdly whether participants deemed safe/unsafe, and finally, by date of study.

Practical fitness-to-drive is being safe to drive regardless of a physical impairment (Coekelbergh *et al*. 2002b). People who have been driving for years can be unaware of a congenital VFL due to adaption and modified scanning (Rauscher *et al*. 2007). Driving is an over learned skill and drivers can compensate for any impairments and it has been found that using viewing strategies to compensate for VFL results in better driving performance than those who do not (Coeckelbergh *et al*. 2004, Coekelbergh e*t al*. 2002b, Kasneci *et al*. 2014). The measurement of the visual field itself has been found to not represent an adequate predictor of successful collision avoidance (Sandlin *et al*. 2014) and fitness-to-drive (Haan e*t al*. 2014, Kasneci *et al*. 2014) in hemianopic patients. Consideration of compensatory strategies utilising head and eye movements should be considered. It has also been found that older people with poor cognitive function make less rapid decelerations than their cognitively superior counterparts. This is presumed to be due to adaption and caution taken by the driver to compensate for poor cognitive ability and interestingly those with VFL were not as likely to fail to stop at a stop sign, which is assumed to be due to the driver taking added precautions. Although the findings did not follow through when the requirement was to stop at a red light (Keay *et al*. 2013).

Different field defects present with different limitations in the use of vision when performing tasks and it is likely to reflect in driving performance. Those with CFL have been found to compensate by reducing their driving speed whereas those with PFL opt for increased scanning including scanning for longer distances (Coeckelburgh *et al*. 2002b). Varied results have been shown with identical visual field defects in the hemianopic patient (Sandlin e*t al*. 2014) with those making saccadic eye movements into the area of field loss having the same driving performance in a simulator as healthy controls although presenting longer reaction times. They were still able to avoid collisions. Those considered unfit-to-drive have poor visual scanning (Haan *et al*. 2014. Hamel *et al*. 2012). Hemianopic and glaucoma patients who passed an on-the-road assessment focussed longer on the central area and conducted more glances into their blind side (Kasneci e*t al*. 2014. Papageorgiou e*t al*. 2012). Right hemianopic patients have been found to take up lane positioning significantly to the left and left hemianopic patients took up lane positioning significantly to the right (Bowers *et al*. 2010). People with PFL cross over lane boundaries more so than those with CFL (Coekelburgh *et al*. 2002b). Increased saccadic eye movements, fixations and smooth pursuits per second have been found to be significantly increased in those with glaucomatous defects with fixations and smooth pursuits being of shorter durations (Crabb e*t al*. 2010). In

contrast, Vega e*t al* (2013) found that glaucoma patients did not use any more eye scanning than controls (Vega e*t al*. 2013).

The driving field viewed by glaucomatous participants has been found, on average, to be the same as controls. Individual participants with glaucoma have, however, been shown to vary, with some not identifying emerging hazards (Crabb *et al*. 2010).

A different story is presented with CFL. With more participants with CFL failing an on-road examination when compared to those with PFL (Coeckelbergh *et al*. 2004). It has been found that those with central scotoma do make lengthier saccadic eye movements suggesting that some participants do compensate for their CFL (Rauscher *et al*. 2007). It has also been found that CFL presents with slower reaction times which are correlated to the size of the scotoma (Legge e*t al*. 2013), and drive slower than their counterparts who possess PFL and significantly slower when the PFL is considered mild (Coeckelburgh *et al*. 2002b), and that eye movements could not be used to predict the outcome of whether the participant was an at risk driver (Coeckelbeorgh *et al*. 2002a).

The studies used different methods to assess driving and safety. This results in studies that are not necessarily comparable with each measuring a different aspect due to the differing methodology. The results may therefore not necessarily be interchangeable (Wood & Black. 2016). Many of the studies utilised a simulator to assess driving. This is potentially because it is a controlled environment (Racette *et al*. 2005) and collisions would only have a virtual impact and hence it is a safe environment to assess a patient (Bowers *et al*. 2005). Medieiros *et al* (2012) produced an article looking at evidence for its usage in assessing visual function impairment and in particular as a performance based test for those with glaucoma. They established that on-road performance tests and those with a simulator had a high correlation and related to people's self-reported driving history. Overall, they concluded that the use of driving simulators can play an important part in terms of linking visual and task performances (Medieiros *et al*. 2012). Although their article was providing a positive light on the use of simulators they do not necessarily encompass real-world driving conditions (Bowers *et al*. 2005). They can be less challenging than an unpredictable on-road environment (Racette e*t al*. 2005) and it could be added that a change of car for patients who are and who are not visually impaired always poses an initial challenge to the driver as they familiarise themselves with controls and car handling whilst on the road. A simulator in essence, could be considered a change of car.

1.13.7. Factors Other Than Vision That Impacts Upon Driving Ability.

It is interesting to note the opinion of The RCO (Elliot & Newman. 2016) on ascertaining a link between MVCs and poor vision. In their Vision Standards for Driving they state that accidents caused by a poor level of vision are not all that common. Driving also requires coordination of physical movements (Ball *et al*. 2006). More commonly are accidents due to being young, old, under the influence of alcohol and being distracted (Elliot & Newman. 2016).

Younger drivers have the highest accident reports. This alters when the actual driving time (MVC per kilometre) is considered resulting in an increase in older drivers (Wood & Black. 2016). Older persons can show visual decline with no obvious clinical basis but have been shown to be linked to visual attention deficits, which are predictive of driving problems (Ball & Owsley. 1993). Drivers who are 78 years or older have been found to be 2.11x more likely to be involved in an at-fault MVC. Those who have an attentional disorder or score low on tests that examine mental ability are up to 4x more likely of having an MVC and this increases at intersections to 15x (Owsley *et al*. 1997). Older drivers are set to increase, along with the acquired visual impairments that arise with age, as the ageing population increases (Wood & Black. 2016).

Gender has also been found to be linked to at fault MVCs with being male increasing risk of MVCs over a preceding 3 years (Ball *et al*. 2006). However, the RCO also state that the evidence of how poor vision affects road safety is not complete due to the confidentiality imposed by the Data Protection Act making it not possible to directly link a driver's condition with an accident. As prospective trials are not appropriate to ascertain the link between vision and accidents means that the current studies are not particularly adequate, with observational studies being limited to only those participants who would fit the current criteria. They also acknowledge that patients with poor vision do adopt strategies limiting the risk. But on the other hand there could be a potential that someone who has a minor impairment, but adds another risk factor, such as alcohol, may raise the potential hazard compared to those without a loss of vision and also partakes in an alcoholic beverage (Elliott & Newman. 2016).

1.13.8. Visual field Loss and Motor Vehicle Collisions Conclusion.

In summary, the body of evidence makes it difficult to determine whether VFL is indeed linked to unsafe driving. It is possible for a person to adapt to their VFL and hence may be considered as safe to drive and hence unlikely to be a risk on the road (Coeckelbergh e*t al*. 2004, Tanja e*t al*. 2002, Coeckelbergh *et al*. 2002b). However, looking specifically at the studies that collated information on the prevalence of MVCs

with VFL, there is indication that VFL increases MVCs. Evidence indicates that those with binocular VFL are twice as likely to have an MVC than someone without binocular VFL (Johnson & Keltner. 1983), and MVCs are likely to increase when 15 missed stimuli, at 24 dB intensity, are missed across the extent of a 60º binocular visual field (Rubin *et al*. 2007). Although there is no evidence linking the conditions of AMD, diabetic retinopathy, hemianopia and quadrantanopia specifically to an increase in MVCs (Wood & Black. 2016), there is evidence that patients with glaucoma are at risk of increased MVCs. Figures vary, but the likelihood of a MVC occurring in those with glaucoma has been found to be between 1.65x (Kwon *et al*. 2016) to 10x (Blane. 2016) more likely than someone who does not have the disease. However, this may not occur until advance stages of the disease (Wood & Black. 2016). Increases in MVCs have been found to occur when the mean visual field sensitivity is ≤22.5 dB (Kwon *et al*. 2016), the PSD is <-3.97 dB (McGwin *et al*. 2016) and MD is -10 dB or worse (Tanabe e*t al*. 2011). Therefore, the evidence indicates that patients with binocular VFL and advanced glaucoma have an increased risk of a MVC occurrence compared to those who do not have VFL.

With evidence establishing that patients with VFL are a risk on the road it is highly important that a visual field test that determines whether a person is able to drive or not, is highly repeatable. The test should also be able to provide the same result should differing machines be utilised.

1.14. One Test. Different Instruments.

The EVFT is included within the test menu of the HFA (Ayala. 2012, Jampel e*t al*. 2002) and other standard automated perimeters (Owen *et al*. 2008). Of these perimeters the EVFT is most commonly performed on the HFA (Rauscher *et al*. 2007). The DVLA states that the interpretation of the visual field charts for the given criteria relate to tests performed on the HFA (Driving Vehicle Licensing Agency. 2014). However, the current standard is not specific to the instrument. The EVFT is also included in the test menu of the Henson Perimeter, which is a bowl perimeter that is instructed via a computer (Artes *et al*. 2002). The comparative aspects of the HFA and Henson Pro 5000 EVFT are detailed in table 5-1 within chapter 5.

1.15. Impact of Background Luminance, Stimulus Type, Size and Intensity on Perimetry.

Table 1-10 collates evidence for the impact of varying luminance, illumination, wavelength and stimulus size in perimetry.

Parameter evaluated	Author & Year.	Sample	Purpose	Measures/ intervention	Results	Conclusion
Luminance/ illumination	Klewin & Radius. 1986.	31: Normal. (right & left eye)	To evaluate normal participants on the Octopus perimeter using neutral density filters,	Tested on: Octopus perimeter adding neutral density filters. Measure of: Threshold sensitivity.	Threshold sensitivity reduced with filters of 0.5 log units or greater. No effect in threshold sensitivity with 0.25 log filter.	Reduction in background luminance reduced threshold sensitivity.
	Mutlukan & Damato. 1992.	8: Normal.	To determine the disappearance eccentricities of dark & bright stimuli of equal size in the inferonasal central visual field using oculokinetic perimetry.	Tested on: Black tangent screen. Grey tangent screen. White tangent screen. Using a white & a black stimulus for all screens & two levels of illumination (13 lux & 400lux). Measure of: The eccentricity from fixation the target could no longer be seen.	The isoptre was smaller for the black stimulus on the white background compared to the white stimuli on the black background. At 400lux the white stimulus isoptre increased by 59% & the black stimulus isoptre increased by 36%. On the grey background at 400lux the white stimulus isoptre increased by 117% & the black stimulus isoptre increased by 75%.	A bright stimulus on a dark background has a larger ispotre than a dark stimulus on a white background. The variation in ambient illumination & consequent alteration in background luminance has less impact on the visibility of a dark stimulus than a bright one.
	Garcia-Perez & Peli. 1997.	None.	To question the validity of Rovamo *et al's* (1996) conclusion that the critical illuminance for the transition from DeVries-Rose to Weber's law is proportional to squared frequency at all retinal locations.	Inspection of raw data. Measure of: Determining if the data fulfils the DeVries-Rose & Weber's law.	Without the guiding line the data did not show the characteristic reported. Data displayed increasing sensitivity which then decreased with increasing illuminance without traces of Weber's law. Author of research in question previously acknowledged a decreasing range in 50% of their data, but this was not discussed. The author of the research in question fitted a function to accommodate the transition even when the transition did not occur.	The data only provided strong evidence that the DeVries-Rose range is sometimes followed by a range that is different to the Weber's range.

Manji & Plant. 2000.	24: Previous temporal lobe surgery for epilepsy.	To compare the identification of defects with Goldmann & EVFT.	Tested on: Goldmann with stimulus of 1000asb. EVFT with stimulus of 3150 asb. Measure of: Detection of defect. Fitness-to-drive pass/fail frequencies.	Goldmann found 13/24 defective fields. EVFT found 11/24 defective fields. EVFT failed 25% as fit-to-drive. Goldmann failed 42% as fit-to-drive.	The EVFT with stimulus of 3150asb, is more lenient than Goldmann, with stimulus of 1000asb, in patients with VFL resulting from temporal lobe surgery for epilepsy.
Kang *et al*. 2009.	3: Normals (+ 2 cats)	To compare sensitivity in dim light for cats & humans. To measure contrast sensitivity for Gabor functions and adaption levels over the majority of the mesopic & all of the scotopic range.	Tested with: Greyscale Gabor functions of spatial frequencies of 0, 1/8, 1/4, 1/2, 1, 2 or 4cpd at varying luminance levels using neutral density filters. Measure of: Contrast threshold.	Contrast thresholds decreased linearly with display luminance. Thresholds decreased with longer presentation times. For humans, the incremental thresholds were mostly proportional to the square root of illuminance. Contrast sensitivity was absent to 4cpd in scotopic conditions.	In dim light levels incremental thresholds followed DeVries-Rose law. Lower luminance & longer presentation times decreased contrast sensitivity.
Gruber *et al*. 2013.	None.	To review the literature to ascertain the impact of vision on night driving abilities in older people.	Literature review.	Correlation between impaired mesopic vision & impaired night driving. Mesopic VA decreases with decreasing illumination. In mesopic light conditions, VA drops to approximately half of the photopic VA.	Photopic VA alone is not a good predictor of night driving ability. Mesopic VA seems relevant to night driving.

Swanson *et al*. 2014.	Experiment 1: 20: Younger participants. 10: Older participants. Experiment 2: 12: Younger participants.	To develop perimetric stimuli which are resistant to reduced retinal illumination.	Tested on: For experiment 1: Matrix using a stimuli of 0.25cpd & background luminance of 314asb. Custom test contrast sensitivity perimetry 1 (CSP-1) using stimulus 0.38cpd & background of 157asb. For experiment 2: CSP-1 at 42º & 24.4º eccentricity using a stimuli of 1cpd & background luminance of 58.72asb. 0.25º & 0.5º Gaussian blobs with background luminance of 31.4asb. Use of neutral density filters for all tests. Measures of: Contrast sensitivity. Change in mean sensitivity for each stimulus & neutral density filter.	Decrease in contrast sensitivity with decreased retinal illumination with Matrix & CSP-1. CSP-1 adhered to Weber's law. CSP-1 with lower temporal frequencies more consistent with Weber's law than Matrix with higher temporal frequencies.	Perimetric sensitivities are consistent with Weber's law when higher temporal frequencies are used. Contrast sensitivity decreases with decreased retinal illumination.
Seim & Valberg. 2015.	9: Normal.	To analyse psychophysical, achromatic luminance threshold & scaling data.	Tested with: Three surrounds with luminance of 19.78, 197.82 & 1978.2 asb surrounding grey fields of sizes 15, 12 & 3.5º. Test flash used with durations of 0.1 & 26 seconds. A test field of 1º, with luminance range of 0.003 to 3140asb surrounded by a 180º hemisphere illuminated by white light.	Increasing presentation time increased the threshold sensitivity. Increasing surround luminance increased contrast sensitivity. Response to surround luminance increased close to linearly.	Increasing surround luminance increases contrast sensitivity. Threshold data can be traced to cone-specific responses over a larger range of stimulus intensity than previously anticipated. The adaptive responses followed Weber's law.

	Seim & Valberg. 2015 continued			Measures of: Threshold & contrast sensitivity.		
Luminance/ illumination/ wavelength	Sharpe *et al*. 1992.	5: Normal. 1: Achromat. 1: Blue-cone monochromat. 4: Deutranope. 1: Protanope.	To measure incremental thresholds of a 6º, 200 ms duration target, 12º temporally from the fovea on various background intensities & wavelengths, in rod-isolation conditions.	Tested with: 6º target presented in an 18º adapting field using a 520 nm stimulus on backgrounds with wavelengths of 450, 520, 560 & 640 nm. Neutral density filters used to alter luminance. Measures of: Rod-detected portions of incremental thresholds. Rod-detected portions of incremental thresholds in a bichromatic field. Target thresholds following transition between two backgrounds of different wavelengths (506 & 640 nm).	Rods determine threshold up to the higher scotopic background intensities on the 640nm background more than on the shorter wavelength backgrounds. Rod adaption is independent of field wavelengths of 450 to 560 nm, but not on the 640nm background. Achromatic rise in threshold with backgrounds of 450-560nm was similar to normal participants.	Adaptive behaviour of the isolated rod visual system is influenced by cones. Sensitivity of rods is not determined by the quantal absorption of rods alone, but also by the quantal absorption of cones. There is rod-cone interaction.
	Rovamo *et al*. 1996.	2: Normal.	To measure contrast sensitivity as a function of integrated radiance for a series of interference filters with peak wavelengths of 400 to 700 nm.	Tested with: Cosine gratings with spatial frequencies of 2 c/cm & display setting to 157 asb, with interference filters ranging from 400 to 700 nm & neutral density filters to lower luminance. Measures of: Contrast threshold. Contrast sensitivity as a function of integrated radiance.	Irrespective of wavelength, the grating field retained its normal colour at all radiance levels. Contrast sensitivity increased with increased integrated radiance. Contrast sensitivity was highest at 550nm & decreased at shorter & longer wavelengths. The increase in contrast sensitivity obeyed DeVries-Rose law at lower radiances & a clear transition to Weber's law occurred at higher radiances.	Results suggest the contribution of rods to contrast sensitivity was minimal even at the lower radiance levels. Contrast sensitivity is highest at 550 nm. At low levels of radiance, increase in contrast sensitivity obeys DeVries-Rose law, & Weber's law at higher radiances.

Nieve *et al*. 2002.	3: Normal.	To examine the mean luminance for red-green gratings.	Tested with: Sine-gratings at three spatial frequencies. Red-green gratings. Measure of: Mean threshold.	At the lower spatial frequencies, the flux was not a critical factor for the red-green gratings.	Luminous flux is not a critical factor in chromatic grating at lower spatial frequencies.
Cengiz *et al*. 2005.	10: Normal.	To determine reaction times to an achromatic stimulus appearing along horizontal & vertical meridians on uniform & non-uniform backgrounds under mesopic conditions.	Tested on: Three uniform backgrounds (red, blue & white) with background luminance of 0.31 asb & 3.14 asb. Three non-uniform white backgrounds using three different luminance patterns (elliptical, road scene & windscreen) of luminance 0.31 asb & 3.14 asb with 1.5º achromatic stimuli. Measure of: Reaction time.	Mean reaction times for foveal targets for blue & white backgrounds were longer than those at 10º eccentricity. Red background reaction times were higher than those on white or blue backgrounds. Reaction times in the periphery on white backgrounds of 3.14 asb were lower than on red & blue backgrounds. Blue backgrounds had the highest missed targets in the extreme periphery at 3.14 asb, & shorter reaction times than those for red & white backgrounds at 0.31asb. At 0.31 asb & 3.14 asb, the furthest a target could be detected was 60º from fixation for uniform backgrounds. For non-uniform backgrounds, reaction times were affected by the local luminance in the periphery & detection was lower for non-uniform backgrounds.	The effect of light spectral sensitivity on reaction times is more significant at lower luminance. Blue backgrounds provide faster reaction times in the periphery at lower luminance. Reaction times depend upon the local luminance of the task. Luminance distribution also affects visual performance.

Luminance/ stimulus size	Dengler-Harles. 1991.	20: Control. 9: Glaucoma. 8: Ocular hypertension. 1: Low tension glaucoma. 2: Suspect glaucoma.	To investigate the efficacy of variations in stimulus size, duration, location & adaption level for the earliest detection of VFL in glaucoma.	Tested on: Octopus with background luminance of 4 asb. HFA 30-2 with size I & III stimuli with background luminance of 31.5 asb. Measures of: Defect detection. Mean sensitivity values.	No difference in defect detection between size I & III. Group mean sensitivity values were lower on the HFA than on the Octopus perimeter.	The HFA, with background luminance of 31.5 asb, may be more sensitive for the detection of diffuse glaucomatous VFL than the Octopus, with a background luminance of 4asb. No difference in detection of defect between sizes I & III stimuli.
	Gloriani *et al*. 2016.	3: Normal.	Considering rod-cone interactions, photon noise & spatial summation, to analyse links between psychophysical measurements & retinal physiological evidence.	Tested with: Two concentric beams aimed at the pupil of the observer. One beam being the background (1º to 10º), the other being a 640 nm red light stimulus (0.45º & 2º). Neutral density filters employed to control luminance. Measure of: Incremental threshold.	The incremental threshold increased with background luminance. Weber's law observed. When test size reduced, the incremental threshold increased. Incremental threshold increased at greater eccentricities. When the background field was reduced to 1º with a 0.45º stimulus, the linear relationship disappeared, particularly at background luminance of 15.7 asb.	Weber's law maintained at 10º backgrounds, but not for 1º backgrounds. For small background & test size combinations, at background luminance of 1.88 to 15.7 asb & eccentricity beyond 6º, there is rod-cone interaction.
Stimulus size	Fankhauser & Haeberlin. 1980.	2: Normal.	To measure the blind spot to establish the effects of stray light.	Tested on: Octopus with background luminance of 4 asb with varying stimulus sizes of I to V. Measure of: Blind spot.	Increasing the target size provided a false profile of the blind spot.	Increasing target size results in stray light falsifying profiles of the blind spot.

Rijn. 2002.	20: Glaucoma.	To investigate the level of agreement between the EVFT & Goldmann techniques.	Tested on: HFA 30-2 SITA Standard. Binocular Goldmann with varying stimuli. Binocular EVFT. Measures of: Defect location. Horizontal field extension. Fitness-to-drive pass/fail frequencies.	Horizontal field extension: EVFT tends to be stricter than Goldmann with V4. Goldmann tends to be stricter with III4 than EVFT. Pass/fail frequencies: Goldmann with III4 & EVFT in full agreement. Three subjects who passed the Goldmann with V4 failed the EVFT & Goldmann with III4. 9 subjects failed Goldmann with I4 & passed EVFT & Goldmann with III4. Defect location agreement with HFA 30-2: EVFT agreed with 14/20 fields. Goldmann with I4 agreed with 13/20 fields. Goldmann with I3 agreed with 16/20 fields.	Pass/fail frequencies are independent of any of the techniques used. Goldmann with I3 & HFA 30-2 have better agreement in location of defect than the other techniques used. Goldmann with III4 is stricter than EVFT & Goldmann with V4 for horizontal extension of field. No agreement on size of defect in any of the methods. EVFT stimulus 1.6x more visible than Goldmann with III4.
Patel *et al*. 2007.	50: With field defects found on SITA.	To compare visual field defects found by SITA & Matrix perimetry.	Tested on: HFA 24-2 SITA size III (0.43º). HFA 24-2 Matrix with stimulus 5º square. Measures of: Defect identification. Mean threshold. Defect size. Defect depth. Global indices.	36% of defects missed on Matrix. Defects on SITA were larger & shallower. Location of defect congruent in 30% of eyes. Glaucoma Hemifield Test agreement was poor.	Matrix did not detect 36% of defects found by SITA with size III. Defects on Matrix were smaller & deeper than those found with SITA with size III.

Wall *et al*. 2008	120: Glaucoma. 60: Control.	To compare empirical probability plots in patients with glaucoma for size V & III perimetry testing.	Tested on: HFA 24-2 SITA Standard size III. HFA 24-2 FT size V. Measure of: Amount of abnormal test locations.	Similar number of test locations found with both strategies.	Size V FT provides a similar number of abnormal test locations as size III SITA Standard.
Wall *et al*. 2010	Tested once a week for five weeks: 32: Glaucoma. 20: Control. Tested at baseline & again at separate sittings within one to eight weeks: 120: Glaucoma. 60: Control.	To establish the associations between the threshold estimated by 4 perimetric tests & to define & compare the tests effective dynamic range.	Tested on: HFA 24-2 SITA Standard size III. HFA 24-2 FT size V. Motion perimetry. Matrix perimetry. Measures of: Dynamic range. Discernible steps.	The association of sizes III & V was linear up to 20 dB & with motion & Matrix perimetry up to approximately 25 dB from 0 dB.	Size V stimuli have a greater dynamic range than size III. Size V stimuli has twice as many discernible steps than size III.
Kalloniatis & Khuu. 2016	10: Glaucoma. 1: Glaucoma suspect. 2: Optic nerve drusen.	To determine if target stimuli close to complete spatial summation results in larger threshold elevation than a size III target.	Tested on: HFA 30-2 with size III. HFA 30-2 with sizes I, II & III. Measures of: Threshold sensitivity. Global indices.	Target sizes increasing with eccentricity found a greater number of events than just using size III by 40%. MD & PSD are significantly worse using varying target sizes than just using size III.	When compared to the current paradigm, the use of varying target sizes reveals a greater loss in patients with optic nerve disease for both event analysis & global indices.

	Phu *et al*. 2017	60: Control. 20: Glaucoma.	To determine if size V thresholds could predict size III thresholds. To test the suitability of size V for detecting VFL in patients with early glaucoma, & to examine eccentricity dependent effects on the number & depth of defects. To determine if stimuli operating in complete spatial summation would detect more & deeper defects.	Tested on: HFA 30-2 FT with size III & V stimuli. Measures of: Thresholds at each location. Global indices.	Size III & V were within +/-3 dB in 90.5% of control participants & 62.3% of glaucoma participants Difference in defects found was not significant, but size III detected more defects than size V at increasing eccentricity. . MD & PSD for size V were significantly lower compared to size III. Defect depth greater with size III than size V.	Size III locates more defects than size V, but only at the outermost regions of the visual field. Size III locates greater defect depth than size V. Global indices with size III indicate more VFL than size V.

Table 1-10. Evidence for effects of varying luminance, illumination, wavelength & stimulus size in perimetry. Studies presented are grouped into categories of luminance/ illumination, luminance/ illumination/ wavelength, luminance / stimulus size and stimulus size. Within each category studies are presented in date order.

1.15.1. Retinal Illumination and Adaption.

The retina has neuronal abilities to allow for adaption. Parvocellular cells provide us with the perception of brightness and lightness (Seim & Valberg. 2015). At different levels of illumination there will be a different response from the photoreceptors of the retina. Cones mediate when exposed to bright background levels and rods mediate alone at dim background levels where the rod threshold is elevated but has no direct effect upon the cones. Under mesopic light levels then there is rod-cone interaction. Increasing the intensity for a rod adapting background not only desensitises the rods but will also desensitise the cones (Sharpe *et al*. 1992). The shifting of retinal adaption to scotopic levels will increase the sensitivity of the rods and lower the sensitivity of the cones. Detailed vision also reduces (Argus & Brenton. 1986). In addition, the density distribution of these photoreceptors varies across the retina. Rod-cone interaction has been found at luminance levels between 1.88-15.7 asb at retinal eccentricities of 6-9° (Gloriani *et al*. 2016).

Contrast sensitivity at low mesopic conditions, i.e. mid-range luminance and at rod light levels, follow DeVries-Rose law (Kang e*t al*. 2009) increasing in proportion to the square root of the luminance (Rovamo e*t al*. 1996, Rudd & Rieke. 2016), being found to be constant at background luminances of both 4 asb and 31.5 asb (Fankhauser. 1986) and holds for backgrounds of 3.99 asb (Fankhauser. 1979). This law is followed with both gratings and spots presented at short duration (Kang *et al*. 2009).

Higher luminance follows Weber's law (Nieve *et al*. 2002, Rovamo e*t al*. 1996). Factors that affect retinal illumination are pupil diameter and the density of the crystalline lens (Swanson *et al*. 2014). Weber's law states that the when the background and stimulus luminance is reduced by the same amount there is no effect due to pupil size or lens ageing, therefore, Weber's law is independent of pupil size (Dengler-Harles. 1991) and predicts that the contrast sensitivity does not decrease when retinal illumination decreases (Swanson e*t al*. 2014) therefore being constant. At the photopic range retinal sensitivity behaves under Weber's law and the just noticeable increment is proportional to the background luminance (Koenderink *et al*. 1969), and decreases inversely proportional to the light level (Freeman *et al*. 2010).

It is known that the DeVries-Rose and Weber transition holds for above threshold and at the threshold for stimuli presented for short durations in the form of a small spot (Garcia-Pervez. 1997).

How brightness is distributed within the visual field has a direct impact on vision processing (Dorosz *et al*. 2002). The retina undergoes both luminance and contrast

adaption. Variations in ambient lighting, spectral distributions and angular subtense (Cengiz *et al*. 2015) are adapted to by the visual system with adjustment to its sensitivity (Sharpe *et al*. 1992, Virsu & Lee. 1983). The retina will adjust to the mean light sensitivity within the visual field. The average light level that the human eye is exposed to influences the eyes sensitivity (Rasengane *et al*. 2001. Freeman *et al*. 2010) and results in a change in the hill of vision profile, also known as the island of vision (Henson. 2001). Due to the visual systems regulation of sensitivity the response is more akin to contrast than the differences in luminance or the absolute luminance (Virsu & Lee. 1983). Luminance adaption allows normalisation of the ambient lighting. Contrast adaption allows modulation of retinal gain due to variations on the visual field which occurs when a white-noise is presented for a space of time (Tchoudomira *et al*. 2015), the essence of perimetry. Within a large dynamic range of light levels, retinal adaption allows detection of a stimulus (Gloriani *et al*. 2016, Freeman *et al*. 2010).

Detection thresholds are affected by various factors including luminance and contrast of the background (Sebastion *et al*. 2017). The detection of a bright flash of light is dependent upon the background luminance. When the background intensity decreases, the retinal sensitivity increases across the entire retina. The profile also becomes flatter with the increase in sensitivity with eccentricity, but this aspect becomes irrelevant with SAP, the result is not dependent upon the sensitivity profile (Henson. 2001). There is a rise in threshold as the luminance of the background rises (Lennie. 1979). Using spatial frequencies of 0.0-0.1 cpd presented as a rectangular temporal pulse and spatial frequencies of 0.14-0.5 cpd presented in 57 locations and being presented more peripherally across the 30º visual field gives rise to a reduction in contrast sensitivity when retinal illumination is decreased (Swanson. 2014).The higher the luminance presented there is less likelihood of false-positive results, but a higher likelihood of shallow defects being undetected (Johnson & Kettner. 1983). It has been found that using neutral density filters in an attempt to lower the background luminancce of a perimeter resulted in the production of significant visual field defects. Also due to the low level background luminance of 4 asb of the perimeter combined with the optical media reducing the light transmission may result in changes in the retinal sensitivity that was of significance (Klewin & Radius. 1986). Rijn (2002) found that according to Ricco's law a Goldmann stimulus (I4) was 1.6 x less visible than the EVFT. The dimmer stimulus was more sensitive. Variations in retinal illumination has been shown to have an influence on FDP (Swanson e*t al*. 2014). The dynamic range of a perimeter is the measurement range of the perimeter (Pfau *et al*. 2017). A benefit of lowering background luminance is to increase the dynamic range of the instrument.

Lowering backgrounds to 3.99 asb can increase the dynamic range by 5 dB (Fankhauser.1979). Diffuse VFL with backgrounds of 31.5 asb is detected easier than with a 4 asb background using the same size stimulus (size III) and providing different exposure times to the stimulus (200 ms and 100 ms respectively) (Dengler-Harles. 1991). Between-subject variability is affected by retinal illumination (Swanson *et al*. 2014).

Dark adaption is known to be compromised in certain pathological conditions. When a patient enters a darkened room from a lighter room then the eyes need time to dark adapt. This process usually only takes a few moments when visual field screeners have a background luminance within the upper mesopic and lower photopic range (Henson. 2001).

The detection of a stimulus has a strong dependence on the size of the stimulus as well as the eccentricity and wavelength of the stimulus (Virsu & Lee. 1983).

With respect to driving performance, lower contrast sensitivity scores, measured on the Pelli-Robson contrast sensitivity test chart, of 1.5 log contrast sensitivity or lower, has been found to be correlated to poorer performance in lane changing, speed matching and steady steering ability (Bowers *et al*. 2005). Contrast sensitivity is reduced when retinal illumination is reduced (Swanson *et al*. 2014). People who have some loss of visual field have been found to restrict their night-time driving (Kaleem *et al*. 2012). This is likely to be due to the reduction in visual field due to the lower level of luminance. It has been found that there is a higher sensitivity to vision loss under mesopic testing compared to photopic testing (Maynard *et al*. 2016).

If the background luminance varies between perimeters, the state of retinal adaptation is different and therefore the normal hill of vision profile. The HFA and Henson Pro 5000 background luminance differs and is further discussed in chapter 5.

1.15.2. Light Emitting Diode (LED) Lights and Colour Influence on Visual Field Loss.

Pathology has an impact on colour vision. Rauscher *et al* (2007) examined the colour vision in patients with central VFL and showed that the detection of colour was one of the stimulus attributes most affected, finding them to be outside the normal range for blue/yellow and red/green determination within the paracentral areas external to the scotoma (Rauscher *et al*. 2007). Glaucoma causes damage to the optic nerve and in the early stages is proposed to show damage in the magnocellular and koniocellular pathways. Although initially thought to be mediated by the parvocellular pathway, it is

now thought that short-wavelengths are mediated by the koniocellular pathway (Gardiner *et al*. 2006b). Therefore, damage to this pathway has the potential to exhibit colour vision defects within the blue-yellow parts of the visible spectrum. These defects demonstrated with blue stimuli have only been determined with a yellow background. This strategy is utilised by short wavelength automated perimetry (SWAP) which presents stimuli of short-wavelength on a yellow background and can detect blue-yellow colour vision defects earlier than SAP. (Delgado *et al*. 2002, Henson. 2001). When blue-yellow defects progress, and are found on white-on-white the blue-yellow defects are larger (Henson. 2001).

When measuring contrast sensitivity as a function of integrated radiance using gratings, contrast sensitivity has been found to be highest at wavelengths of approx. 550 nm regardless of the radiance level (Rovamo e*t al*. 1996). In those with retinitis pigmentosa it has been found that sensitivity increases at eccentricities of 10° with the increased pupil size that occurred with LED stimuli (Wood. 1987).

In experiments aiming to increase miner's safety by enabling better detection of peripheral hazards, LED lighting combinations increase illuminance and in turn increase peripheral visual performance (Reyes *et al*. 2013. Sammarco *et al*. 2009, Reyes e*t al*. 2014, Sammarco e*t al*. 2010) with detection times of hazards being on average 13.6% faster compared to the use of incandescent lamps. It may be that the illumination methodologies were different, but it could also be due to the differences in spectral emission produced by the different lighting. LEDs can be classed as cool white and possess more shortwave energy compared to the longer wavelength energy possessed by incandescent bulbs (Sammarco *et al*. 2010). At lower light levels, the eye is more sensitive to shorter wavelengths, this shift is known as the Purkinje effect (Uchida & Ohno. 2014).

The difference in sensitivity between the rods and the cones is less noticeable with increased wavelengths of light and therefore shorter wavelengths cause the cones to obscure responses from the rods (Sharpe *et al*. 1991). Sharpe e*t al* (1991) found that by varying the background wavelength for a normal participant and an achromat, who had no functioning cone vision, it gave rise to rod threshold variations particularly with the 640 nm field compared to shorter wavelengths. They also determined by field-mixture experiments, where the incremental threshold was measured against bichromatic backgrounds, that a transition only visible to cones still gives rise to an increase in rod threshold and therefore concluded that rods do not adapt independently of cones.

The ageing effect exhibited in SWAP is more than that exhibited in SAP, and for both it is greater in the peripheral visual field than in the central visual field (Gardiner *et al*. 2006).

Colour rendering index (CRI) provides on a scale of 0-100 the ability of a light to render colour accurately. 100 is the value for the most accurate rendition of colour (Optical Radiation Group. 2016). The CRI value of the halogen bulb of the HFA is 100. For the LED lights used in the Henson Perimeter it is quite elusive and no reference to it has been able to be sourced. In the manual for the Henson Perimeter the CRI value is not provided.

1.15.3. Stimulus Size.

Larger stimuli allow a greater dynamic range (Fankhauser. 1979) and less variability (Wall *et al*. 2010, Gardiner *et al*. 2006). The effects of blur are also reduced. The effect of masking blur effects for targets larger than 0.43º (HFA size III (Patel *et al*. 2007) can be up to 3D. The effect of increasing dynamic range is more pronounced in the periphery than within the central visual field. Using background luminance of 3.99 asb and increasing target size from 0.11º(size I) to 0.43º(size III) has given an increase of 12 dB in dynamic range 50º from fixation and an increase of 3-4 dB near fixation (Fankhauser. 1979). Comparison of size III versus size V on the HFA has been shown to be comparable within +/- 3 dB for 90.5% of patients with no VFL but only comparable for 63.2% for those with glaucoma and this decreased with increasing eccentricity. However, the size III located more defects in the more peripheral areas of the visual fields in these patients and was able to determine more severe loss when compared to the size V stimulus (Phu *et al*. 2017). A smaller size stimulus has greater resolution in detecting small scotomas compared to a larger stimulus and greater defects have been established in patients with optic nerve disease (n=13) when using combinations of size I, II and III sized targets with MD having a mean of -6.25 dB compared to the -3.47 dB found when only utilising a size III target (Kalloniatis & Khuu. 2016). However, it has also been found that a large size V stimulus can locate similar abnormal test locations when compared to a size III stimulus with no significant difference between the abnormal test locations (Wall *et al*. 2008). In contrast, although dynamic range increases, larger stimuli presented at a luminance of 1000 asb on a background of 4 asb produce more stray light (Fankhauser & Haeberlin. 1980).

1.16. Comparing the Sensitivity of the Humphrey Visual Field Analyser and Henson Pro Perimeter EVFT.

The EVFT test is uniformly conducted at 10 dB. However, the HFA and Henson Pro 5000 Perimeter have differing backgrounds. Comparative and differing aspects of the two perimeters are further discussed in chapter 5.

2. Research Rationale.

2.1. The Repeatability and Reproducibility of the Esterman Visual Field Test in Cases of Established Visual Field Loss.

In accordance with the DVLA, to determine a person's fitness-to-drive, two aspects of vision are the deciding factors. These are the visual acuity and the visual field. The visual field examination used, recommended by the A.M.A and recognised by the International Perimetric Society is the EVFT. This binocular ST examination, that was devised more than 40 years ago (Crabb *et al*. 2004), is considered to possess many limitations. Although, the main visual aspect that contributed to accidents in Great Britain during 2014 was "looked but failed to see" (Department of Transport. 2014), which may relate to attention rather than the measured visual field, it is the EVFT that holds the important status of allowing retention or the revocation of a driving licence based upon the visual field. Visual field examinations are subjective and highly variable (Kim *et al*. 2005) suffering from long-term fluctuation when testing occurs at different sessions (Wroblewski e*t al*. 2014). This can be evident over a period of weeks (Nouri-Mahdevi *et al*. 2011) and can make identifying defects difficult (Fankhauser & Bebie. 1978) due to the within-subject variability (Swanson e*t al*. 2005). Visual fields can also suffer from the learning effect (Birch e*t al*. 1995), where results improve with repeat testing (Tattersall *et al*. 2007. Hitchings. 1994). It is well established that variability in visual field results occurs in areas of damage where sensitivity is reduced (Miranda & Henson, 2008, Wall *et al*. 2008, Haley. 1993, Crabb *et al*. 1996. Henson *et al*. 2000, Turpin *et al*. 2007, Gardiner e*t al*. 2006, Artes *et al*. 2003, Viswanathan e*t al*. 1997, Birch e*t al*. 1998, Heijl e*t al*. 2012, Birch e*t al*. 1995, Bentley e*t al*. 2012, Spry *et al*. 2003). Patterns of variation for same day testing have ranged from quadrantanopic to hemianopic (Wall e*t al*.1998) and in glaucomatous individuals they have ranged from no defect to absolute scotoma on follow-up examination (Heijl e*t al*. 1989). Variation can reach up to 14/15 dB (Nouri-Mahdavi *et al*. 1997, Swanson e*t al*. 2014, Gardiner. 2003). The EVFT provides a score known as the EES, which is a percentage of the stimuli detected. In those with glaucoma, the EES has provided a limited range, averaging in the high 80% and skewed around this score (Jampel *et al*. 2002b). The EVFT does not permit objective fixation monitoring (Chisholm. 2008b. Crabb et *al*. 2016, Ayala. 2012). Those with CFD can find it difficult to maintain fixation and even view stimuli eccentrically (Esterman. 1985). This lack of fixation can cause an inaccurate representation of the visual field (Nowakowski. 1994).

Short term fluctuation can occur within the same testing session (Wrobleski *et al*. 2014). The EVFT examines with a size III stimulus at a set value of 10 dB. The decibel is a relative value of attenuation from the maximum intensity of the stimulus available (Imaging and Perimetry Society. 2010) hence, this is a relative scale and can differ between perimeters. The EVFT is not instrument specific and can be performed on other perimeters other than the HFA. One such perimeter is the Henson Pro 5000 Perimeter. The Henson Pro 5000, although an older version with newer model's now available, has the potential of still being found within optometric practice. This perimeter performs the EVFT with a stimulus of 31.80 asb on a background bowl luminance of 10 asb. Whereas the HFA performs the EVFT with a stimulus of 1000 asb on background luminance of 31.50 asb. The HFA background luminance matches that used by the Goldman perimeter and is the recommended standard of the International Perimetric Society. The background luminance of the HFA at 31.50 asb is at the lower end of the photopic range (Heijl e*t al*. 2012). The background of the Henson Pro 5000 Perimeter, although has been considered to also be at the lower photopic end (Henson. 2001), at 10 asb/3.15 cd/m^2 can be considered to fall within the mesopic range of vision as defined by the International Commission on Illuminations system of mesopic photometry (Halonen & Bizjak. n.d.) of 0.02-15.70 asb. There is higher sensitivity to vision loss under mesopic testing compared to photopic testing (Maynard *et al*. 2016). Differences calculated in contrast threshold using known formula are presented within appendix 3. Detection thresholds are affected by various factors including luminance and contrast of the background (Sebastion *et al*. 2017). The average light level that the human eye is exposed to influences the eyes sensitivity (Rasengane *et al*. 2001). The retina will adjust to the mean light sensitivity in the visual field (Freeman *et al*. 2010) and there is a rise in threshold as the luminance of the background rises (Lennie. 1979) and hence a reduction in sensitivity as it decreases (Swanson *et al*. 2014). The higher the luminance therefore increases the likelihood of shallow defects being undetected (Johnson *et al*. 1983) and likewise, lower luminance gives rise to more significant visual field defects (Klewin & Radius. 1986). This also impacts on within-subject and between-subject variability (Swanson *et al*. 2014). In 2015 there was an incident whereby many people had their licences revoked due to failing the EVFT and due to a fault of the machine or program. The DVLA has not been able to disclose the model or make of the machine that was at fault (Phillip. 2016, personal communication, 04 May).

A driver found to have reduced visual fields, in as much as not meeting the DVLA criteria, can have their licence revoked. Losing a licence is psychologically traumatic

and reduces quality of life (Medirios e*t al*. 2012, Ramulu e*t al*. 2014, Trento e*t al*. 2013) and can lead to depression (Racette e*t al*. 2005, Ragland e*t al*. 2005, Langham e*t al*. 2013, Kaleem e*t al*. 2012). Losing a licence impacts on the practicalities of life such as freedom to work and go shopping and the loss is considered to be a significant life event (Owen *et al*. 2008). Reducing travel options can result in social isolation (Racette *et al*. 2005) and social isolation can subsequently add to the incidence of depression (Bradley & Mitchell. 2006). A test determining someone's fitness-to-drive should possess high sensitivity and specificity (Coeckelbergh e*t al*. 2004). It is imperative that the visual field test to determine fitness-to-drive is repeatable and reproducible to avoid a licence being revoked for a person who is potentially safe to drive. It also needs to be stringent enough to establish those who would pose a risk to themselves and others and hence, should not be driving.

2.1.1. Aims.

2.1.1.1. Sub-study 1: The Repeatability of the Esterman Visual Field Test in Cases of Established Visual Field Loss.

The primary aim of the first sub-study was to establish if the EVFT is repeatable in those it has the potential to impact, namely those with VFL. Repeatability is defined here as the ability of the EVFT to repeat test results when testing on different occasions using the same perimeter. Due to evidence that perimetry results for those with VFL possess retest variability then it is predicted that there will be more variance in EES in those with VFL compared to those without VFL. It is also predicted for the members of the VFL population, that the location of defect will also possess more variance compared to those without VFL. If these factors provide differing pass/fail frequencies across visits this will have a significant impact upon an individual. Repeatability was to be determined via analyses of EES, pass/fail frequencies, and point-by-point analyses across three visits conducted one week apart. Secondary aims were to determine any inconsistencies in pass/fail frequencies in those who would be able to hold a driving licence with the visual field criteria excluded. To determine an overlap zone of the EES for when a participant is likely to pass on one visit and fail on another as well as the EES threshold when a participant would fail on all tests or pass on all tests. In addition, any influence on age and EES were also to be analysed.

2.1.1.2. Sub-study 2: The Reproducibility of the Esterman Visual Field Test in Cases of Established Visual Field Loss.

The primary aim of the second sub-study was to determine if the EVFT is reproducible in those with VFL. Reproducibility is defined here as the ability of the EVFT to create

the same test results when testing occurs on two different perimeters. This was to be achieved by comparing agreement and any subsequent differences in EES between two perimeters that can be used to undertake the EVFT in optometric practice, and to compare each result of stimuli seen or not seen point-by-point. In addition, agreement was to be established via pass/fail frequencies between perimeters. Secondary aims were to establish the range in variance of the EES between perimeters, to determine an overlap zone whereby it could be possible to predict the pass/pass; pass/fail and fail/fail frequency based on the presenting EES, to determine agreement in pass/fail frequencies in those who would be able to hold a driving licence when the visual field criteria is excluded, and to establish any impact of age on EES.

2.1.2. Previous Work.

A review of the literature established that to date there have been no studies to evaluate the repeatability or reproducibility of the EVFT. This research is therefore novel.

2.2. The Reproducibility of the Ring of Sight Visual Field Screener.

The ROS (Ibis Vision, Lanarkshire, U.K.) is a novel computer program for visual field testing and is further discussed in section 6.1.1. and illustrated in section 3.2. This instrument is different to conventional visual field screeners in terms of ergonomics. It is a computer software program and the patient views the stimuli on a computer monitor. The ROS includes a FT strategy. The grid design used for this visual field test matches the HFA 24-2 grid. When designing this perimeter, the manufacturers intended the greyscale of the ROS to be comparable to the results produced by the HFA (Donaldson. 2016b, personal communication, 07 October). Therefore, the ROS can be anticipated to find the same abnormal test locations overall. The ROS varies the contrast of the stimuli by the alteration of greyscale target depth (Donaldson. 2016a, personal communication, 15 February) rather than altering the luminance of a bright target that occurs in conventional perimetry. The stimuli presented are circular and remain at a constant size, which measures 6 mm. The stimuli are based on the Digital Imaging Communications in Medicine (DICOM) greyscale on a monitor. DICOM is a greyscale standard commonly used in radiography. The standard commonly used is the DICOM part 14: Greyscale Standard Display Function. The purpose of this standard is to ensure images are harmonised with equal contrast sensitivity (NEMA. 2009) regardless of differing monitor luminance and settings. Most colour monitors have 3 colour channels, red, blue and green. When all these sub-pixels have the same input value grey is perceived. Different greyscales can be obtained by allowing a colour

tint. This permits approx. 1,700-1,800 greyscale values (Sund *et al*. 2010). The various depths of presenting contrast of the ROS stimuli range from near white through to black. The stimulus alters in contrast until the target is detected by the patient at which point the sensitivity is determined. When a new stimulus is detected the patient moves their fixation to the new stimulus and then this becomes the new fixation point. Once indicated by the patient, the target, now acting as the fixation target, acquires the addition of rotational 'wind-mill' arms that surround the circular target. To inform the program the stimulus has been detected, the patient indicates this by having the task of moving a green circular target to the new stimulus via a Wacom electronic pen and pad. The program records the patients reaction times to five stimuli presented at the maximum level of contrast the stimulus can obtain at the beginning of the program. It uses the mean average of these reaction times to correct the final threshold results. It presents a further five stimuli presented from the lowest possible depth of colour that will increase in greyscale depth until it is noticed by the participant. It then presents the stimuli for the test at a pre-determined level it has established from the identification of these five stimuli. The examination only re-examines a visual field if the patient does not identify a stimulus at the pre-determined greyscale level obtained from the initial calibration during the test. If the patient does indicate they have seen all the stimuli at the pre-determined greyscale it was expecting, the program will only examine all the locations once. The patient sits in a chair at a measured 40 cm from the monitor in normal room lighting. The test is conducted with habitual correction worn by the patient, and the machine allows for either distance or near correction to be used. The patient details section allows indication of whether the near or distance correction has been worn. Fixation is monitored subjectively by the clinician who informs the program if fixation is lost by pressing a space bar on a laptop. The results of the visual field test can be stored on the computer and printed off as desired in-line with other conventional perimeters.

2.2.1. Intended Use of the ROS and the Potential Advantages.

The designer's rationale for the ROS was to produce a visual field screener whose portability could be utilised for domicillary visits and be considered more pleasant for the patient to undertake. Ergonomically the ROS may be advantageous to the patient in terms of comfort as there is no chin rest or forehead rest, which are normally used with other conventional perimeters. Therefore, the lack of forehead or chin rests may potentially make the ROS a more pleasant test to undertake compared to conventional perimeters. The portability and the potential of a more pleasant test than conventional

perimeters, may make it an attractive perimeter to invest in for both domicillary settings and within practice.

There are other attractive aspects to this novel perimeter. The designers anticipated that the ROS would be a quicker test than other FT methodologies. The shorter duration could reduce the fatigue (Tattersall *et al*. 2007) found in long duration FT examinations (Wall *et al*. 2001) which can lead to the depression of the visual field. The ROS has a stimulus size larger than the HFA. Larger stimuli allow a greater dynamic range and provide less variability (Wall e*t al*. 2010, Gardiner e*t al*. 2006). Therefore, various aspects could make this perimeter attractive and hence a practice may invest in this perimeter.

2.2.2. Potential Deficiencies of the ROS.

There are factors that may confound the instruments validity which have not yet been tested. The lack of chin and forehead rest may hinder the accuracy of the ROS due to the test location of the participant only being measured at the beginning of the test. It is impossible to measure throughout the test with the current set-up. Varying distance equals varying angular subtense of the target at the eye. Movement of the participants head may alter the position of the targets in the visual field and be a factor for variability. Variances in stimulus sizes impact on the hill of vision profile (Heijl *et al*. 2012) and can produce differences from absolute to relative scotomas (Haley. 1993). The ROS has a much larger measured stimulus size than the HFA. A smaller size stimulus has greater resolution in detecting small scotomas compared to a larger stimulus (Kalloniatis & Khuu. 2016). Therefore, the ROS may not locate small defects. The maximum presentation time possible on the ROS was measured to be on average 9.96 seconds. The stimulus being presented until it is detected leads to variable presentation times of the stimulus, in contrast to the HFA's standardised 200 ms presentation time. Foveal contrast sensitivity increases with increased presentation time and becomes constant at higher luminance within a test field (Seim & Valberg. 2015). Presentation time therefore impacts upon the hill of vision profile (Haley. 1993). Although it can be advantageous to have a quicker FT examination, there is a possibility that a rapid thresholding strategy can impact on the precision of the result (Spry *et al*. 2003). The method the ROS determines threshold, with the lack of the retesting of the test locations, has the potential of creating a ceiling effect and calls into question whether the FT program is actually measuring the patients FT and whether the manufacturers are correct in their claim that this is a FT examination.

Fixation is monitored subjectively on the ROS and the lack of objective monitoring may mean that poor fixation may be missed and an examination deemed reliable when it could in fact be unreliable. There is also currently no guidance on the ambient room lighting for this visual field examination. Heijl *et al* (2012) state that room lighting and differences in room lighting will impact on the hill of vision profile (Heijl *et al*. 2012). As far as the author is aware, the ROS has no normative data to assist in the detection or elimination of disease. How all of the aforementioned factors impact on the perimeters sensitivity and specificity is currently unknown. The use of new stimuli is difficult to ascertain if they will perform better than another test. McKendrick *et al* (2005) states that it is imperative to compare new testing methodologies with those already existing (McKendrick e*t al*. 2005).

2.2.3. Validation.

Although not yet validated the ROS is already available to purchase by practitioners, https://www.ibisvision.co.uk/ringofsight.html (IbisVision. 2019), and various factors make it a potentially attractive perimeter to invest in, including the expectation in finding the same defect depth and defect location as the HFA. Yet the ROS currently has no validation to determine whether it is a capable perimeter in determining disease or ruling out disease. There are factors that potentially limit the ROS's ability as a perimeter, but the impact of these factors have not been tested. A test that is already available for practices to purchase, which does not have the ability to detect or rule out disease poses severe consequences to members of the public. The consequence being unable to assist in the prevention of further avoidable sight loss. Furthermore, domiciliary visits are performed on patients with already existing ill-health from a physical or mental disability (College of Optometrists. 2019). Comorbidity gives rise to a reduction in health-related quality of life (Xuan *et al*. 1999). If the ROS perimeter is invested in to be used for domicillary visits and does not identify disease, this can lead to further reduction in health-related quality of life. Therefore, it is essential that any available perimeter for use on members of the public is evaluated and its validity determined.

2.2.4. Aims.

The primary aim of this study was to establish if the ROS perimeter is comparable to established perimeters and to determine the reproducibility of the ROS FT examination to the HFA SITA Standard in those with VFL. This was to be achieved with comparison to the HFA SITA Standard, by establishing agreement in threshold values at individual locations and across specific visual field zones, agreement of establishing defective or

non-defective fields, agreement of unweighted MD, agreement of point-by-point threshold values and agreement of point-by-point defect depth using the ROS Error Greyscale and the HFA probability plot. Secondary aims were to determine the sensitivity and specificity of the ROS FT examination, locate areas of uncertainty for ability of the ROS to determine defective and non-defective fields, compare fixation loses, duration of the examinations, impact of age on sensitivity values and compare participant experience.

2.2.5. Previous Work.

This perimeter has not previously been subject to evaluation with other perimeters in patients with or without VFL. The lack of validation limits this perimeter to be marketed as a competitor to established perimeters. It is considered that new methodologies should be validated against the HFA (Foster e*t al*. 2002). Using a sample of participants with VFL and those without VFL would assist in determining the programs ability to establish a defective field and a non-defective field.

3. Methods.

3.1. Participants.

Participants were recruited from Aston University Optometry School and local and national eye charities over a period of 18 months from September 2015 to May 2017. Glaucoma participants were recruited after responding to an advert in the International Glaucoma Associations publication, which the charity sends to its members. Those with central VFL were recruited after responding to mail shots sent by the local Macular Society group. Participants with a variety of conditions, which also included those with glaucoma and central VFL, responded to leaflets positioned in the Aston University Eye Clinic and Focus for Birmingham which is a local charity helping those with sight loss, mail shots sent by the Sandwell Visually Impaired group, the local Action for Blind and Royal National Institute for the Blind group and the Aston Research Centre for Healthy Ageing unit. In addition, participants with a variety of VFL were recruited via talks provided at events scheduled by Action for Blind and Sandwell Visually Impaired, and by the potential participant being asked directly when attending low vision appointments at the Aston Eye Clinic. Those recruited as controls, responded to leaflets in the Aston University Eye Clinic and mail shots sent from the Aston University Research Centre for Healthy Ageing unit. Seventy-six participants were recruited for the three studies. Ethical approval was obtained from Aston University Research Committee and conducted in compliance with the Declaration of Helsinki and within the Good Clinical Practice Guidelines. Written consent was obtained from all participants after they had read and understood a participant information sheet explaining the purpose and the procedures involved in the research.

The same participants were recruited to participate in all three studies. These three studies are as follows; The repeatability (study 1) and the reproducibility (study 2) of the EVFT in cases of established VFL and the reproducibility of the ROS visual field screener (study 3). Each study had a different representation taken from all the available participants recruited due to either, exclusion of the data or arising factors that meant there was no data from some of the participants to include within the study. Exclusions for each study are outlined later.

Those with VFL had a variety of presenting conditions. The variety of conditions within this cohort were discussed in section 1.2 and are detailed below. Age and gender matched controls were used in order to distinguish effects of repeatability and reproducibility of the EVFT, and the reproducibility of the ROS. The initial sample sizes

aimed for were found by *a priori* power calculations using GPower 3.1 software (Gpower 3.1.9.2 softpedia, Prajapati *et al*. 2010, Faul *et al*. 2007). To determine reproducibility of the EVFT between visits and between the HFA and Henson, and the validity of the ROS when compared to the HFA, the calculations to determine sample sizes were two-tailed, due to no previous evidence of a direction, and hence a direction could not be assumed. All calculations had an α level set at 0.05 and the power set at 0.80. There are no previous studies examining these factors and hence a small effect size was chosen in order to be conservative. Cohen's d of 0.10 was used when there was comparison of more than two means (Prajapati *et al*. 2010). The many different statistical tests being utilised throughout these studies resulted in many differing sample sizes. The largest sample size that would encompass all of the studies was 805. This sample size was not achieved upon recruitment, and subsequently power calculations were used to determine the power of any non-significant results. Although no previous studies examining the repeatability and reproducibility of the EVFT or the reproducibility of the ROS have been found to draw a comparison of suitable sample sizes, sample sizes recruited were similar to other reproducibility studies, such as that for the UFOV by Bentley *et al* (2012) where they used 56 participants separated into three groups; young controls, older controls and glaucoma patients, Nazemi *et al* (2007) where 55 participants were used, with 33 being the study glaucoma group, examining the repeatability of a 3D computer-automated visual field method and Spry *et al* (2005), where they recruited 62 participants to evaluate the FDT using the HFA 24-2 matrix.

Inclusion criteria were established VFL (study) or normal visual fields (controls), previous experience of a visual field test, no non-ocular health condition that could prevent following instructions or impact on visual field results, not taking medication known to effect the eye or the visual field, not suspected of an eye condition or ocular changes other than the diagnosed eye condition. Any visual field defect qualified the participant to take part, to represent those encountered in standard optometric practice. Controls were included if they had no history of eye disease. Any level of refractive error was permitted. All participants had a unique code for identification and anonymity.

Those participants recruited with VFL had conditions including primary open angle glaucoma (n=7), normal tension glaucoma (n=2), congenital glaucoma (n=3), severe bilateral optic atrophy (n=1), multiple sclerosis with optic nerve involvement (n=1), AMD (n=6), macular hole (n=1), Stargardt's disease (n=1), diabetic retinopathy (n=4), retinitis pigmentosa (n=1), vascular accident and trauma (n=1), retinal detachment

(n=1), retinal detachment and diabetic retinopathy (n=1), aphakia resulting from congenital cataract presenting with VFL (n=1), unknown conditions resulting in VFL (n=2) and quadrantanopia (n=1).

After an initial examination on the SITA Standard 24-2, which occurred on visit 1, two participants were excluded from the data analyses for all of the studies. Exclusion occurred when a participant had a diagnosed ocular condition, but no VFL was found on the SITA Standard 24-2 visual field test, this resulted in one participant being excluded. The other participant was referred and lost to follow-up.

For study 1 (The repeatability of the Esterman visual field test in cases of established visual field loss, chapter 4), a further participant was lost to follow-up and the final sample consisted of 33 participants with VFL ranging in age from 37-82 years with a mean age of 65.22 (SD=15.74), and 40 controls ranging in age from 37-84 years with a mean age of 69.23 (SD=8.68). The study group included 16 males and 17 females. The control group included 20 males and 20 females. Characteristics of all participants for study one are shown in tables 3-1 to 3-3.

For study two (The reproducibility of Esterman visual field in those with established visual field loss, chapter 5), a further eleven of the participants were excluded from the data analysis. Three were excluded for problems with the equipment and participants unable to return for retesting. Seven were excluded for false positive readings >30% on the EVFT performed on the Henson, and one was lost to follow-up. The final sample consisted of 32 participants with VFL ranging in age from 35-90 years with a mean age of 66 years (SD=15.70), and 31 normal controls ranging in age from 37-81 years with a mean age of 68.23 (SD=8.54). The study group included 15 males and 17 females. The control group included 16 males and 15 females. Characteristics of the participants for study two are provided in tables 3-4 to 3-6.

For study 1 and study 2, participants who would be eligible to drive if the visual field criteria were ignored, based on the visual acuity alone (+0.3 LogMAR) and condition were considered for separate analysis when analysing pass/fail results. Characteristics of these participants are shown in tables 3-2 and 3-5.

For study three (The reproducibility of the Ring of Sight visual field screener, chapter 6), seventy-six participants were recruited to compare the HFA 24-2 SITA Standard with the ROS FT examination. Both eyes were examined and the data for the right eyes were selected for analysis. After the two participants who were excluded from all studies, this left 74 participants. Of these 74 participants, one participant refused to

have their right eye examined due to having no light perception in that eye. One participant found the posture for the examinations difficult and were unable to proceed. One participant abandoned the examinations due to time restrictions and was unable to return. One participant could not undertake the examinations for a painful right eye awaiting enucleation. Therefore, a total of 4 eyes were not examined. Of the 70 examination results attempted on the participants right eye, a further 34 results were excluded for reasons that will be outlined in chapter 6. Reliability was determined with the HFA reliability indices and calculating the percentage of fixation losses present on the ROS. The reliability criteria followed the following, exclusion of data would result if fixation losses >20% (Cubbidge. 2015), false positive and false negative >30% (Patel *et al*. 2007). After exclusion, a final 36 results were available for analysis. Eighteen for the study participant group (mean age=70.56; SD=10.12) and age and gender matched controls were used in order to distinguish effects of comparing the HFA SITA 24-2 and the ROS 24-2 testing methodologies of which there resulted in 18 for the control group after exclusion (mean age=67.12; SD=9.63). Characteristics of the participants are presented in table 3-7.

To analyse fixation losses between the HFA and the ROS, the reliability criterion for exclusion of the examination for the fixation losses was removed. This resulted in 18 examinations from the study group and 28 from the control group to compare the ROS perimeter with the HFA. The characteristics of these participants are shown in table 3-8.

The EVFT does not present stimuli within the central 7.5º and the central 10º of the visual field is largely untested (Rauscher *et al*. 2007). As well as comparing those with VFL and normal controls, the studies also investigated whether any differences found between visits or perimeters, were attributable to any particular type of defect and if there was a difference in repeatability and reproducibility when evaluating those with central field loss (where test locations are sparse) and those with peripheral field loss separately. The field defects in participants recruited who had diseases affecting the optic nerve could not be classified into purely central or purely peripheral defects. Glaucoma can present with defects in all areas of the visual field (see section 1.2.2.1), dependent upon the stage of the disease (Rijn. 2002a, Jampel *et al*. 2002). Those with diseases affecting the optic nerve were therefore categorised separately. The HFA's database is based on glaucomatous and normal fields (Wall *et al*. 2001). The study which aimed to investigate the ROS (Chapter 6) evaluated whether it could determine those with diseases of the optic nerve, including those with glaucoma. Central and

peripheral field losses affect different photoreceptors within the retina (Sammarco *et al*. 2009, Eloholma *et al*. 2005). The study also evaluated if visual field defects which are not attributable to involvement of the optic nerve, would cause a difference in the performance of the ROS in terms of depth and location of defects. Consequently, these categories were also considered for analyses within study 3. In situations where the participant's ocular condition could not be assigned into a category, and the participants visual field examination results showed both central and peripheral involvement, they were categorised as unclassifiable.

In summary, the study groups for all studies were sub-classified into categories of nerve fibre defect (NFD), central field defect (CFD), peripheral field defect (PFD) and unclassifiable or unknown defects (Un) dependent upon diagnosed condition and the area of VFL present on the SITA Standard 24-2 examination. Those participants who had a diagnosed eye condition, with no VFL present on the SITA Standard 24-2 were excluded from the studies. Those participants who had an ocular condition with optic nerve involvement were categorised into the NFD category. The participants with central VFL were categorised into the CFD category, these included those with AMD, macular hole and Stargardt's disease. Participants with peripheral visual field loss were positioned into the PFD category. These included retinitis pigmentosa, vascular accident and trauma, and diabetic retinopathy (n=2). The SITA Standard 24-2 examination examines the central 30º field (McKendrick. 2005). For each of these participants a VFL was present on the 24-2 examination and the PFD was confirmed with the baseline EVFT that occurred on the first visit. Those participants included in the Un category included participants with retinal detachment, unknown condition resulting in VFL, quadrantanopia, albinism, diabetic retinopathy which presented with both central and peripheral VFL on their visual field result (n=2) and aphakia resulting from congenital cataract presenting with VFL.

Characteristic.	Study. n=33	Control n=40
Age (years) mean	65.22 (SD=15.74)	69.23 (SD=8.68)
Range	37-82	37-84
Male	16(49%)	20(50%)
Female	17(51%)	20(50%)
Ocular factors		
Sphere (D) mean	+0.56 (SD=3.37)	+0.91 (SD=3.08)
Range	-4.75-+10.75	-8.25-+8.25
Cylinder (D) Mean.	-0.84 (SD=1.00)	-0.69 (SD=0.69)
Range	-3.75-0	-2.75-0
VA (Mean). LogMAR.	0.41 (SD=0.36)	0.03 (SD=0.11)
Range	-0.24-+1.26	-0.3-+0.32
SAP MD (dB) mean.	-11.70 (SD=8.89)	-1.54 (SD=1.96)
Range	-29.47-0.17	-7.37-2.12
SAP PSD (dB) mean.	6.82 (SD=4.20)	2.22 (SD=1.47)
Range	0.13-14.4	-2.39-9.23
Spectacle wearers	23(69.70%)	32(80%)
Number of potential drivers if excluding visual field criteria (based on VA and condition alone)	17(51%)	40(100%)

Table 3-1. Characteristics of all participants for study 1. D= dioptre. VA= Visual acuity. SAP was performed on the HFA. Details for the better seeing eye provided.

Age (years) mean	69.82 (SD=11.59)
Range	39-83
Male	7(41%)
Female	10(59%)
Ocular factors	
Sphere (D) mean	-0.17 (SD=2.59)
Range	-4.75-+4.5
Cylinder (D) Mean. Negative cylinder	-0.97 (SD=0.75)
Range	-3.25-0
VA (Mean). LogMAR	0.18 (SD=0.14)
Range.	-0.24-0.3
SAP MD (dB) Mean	-8.80 (SD=8.73)
Range	-29.46- -0.17
SAP PSD (dB) Mean	6.27 (SD=4.23)
Range	1.38-13.98

Table 3-2. Characteristics of study participants for study 1 who would be able to hold a driving licence if the visual field criteria were excluded (n=17) D= dioptre. VA= Visual acuity. SAP was performed on the HFA. Details for the better seeing eye provided.

Sub-classifications	**NFD n=14**	**CFD n=8**	**PFD n=4**	**Un n=7**
Age (years) mean	63.43	73.25	57.25	65.29
Range	35-84	41-85	45-70	46-90
Male	8(57%)	2(25%)	3(75%)	3(43%)
Female	6(43%)	6(75%)	1(25%)	4(57%)
Ocular factors				
Sphere (D) mean	-0.40 (SD=2.13)	-0.46 (SD=2.57)	+1.54 (SD=2.03)	+3.50 (SD=4.86)
Range	-4.75-+4.50	-4.75-+3.75	-0.50-+5	-2.25-+10.75
Cylinder (D) mean, negative cyl	-0.47 (SD=0.80)	-1.05 (SD=0.92)	-1.25 (SD=1.20)	-1.31 (SD=1.32)
Range	-3.00-0	-3.25-0	-3.25-0	-3.75-0
VA mean	0.34 (SD=0.36)	0.35 (SD=0.38)	0.36 (SD=0.18)	0.64 (SD=0.34)
Range	-0.16-+0.82	-0.24-+1.12	+0.2-+0.64	+0.1-+0.82
SAP MD (dB) mean	-11.26 (SD=7.54)	-10.37 (SD=10.08)	-18.42 (SD=8.59)	-9.46 (SD=6.51)
Range	-29.46- -0.17	-28.42- -0.67	-29.47- -11.16	-19.54- -1.11
SAP PSD (dB) mean	7.50 (SD=4.48)	6.81 (SD=4.77)	9.21 (SD=3.02)	6.18 (SD=3.52)
Range	0.13-13.98	1.70-12.99	3.78-13.13	2.85-12.96

Table 3-3. Characteristics of study participants in defect classification for study 1. Details for the better seeing eye provided. D= dioptre. VA= Visual acuity. SAP was performed on the HFA.

	All study (n=32)	Control (n=31)
Age (years) mean	66 (SD=15.70)	68.23 (SD=8.54)
Range	35-90	37-81
Male	15(47%)	16(52%)
Female	17(53%)	15(48%)
Ocular factors		
Sphere (D) mean	+0.58 (SD=3.46)	+0.44 (SD=3.20)
Range	-4.75-+10.75	-8.25-+8.25
Cylinder (D) mean.	-0.81 (SD=1.02)	-0.73 (SD=0.75)
Range	-3.75-0	-2.75-0
VA mean. LogMAR.	+0.42 (SD=0.37)	+0.03 (SD=0.12)
Range	-0.24-+1.26	-0.3-+0.32
SAP MD (dB) mean.	-10.72 (SD=8.04)	-1.47 (SD=2.01)
Range	-29.46- -0.17	-7.37-+2.12
SAP PSD (dB) mean.	6.65 (SD=4.26)	1.98 (SD=1.16)
Range.	0.13-14.4	-2.39-+6.16
Spectacle wearers	22(68.75%)	24(77.42%)
Number of potential drivers based on VA and condition. Employing exclusion of visual field criteria.	13(40.63%)	31(100%)

Table 3-4. Characteristics of all participants for study 2. Data presented is for the better seeing eye. D= dioptre. VA= visual acuity. MD= mean deviation. PSD= pattern standard deviation. SAP was performed on the HFA.

Age (years) mean	72.77 (SD=7.46)
Range	61-83
Male	5(38.46%)
Female	8(61.54%)
Ocular factors	
Sphere (D) mean	-0.48 (SD=2.65)
Range	-4.75-+4.50
Cylinder (D) Mean. Negative cylinder	-0.70 (SD=0.61)
Range	-1.75-0
VA Mean. LogMAR	+0.1 (SD=0.19)
Range.	-0.24-+0.3
SAP MD (dB) Mean	-6.50 (SD=5.52)
Range	-17.61- -0.17
SAP PSD (dB) Mean	5.60 (SD=4.91)
Range	0.13-13.98

Table 3-5. Characteristics of study participants for study 2 who would be able to hold a driving licence if the visual field criteria were excluded (n=13). Details for the better seeing eye provided. D= dioptre. VA= Visual acuity. SAP was performed on the HFA.

	NFD (n=14)	CFD (n-8)	PFD (n=3)	Un (n=7)
Age (years) mean	63.429 (SD=16.57)	73.25 (SD=13.82)	61.33 (SD=12.66)	65.286 (SD=14.32)
Range	35-84	41-85	45-70	46-90
Male	8(57%)	2(25%)	2(67%)	3(43%)
Female	6(43%)	6(75%)	1(33%)	4(57%)
Ocular factors				
Sphere (D) mean	-0.44 (SD=2.19)	-0.46 (SD=2.57)	+2.25 (SD=2.15)	+3.50 (SD=4.86)
Range	-4.75-+4.50	-4.75-+3.75	Plano-+5.00	-2.25-+10.75
Cylinder (D) mean, negative cylinder form.	-0.45 (SD=0.82)	-1.05 (SD=0.92)	-1.19 (SD=1.55)	-1.31 (SD=1.32)
Range	-3.00-0	-3.25-0	-3.25-0	-3.75-0
VA Mean	+0.37 (SD=0.39)	+0.35 (SD=0.38)	+0.44 (SD=0.17)	+0.64 (SD=0.34)
Range	-0.16-+1.26	-0.24-+1.12	+0.3-+0.64	+0.28-+1.00
SAP MD (dB) Mean	-11.38 (SD=7.79)	-10.87 (SD=10.08)	-12.91 (SD=1.28)	-9.46 (SD=6.51)
Range	-29.46- -0.17	-28.42- -0.67	-13.69- -11.16	-19.54- -1.11
SAP PSD (dB) Mean	6.57 (SD=4.23)	6.81 (SD=4.77)	8.94 (SD=3.86)	6.18 (SD=3.52)
Range	0.13-13.98	1.70-12.99	3.78-13.13	2.85-12.96

Table 3-6. Characteristics of defects in the study group for study 2. Details for the better seeing eye provided. D= dioptre. VA= visual acuity. SAP was performed on the HFA.

Characteristics of study participants. Data for right eye. (n=18)		Characteristics of control participants. Data for right eye. (n=18)	
Age (years) Mean	70.56 (SD=10.13)	**Age (years) mean**	68.75 (SD=6.43)
Age range	45-85	**Age range**	37-79
Male	11(61.11%)	**Male**	7(38.89%)
Female	7(38.89%)	**Female**	11(61.11%)
Ocular factors		**Ocular factors**	
Sphere (D) mean	+0.35 (SD=3.38)	**Sphere (D) mean**	-0.13 (SD=3.16)
Range	-5.25-+10.50	**Range**	-8.25-+6.00
Cylinder (D) mean. Negative cylinder form.	-0.74 (SD=0.99)	**Cylinder (D) mean. Negative cylinder form**	-0.95 (SD=0.82)
Range	-3.25-0	**Range**	-2.75-0
VA mean. LogMAR.	+0.32 (SD=0.34)	**VA mean. LogMAR.**	+0.03 (SD=0.14)
Range.	-0.24-+1.12	**Range.**	-0.26-+0.32
MD (dB) mean	-8.03 (SD=8.07)	**MD (dB) mean**	-0.85 (SD=1.64)
Range	-29.39-0.01	**Range**	-5.29-+1.64
PSD (dB) mean	5.53 (SD=4.40)	**PSD (dB) mean**	1.97 (SD=1.63)
Range	1.41-15.97	**Range**	-2.39-+6.16
Spectacle wearers	13(72.22%)	**Spectacle wearers**	17(94.44%)

Table 3-7. Participant characteristics for study 3. Data presented for the right eye. D= Dioptre. VA= visual acuity. SAP was performed on the HFA.

Characteristics of study participants. Fixation losses. Data for right eye	n=18	Characteristics of Control participants Fixation losses. Data for right eye.	n=28
Age (years) Mean	70.56 (SD=10.12)	**Age (years) Mean**	69.82 (SD=9.60)
Age range	45-85	**Age range**	37-84
Male	11(61.11%)	**Male**	13(46.43%)
Female	7(38.89%)	**Female**	15(53.57%)
Ocular factors		**Ocular factors**	
Sphere (D) mean	+0.35 (SD=3.38)	**Sphere (D) mean**	+0.64 (SD=3.13)
Range	-5.25-+10.50	**Range**	-8.25-+6.00
Cylinder (D) mean.	-0.74 (SD=0.99)	**Cylinder (D) mean.**	-0.78 (SD=0.78)
Range	-3.25-0	**Range**	-2.75-0
VA mean. LogMAR.	+0.32 (SD=0.34)	**VA mean. LogMAR.**	+0.04 (SD=0.13)
Range.	-0.24-+1.12	**Range.**	-0.26-+0.32
SAP MD (dB) mean.	-8.03 (SD=8.07)	**SAP MD (dB) mean.**	-1.26 (SD=1.83)
Range.	-29.47- +0.01	**Range.**	-6.57-+1.64
SAP PSD (dB) mean.	5.53 (SD=4.40)	**SAP PSD (dB) mean.**	2.36 (SD=1.94)
Range.	+1.41-+15.97	**Range.**	-2.39-+9.23
Spectacle wearers	13(72.22%)	**Spectacle wearers**	24(85.71%)

Table 3-8. Participant characteristics for analysis of fixation losses for study 3. Data presented for the participants right eye. Exclusion criteria for reliability of examination based on fixation losses was removed. D= dioptre. VA= visual acuity. SAP was performed on the HFA.

3.2. Instrumentation.

The binocular EVFT for each participant was performed on the HFA II model 720 software version 14.2.1. (Humphrey Instruments, Dublin, USA) for both study 1 and study 2. The binocular EVFT was also performed on the Henson Pro 5000 Perimeter (Topcon, UK) on the third visit for study 2.

The HFA matches the EVFT original examination, and was therefore used as the gold standard for comparison with the Henson for study 2.

The HFA II model 720 software version 14.2.1. was chosen for comparison of the ROS for study 3. The HFA program used was the SITA Standard 24-2.

The 24-2 FT test on the ROS (Ibis Vision) was used. The program is run from a HP K7H92ES#ABU-255 G3 15.6” LED laptop (AMD A4-5000 1.5GHz 4GB 500GB) and displayed on an Asus VK278Q 27” LED backlight monitor with normal background setting of 942 asb (dimensions 63.3x22x46cm). A Wacom Intuos Pen CTL-480 graphic tablet with pen (dimensions 17.8x1x21cm) shown in figure 3-1 is connected to the laptop for the participant to indicate they have seen a stimulus by moving a green circular target over the presented stimulus. A Logitech HD webcam C310 (1280x720 pixels) (figure 3-2) with tilt ability and zoom control was utilised for the researcher to observe the participant for fixation. The instruments used are the requirements of the manufacturer of the ROS.

Figure 3-1. Wacom Intuos Pen CTL-480 and Wacom pad. Participant utilises the Wacom Intuos Pen CTL-480 to indicate they have seen a new stimulus by moving identification target to stimulus location on the Wacom pad.

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Figure 3-2. Logitech HD webcam. Utilised for manual fixation monitoring by observing the participant.

3.3. Procedure.

All participants underwent three visits at the Aston Optometry School at Aston University. Figure 3-3 illustrates the journey of the participant. All participants had their VA recorded, monocularly and binocularly. Fundus images were taken of each eye where possible on the first visit. Some images were hindered by senile miosis and dilation was not an option within the scope of the researcher. Images taken for the control group were coded and sent to an optometrist to be optometrically analysed to confirm no pathology was present within the group.

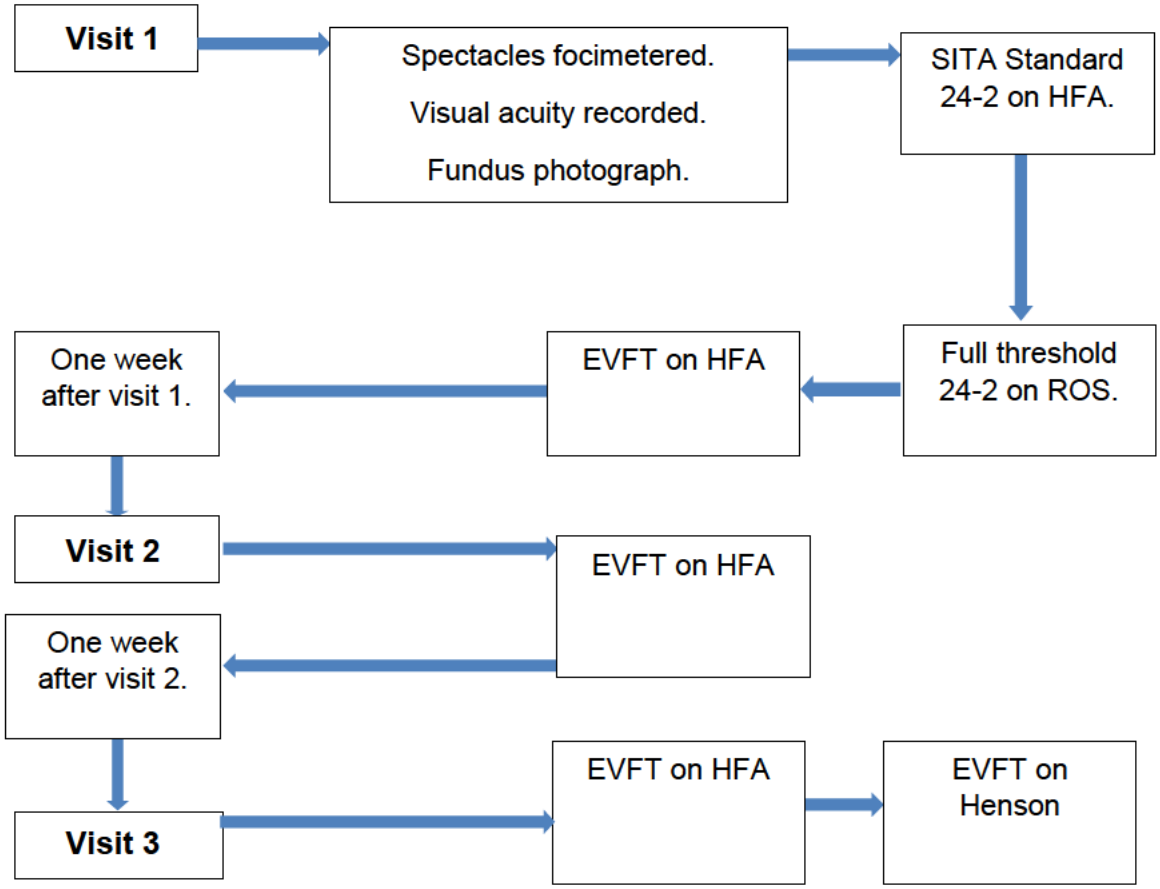


Figure 3-3. Participant journey. The procedures performed on each of the three visits.

The ROS was switched on at least 30 minutes prior to the arrival of the participant on the first visit, to ensure stability of the screen brightness. All participants waited in the same room, with exposure to the same ambient lighting conditions. The area also had natural light being radiated through a windowed area. Although this natural light could not be controlled for, being highly dependent upon time of day and weather conditions, it represents a normal high street practice waiting area. All participants were reassured

that the results of the study would not influence their current driving licence status. Careful standardised verbal instructions were provided to each participant prior to undertaking each test, which are outlined in appendix 2.

Participants visited the Aston Optometry Department on three separate occasions. Visits were spaced one week apart. Some participants were unable to adhere to strict appointment times. The average time between visits was 8.7 days (SD=12.02).

Each visit consisted of the binocular EVFT performed on the HFA and additionally with the Henson on the third visit. On the third visit the EVFT performed on the HFA and the Henson were performed in random order to limit the effects of learning and fatigue upon results. The first visit also consisted of a SITA Standard 24-2 performed on the HFA and a FT 24-2 examination on the ROS. The SITA Standard and the ROS examinations were also randomised. For study one and study two, in line with the DVLA methodology for testing on the EVFT, habitual correction for distance was used (Heijl *et al*. 2012). Those who wore spectacles for testing amounted to 23 study participants and 32 control participants for study 1. For study 2, the participants who wore spectacles for testing were 22 from the study group and 24 controls.

The ROS was utilised as per instructions and set-up by the manufacturers. However, there was no calibration of the spatial or temporal characteristics of the instruments display conducted by the researcher. The set-up was conducted in a room with parabolic reflecting luminaires. There is no recommendation for ambient room lighting, this is possibly to consider the fact that the manufacturer considers this item to be used for domicillary visits. Illuminance was however measured with a photometer when the lights emittance had been allowed to achieve their maximum, 30 minutes after switching on, and found to be 288 lux within the area a participant would be seated which was approximately 4 m from the light source. Participants were positioned as illustrated in figure 3-4. No participants were naive to visual field testing. All participants were however naive to the ROS examination. Therefore, a full and careful standardised explanation was provided on how to move the target, what to fixate on, and when to move the target. Verbal instructions consisted of informing the participant to fixate on the round stimulus on the screen and move the pen on the WACOM pad to move the circular green target to the position of the seen stimulus. They were then instructed to continue to fixate on the position they had moved the target to until they noticed another round stimulus, they were told to move their fixation and green target to this new location and this now became the fixation point. Participants were instructed to continue to do this until the conclusion of the test. The ROS includes a

practice session, which was timed at 42.46 seconds, as part of the examination prior to recording sensitivity values. If a participant does not move the target, reminder instructions appear on the screen with an arrow to indicate where the target should be moved to. The starting procedure, fixation target and appearance of the new target to fixate upon are illustrated in figures 3-5 to 3-8. On testing, the ROS stimulus starts with a low contrast and darkens until there is indication that the participant has seen it.

Standardised verbal instructions were also provided to each participant prior to undertaking the 24-2 SITA Standard visual field test on the HFA (Appendix 2). Both eyes were examined for all participants where appropriate. Some of the participants with VFL only had one eye examined on the SITA Standard and ROS examinations. The reasons for the monocular testing were provided in section 3.1. Where two eyes were examined, the right eye was examined first followed by the left eye. Occlusion of each eye occurred by the use of an eye patch. For the SITA Standard 24-2 examination, in line with the manufacturer's recommendations a trial lens was calculated via the HFA program and used where required on the HFA. Care was taken to avoid rim artefacts by ensuring the eye was central and the vertex distance was as close as could be physically achieved when conducting the test on the HFA. In line with the method of testing as per manufacturer's instructions on the ROS habitual correction was used. Of the examinations included for analysis, thirteen study participants and seventeen control participants wore their habitual spectacles when examined on the ROS. Of the examinations included for analysis to compare fixation losses, thirteen study participants and twenty-four control participants wore their spectacles when examined on the ROS.

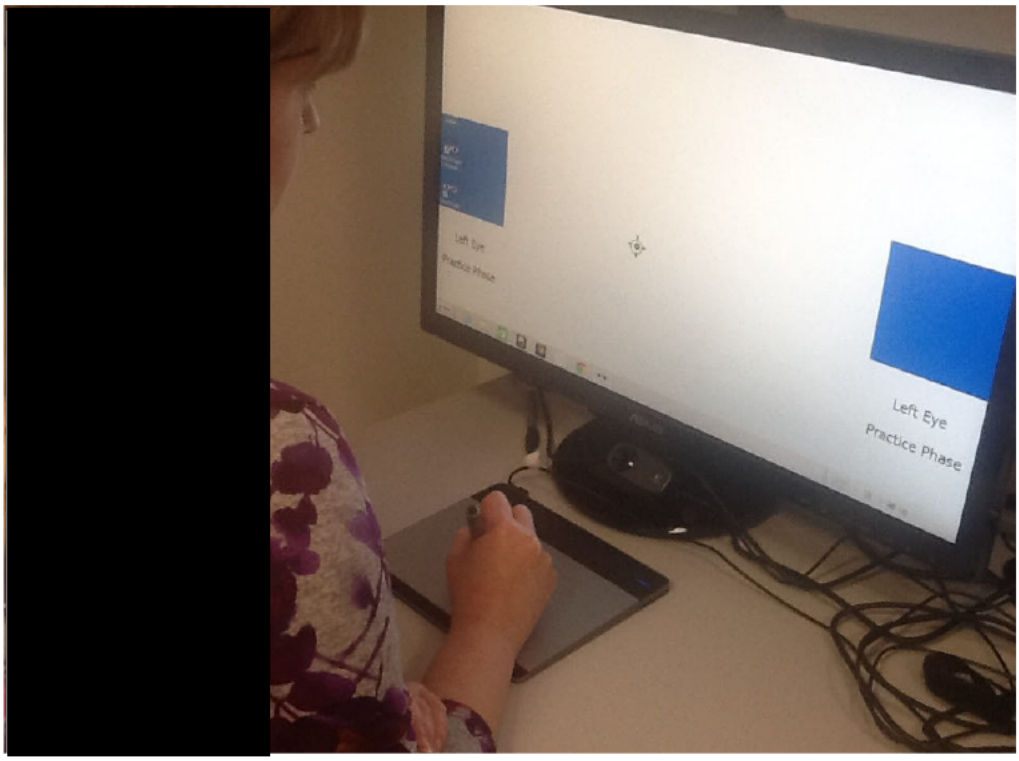


Figure 3-4. The patient/perimeter set-up of the ROS. Demonstrating location of an individual and use of Wacom pad when undertaking the ROS examination.

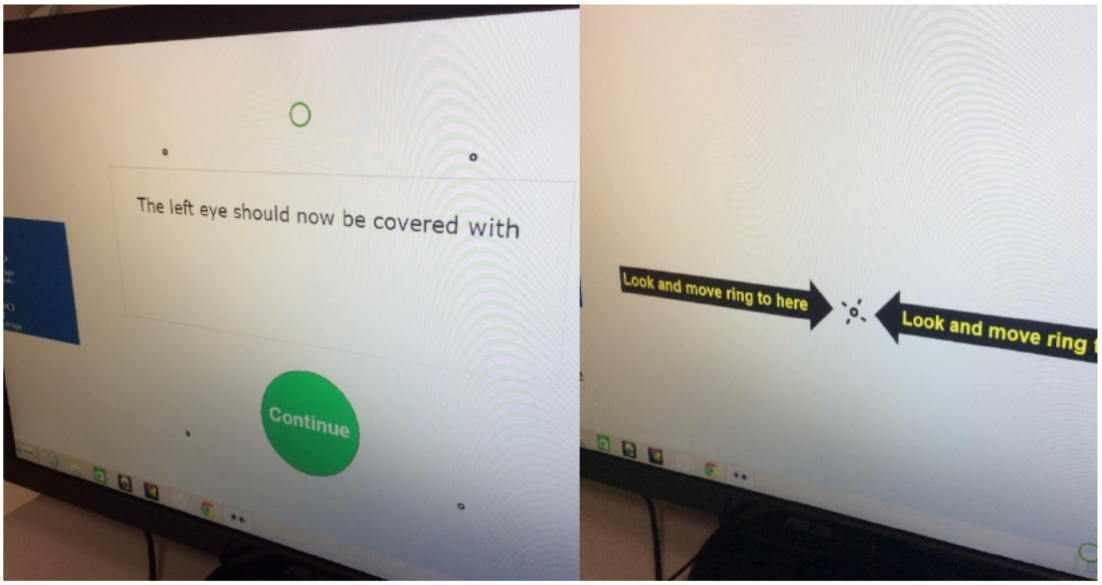


Figure 3-5. The starting procedure and the initial instructions the ROS provides to the participants.

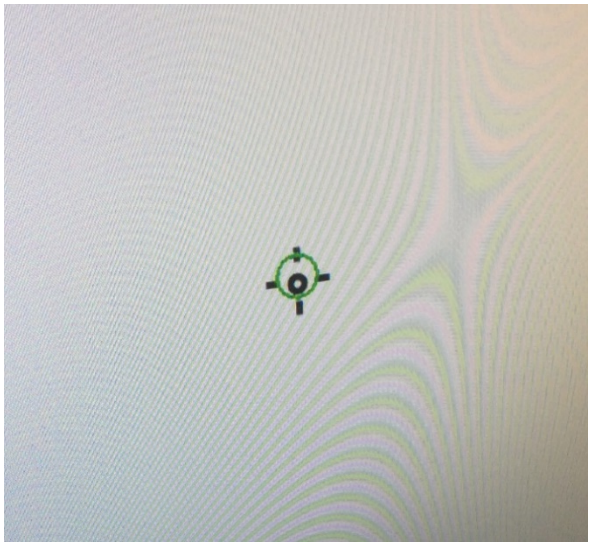


Figure 3-6. The fixation target on the ROS. With moveable green circular target on Asus monitor.

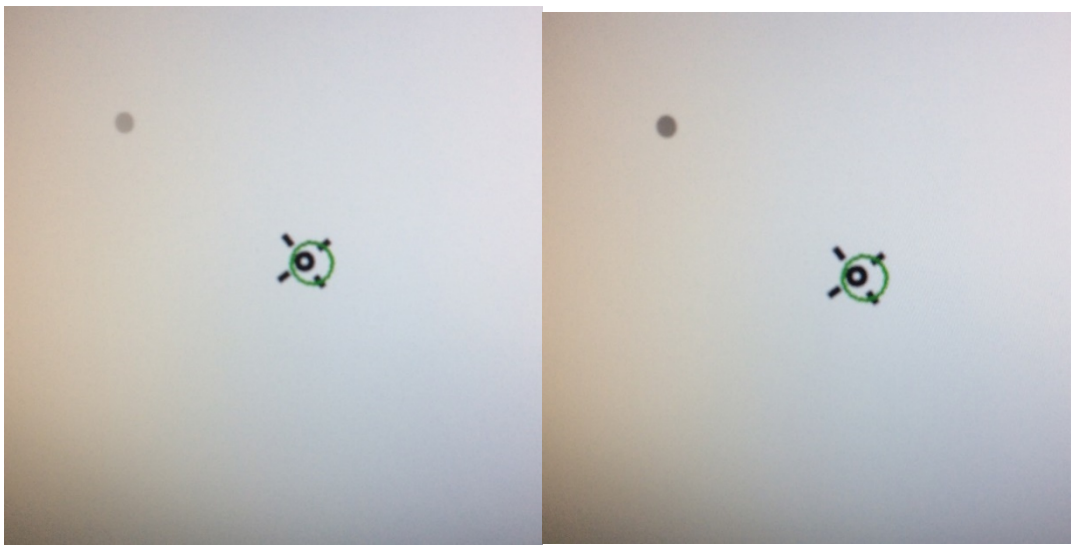


Figure 3-7. The new target appearing and the darkening target on ROS. The target is increasing in contrast from the left to the right image.

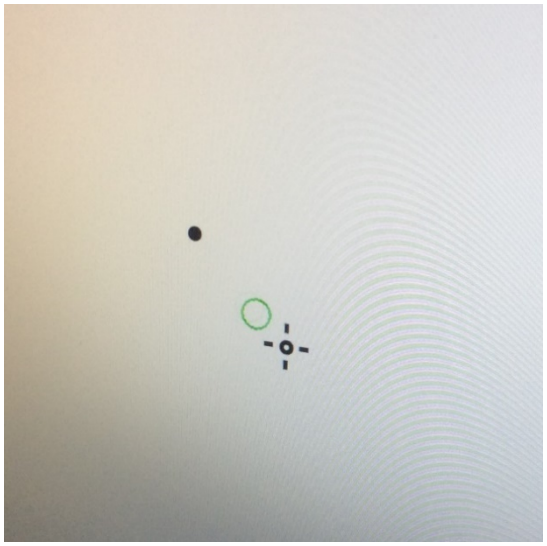


Figure 3-8. The movable circular green target on the ROS. The new stimulus has been identified. The green target (circle) is being moved from the fixation point with the aim of enclosing the green target around the newly identified stimulus.

The habitual correction was focimetered and recorded to check on subsequent visits. The same correction used at visit one was subsequently used at visits two and three. Testing was carried out with natural pupils. Apart from the SITA Standard examination, whereby fixation is monitored objectively by the perimeter, fixation monitoring was managed visually. For the ROS visual observation of the participant was via the camera and the researcher indicated loss of fixation by hitting the space bar on the laptop. All tests were conducted by one examiner.

All the SITA Standard examination results on the HFA were examined for reliability. Reliability was considered to be <20% fixation losses (Wall *et al*. 2008) with false positive and false negative results of <33% (Haley. 1993, Ong e*t al*. 2014, Spry *et al*. 2005). Only those considered reliable were used in the data analyses except for when fixation losses were analysed. In the fixation loss analyses, all fields regardless of >20% fixation losses were included with the other tests considered reliable. Only fixation losses could be considered on the ROS as these could be manually decided if too frequent. There are no other reliability indices provided on the ROS examination.

A rest of no less than 5 minutes occurred between tests.

The EES for each participant and for each visit were recorded. This score is generated by the perimeter and is calculated by dividing the amount of points seen by the amount of points presented.

Participants were provided with a questionnaire (appendix 7), after completing the SITA Standard and ROS visual field examinations, which provided options of machine 1 (first machine examined on), machine 2 (second machine examined on) or neither for a set of five questions aimed at establishing participant's comfort, duration perception and overall preference between the two perimeters.

3.4. Data Analysis.

Data were analysed using SSPS version 23 statistical software (IBM SPSS Statistics for Windows, Version 23.0. Armonk, NY: IBM Corp). Normal distribution of the data were examined with Shapiro-Wilks test for normality. Parametric tests were used when normality of data were confirmed. Non-parametric tests were used where data had non-normal distribution.

The level of statistical significance was set at 0.05 for all analyses except where multiple comparisons were undertaken. Bonferroni correction factors were employed to adjust the P value for multiple comparisons. Analyses were one-tailed where a direction could be determined and two-tailed where a direction could not be assumed.

Levene's test was used to assess homogeneity of variance when data were normally distributed.

Separate analyses occurred for the VFL sub-groups except where sample sizes for each sub-group were too small to consider for analysis, but the data were used in the pooled data for the study group.

Non-parametric tests were used to determine the trend in EES scores, and any significance in duration between visits for study one.

For study three, throughout the data analyses, the SITA Standard on the HFA was considered the gold standard and the benchmark to compare the ROS data.

Non-parametric tests were used to determine the repeatability and reproducibility of the EVFT EES due to the data having a non-normal distribution. Test-retest correlation for study one and correlation of EES between perimeters for study two were determined with Spearman's coefficient. Correlation of sensitivity values between the HFA and ROS were determined with Pearson's correlation coefficient. Bland and Altman plots were generated to establish agreement of EES between visits and between perimeters. Bland and Altman plots were also generated to analyse agreement of sensitivity values between the HFA and ROS. Friedman two-way analysis of variance

assessed the differences in EES between visits. Wilcoxon signed rank tests assessed the differences between the EES from the HFA and Henson perimeter. One-tailed paired samples t-tests were used where data were normally distributed and Wilcoxon signed rank tests were used when data had non-normal distribution, to determine any differences in sensitivity values (dB) between the HFA and ROS, within group, and Mann-Whitney U tests were used to determine any differences in sensitivity values (dB) between groups.

Parametric one-way Anova tests were used to examine the variability in EES between visits, between groups, where the variability had a normal distribution and non-parametric Kruskal-Wallis tests were used where the variability had non-normal distribution. The EES variability between visits were analysed using the mean EES variance between visits for each of the participants. A parametric independent samples t-test was conducted with unequal variances not assumed to compare variability in EES for study two.

The EVFT results were classified as “pass” or “fail” in relation to the current DVLA visual field standard for group 1 licences (DVLA. 2014). Pass/Fail frequencies were examined with the use of 2x2 frequency tables between visits and to determine agreement between perimeters. Consistent and inconsistent results were analysed for all participants with a McNemar Chi-squared test for frequencies between visits and the binominal test assessed frequencies of pass/fail results between perimeters. To determine the pass/fail on first or second visit, the three visits were separated into paired classes, which are outlined in chapter 4. Two-by-two frequency tables were used to examine agreement between establishing defect and disease and no defect and no disease between the HFA and ROS. Defects were defined with the use of the Hodapp-Parrish-Anderson (HPA) grading (appendix 8) which was adapted to consider one visit only, the details of which are outlined in chapter 6. Kappa tests were used to determine agreement between the HFA and ROS when establishing if a defect was or was not present. Sensitivity and specificity values were calculated to examine the ability of the ROS to predict the outcome of the SITA Standard examination.

Further analysis of the EVFT pass/fail frequencies occurred for those participants in the study group who would be able to hold a driving licence if the visual field criteria were excluded, based on visual acuity and condition alone. Participants were not asked about their driving licence status.

Following the method by Latham *et al* (2014) looking for overlap zones where the recorded visual acuity would create uncertainty as to whether the participant would

pass or fail the number plate test (Latham *et al*. 2014), this was adapted to consider if an overlap zone of the EES could be established, whereby, a participant is likely to pass on one visit and fail on another, as well as the EES threshold when the participant would pass on all visits or fail on all visits along with false positives, false negatives, sensitivity and specificity. This method was also adapted to consider if the EES could predict the possibility of passing on one perimeter and failing on another, passing on both perimeters or failing on both perimeters.

Analyses of unweighted MD for the HFA and the ROS perimeter were to be compared. The MD on the printout of the HFA cannot be directly compared to a calculated mean of the deviation across the points for the ROS. Therefore, the MD for both were calculated as an unweighted value and resulted in the actual (true) mean of the deviations from the individual plots of both tests. The differences in unweighted MD values between the HFA and ROS were determined with a Wilcoxon test and Spearman's correlation coefficient was used to assess correlation between the unweighted MD calculated for the HFA and the ROS. Receiver operating characteristic (ROC) curves were generated to assess the accuracy of the tests in predicting disease based upon the unweighted MD values. AUCs were calculated for each ROC curve with 95% confidence intervals (CI).

The ROS provides a count of fixation losses but does not enable a percentage to be ascertained in the same way the HFA provides. The HFA provides a fraction out of how many checks on fixation occurred that fixation was actually lost, this can then be transcribed into a percentage. To enable the data to be comparative the ROS counts were divided by the mean of the HFA checks in order to provide a meaningful value for the ROS fixation that could then be compared. Wilcoxon signed rank tests were used to examine fixation losses between the ROS and HFA when data were of non-normal distribution and Mann-Whitney tests were employed to compare fixation losses between groups.

Wilcoxon signed rank tests were used to compare the durations between the HFA and ROS where data presented with non-normal distribution and paired samples t-tests were employed to compare durations between the HFA and ROS where data demonstrated normal distribution.

Non-parametric tests were used to determine any influence of age on the EES due to the data having a non-normal distribution. Correlation of EES and age was determined by Spearman's correlation coefficient. Correlation of the variance in scores between the EVFT on the HFA and the EVFT on the Henson and age was determined with

Pearson's correlation coefficient. Differences between age groups and EES were assessed with a Kruskal-Wallis test. Age correlation with unweighted MD was examined with Spearmans rank correlation coefficient for both the HFA and ROS perimeter when analysing the study group due to the non-normal distribution of the data. The normal distribution of the data for the control group lent the unweighted MD for the HFA and ROS to the same analysis using Pearson's correlation coefficient.

3.4.1. Pointwise Analysis.

The results of the EVFT were analysed in a pointwise manner whereby the defect locations on one visit were checked for repeatability on other visits for study one and between perimeters for study two.

For study one, for each point, the percentage of times the location altered status from defect to no defect or vice-versa was calculated. An overall percentage of change for each individual location of the EVFT was calculated. The data had non-normal distribution, and non-parametric tests were performed to determine any significance between the percentage of change in defect status per location between visits comparing study and control participants.

For study two, the EVFT sampling between perimeters differs. The coordinates of the EVFT on the HFA and Henson do not coincide. In order to perform pointwise analysis a combined grid was created which is detailed in chapter 5. Using the combined grid, each individual location on the EVFT between perimeters was cross referenced to determine agreement of defect location between perimeters.

For study three, the means of each examination point were obtained to analyse differences between each of the participant groups. The blind spot was removed from analysis. In order to determine differences between the algorithms used by each methodology the total deviation plots were compared. Using a method akin to that utilised by Conway *et al*. (2014), each stimulus location was assigned a numerical value indicative of the depth of defect utilising the values used by the HFA, which informs the percentage of the population the defect would be considered normal for. Zero=not significant, 1=<5%, 2=<2%, 3=<1%, 4=<0.50%. For each participant the sum of these assigned numbers were calculated for each perimeter and compared. The HFA was considered the standard to compare against. Hence, a negative score would mean the ROS pertained to a deeper defect and a positive score pertained to a lesser defect. A Wilcoxon test was used to determine the differences in greyscale between the HFA and the ROS. Variance in the greyscale between groups was determined with a Mann-Whitney test. The same method was utilised to compare individual locations.

The sum of each stimulus location was found and the differences between each perimeter per location was found. Differences were plotted with the HFA as the standard. Therefore, a negative score would indicate the ROS finding a deeper defect than the HFA at the location, a positive score would indicate the ROS finding a lesser defect than the HFA at the location. A Wilcoxon test determined differences in greyscale values per location between the HFA and ROS where there was non-normal distribution. The calculated greyscale differences themselves, between the perimeters, per location presented with normal distribution which lent itself to be analysed with an independent samples, one-tailed t-test to determine differences between those with VFL and controls.

To analyse effects with increasing eccentricity data from the EVFT were additionally separated into 3 zones. Up to 20º (zone 1), >20º and up to 40º (zone 2) and >40º (zone 3) eccentricity from fixation for comparison. The 24-2 grid results from the HFA and ROS were separated into outer, middle and inner zones to determine differences in sensitivity between perimeters for each zone. Friedman two-way analysis of variance tests were used to determine if any differences arose, in any defect status changes with eccentricity, for the EVFT. Wilcoxon tests were employed to compare differences in defect status changes, for the EVFT, between zones. To compare the effect of spectacle wear on changes in defect status within the peripheral field for study one, an independent samples t-test with equal variance not assumed was used to evaluate changes where the data was normally distributed for the study participants and a Mann-Whitney U test was used to evaluate the change in defect status within the peripheral field due to spectacle wear for the non-normal distribution of data for the control participants. For study three, a Kruskal-Wallis test was used to compare the differences in defect status between the HFA and ROS with eccentricity, between groups, for data of non-normal distribution. A one-way Anova was used where the distribution was normal and post hoc Tukey tests were undertaken to determine the areas that showed a significant difference.

3.4.2. Questionnaire.

Evaluation of participant experience on the HFA and ROS was done with the use of a questionnaire. Data were coded for preference, with 2 being the preferred test, and 1 being the least preferred test. A runs test examined whether answers to the questionnaire occurred in random order and Kendall's coefficient of concordance was used to examine questionnaire results regarding participant preferences between each of the two perimeters and their tests.

Post hoc tests to establish power were performed using GPower 3.1 software (Gpower 3.1.9.2 softpedia, Prajapati *et al*. 2010. Faul *et al*. 2007) where no statistical difference was found using an α level set at 0.05. Cohen's d was calculated to determine effect sizes for all parametric tests. Effect sizes for non-parametric tests were calculated dependent upon the test used.

4. The Repeatability of the Esterman Visual Field Test in Cases of Established Visual Field Loss.

Summary.

Those with VFL possess increased variability on visual field results. The EVFT is utilised to assess fitness-to-drive as stipulated by the DVLA. This visual field test is likely to be undertaken by those who have VFL and hence, increased variability. Losing a licence can have life changing and psychological consequences to an individual. The aim of this study was to assess the repeatability of this visual test for those who are likely to be impacted by its result. Thirty-three participants with VFL (mean age: 65.22; SD 15.74) and forty control participants (mean age 69.25; SD 8.68) underwent perimetry on the EVFT on three separate visits spaced one week apart (mean: 8.69 days; SD 12.02). Those with VFL possessed a significant change in EES ($א^2(2)=6.649$; p=0.036) across visits. Point-by-point, there was a significant variation in the location of defect (*U*=2967.500; z=-7.945; p=<0.005) upon repeat testing in those with VFL compared to the controls. Variability in pass/fail frequencies was 12% in those with VFL and was not significant. The presenting EES was not a predictor of those who are will have variability in fitness-to-drive status, but those who had an EES of less than 77% are likely to fail fitness-to-drive and those with an EES over 90% are likely to pass fitness-to-drive. Results suggest that the EVFT has poor repeatability in those with VFL, however, the variability in both EES and location of defect has little impact on the fitness-to-drive status and the fitness-to-drive status has good repeatability with the current criteria. However, for the 12% who possessed variability in driving licence status, although not statistically significant, it can be significant to the individual with psychological consequences. It is therefore recommended that there is a minimum of three examinations spaced at timely intervals to account for the variability in those with VFL, particularly when the presenting EES is found to be between 77 and 90%.

4.1 Introduction.

VFL causes functional consequence to an individual. There are many different reasons for a damaged visual field and subsequently a variety in the areas of the visual field affected as presented in section 1.2. Perimetry allows clinicians to assess visual function and locate the consequence of disease (Miranda & Henson. 2008) with a non-invasive technique (Wroblewski e*t al*. 2014).

One purpose of visual field testing is to determine a person's fitness-to-drive. The DVLA include criteria of the visual field deemed to ascertain if an individual is fit-to-drive within the current visual requirements for driving (Owen *et al*. 2008). The criteria are outlined in section 1.10. The EVFT is currently the visual field test conducted to determine whether drivers have a visual field that complies with the DVLA standards (DVLA. 2014).

The EVFT is a ST examination (Heijl e*t al*. 2012). The methodology of ST examination has been detailed in paragraph 1.6.1. As a ST examination, the EVFT simply rules out the presence or absence of a field defect (Siatkowski *et al*. 1996). The small sampling of ST perimetry provides high levels of variability in the defective field (Artes *et al*. 2003). Blinking tends to occur after the presentation of a ST stimulus, which provides an opportunity for the patient to miss the next presented stimulus (Wang *et al*. 2011) and subsequently adding to the variability.

The EVFT examines 120 white test locations (Zeiss. 2014, Ayala. 2012) once with a repeat presentation if the stimulus at that point is not detected. If the participant fails to respond again, this point is recorded as a defect (Crabb e*t al*. 2004, Owen e*t al*. 2008). The resultant percentage of points seen is known as the EES and is still the gold standard for binocular visual field testing (Rauscher e*t al*. 2007). Binocular testing allows an ability to examine function (Jampel *et al*. 2002) but lacks the ability to measure fixation objectively (Chisholm *et al*. 2008a, Crabb *et al*. 2016, Ayala. 2012). There are other limitations currently documented for the EVFT. These arise due to the EVFT not designed solely for driving, but for mobility (Crabb *et al*. 2004) and this leads to it having non-uniform spacing of stimuli. These stimuli also do not represent differing areas of the field equally in terms of measured distance, with the central 7.5 degrees having no representation (Esterman.1967, Owen e*t al*. 2008, Rauscher e*t al*. 2007). The representation of the visual field and design structure of the EVFT is discussed in detail within section 1.11. Limitations include, lack of range on EES scores (Jampel e*t al*. 2002), the brightness of the stimulus (Chisholm. 2008b, Rauscher e*t al*. 2007, Owen e*t al*. 2008, Ayala. 2012, Haley. 1993), lack of accommodation/correction for the

viewing distance of the perimeter bowl giving rise to optical defocus and reduced visual field sensitivity (Wood e*t al*. 2009, 2010, 2014), difficulty with binocular fusion (Rauscher *et al*. 2007, Chisholm *et al*. 2008a), regression towards the mean (Smith. 1989), lack of strategy for noise reduction, lack of correlation with perceived vision loss (Jampel *et al*. 2002a, 2002b), not representative of the driving task whereby there is a dynamic environment (Underwood e*t al*. 2002, Salvucci *et al*. 2002) and the driver needs to acquire important information (MacInnes *et al*. 2014, Ullman *et al*. 1984) amongst distractions (Lee *et al*. 2016, Ho e*t al*. 2001, Muira e*t al*. 1990, Ball e*t al*. 1991) in differing weather conditions (Konstantopoulos. 2009) and times of the day (Elohoma *et al*. 2005, Wanvik. 2009, Kaleem e*t al*. 2012, Freeman *et al*. 2006). To drive requires the use of eye movements (Roger e*t al*. 2016, Yan *et al*. 2014, Szinte e*t al*. 2015, Adams *et al*. 1988) and gaze strategies (Land & Lee. 1994, Ren e*t al*. 2016, Kandil e*t al*. 2010, Authie & Mestre. 2011, Mars & Navarro. 2012, Lappi e*t al*. 2013, Robertshaw & Wilkie. 2008, Itkonen e*t al*. 2015). In addition, it also requires employment of any previous experience of the task (Wilson *et al*. 2007, Wickens e*t al*. 2004, Crundall e*t al*. 1999, Konstantopolos. 2009, Shinoda *et al*. 2001, Vercher e*t al*. 1997, Lehtonen e*t al*. 2014). Compensatory behaviour that can be utilised in those with an impairment (Coeckelbergh *et al*. 2002b, 2005, Hamel *et al*. 2012) and in addition fatigue (Stass *et al*. 2014) and increased cognitive load (Gasper *et al*. 2016. Ho e*t al*. 2001) can impact upon driving ability.

There are a few difficulties assessing or interpreting the visual field of an individual. Visual field testing is also subjective and highly variable (Kim *et al*. 2005, Spry *et al*. 2000) being subject to long term fluctuation. Long term fluctuation is the variability in threshold sensitivities when testing occurs at different sessions (Wroblewski *et al*. 2014). Long term fluctuation can arise over a period of weeks to years (Nouri-Mahdavi *et al*. 2011). This is known as ‘noise’ (Viswananthan *et al*. 1997) and can make identifying sensitivity loss (Fankhauser & Bebie. 1978) difficult for the clinician due to the normal within-subject variability (Swanson *et al*. 2014, Swanson *et al*. 2005, Fellman. 1995). The fluctuation in sensitivity between sessions is higher than within sessions (Henson. 2001). Long term fluctuation is linked to short-term fluctuation within any examination session (Wroblewski *et al*. 2014). There are many incidental factors that can give rise to variability in perimetry results, within and between sessions, which were previously detailed in section 1.7. The learning effect also has a bearing on results (Birch *et al*. 1995, Hitchings. 1994, Acton. 2010) leading to recommendations that there should be two consecutive examinations to establish the baseline on other

tests, such as the UFOV, aimed at determining an individuals fitness-to-drive (Bentley *et al*. 2012) and within standard perimetry (Acton. 2010).

Areas of damage have been found to increase this variability in visual field testing and is a well documented factor (Wall *et al*. 2008, Haley. 1993, Crabb *et al*. 1996, Henson *et al*. 2000, Wall *et al*. 1998. Turpin *et al*. 2007, Gardiner. 2003, Gardiner *et al*. 2006, Miranda & Henson. 2008, Artes *et al*. 2003, Susana *et al*. 2014, Viswanathan *et al*. 1997, Birch *et al*. 1995, Heijl *et al*. 2012. Bengtsson & Heijl. 2000) as detailed in section 1.8. The challenge of perimetry producing a reliable result for those who are visually impaired is thereby confounded by this variability. The variance in visual field results where there is VFL can be as much as 15 dB (Nouri-Mahdevi *et al*. 1997, Swanson *et al*. 2014) even providing normal fields on one week to a hemianopic defect the next (Heijl *et al*. 2012). Individuals likely to undergo an EVFT are those who have VFL and hence are likely to have increased long term fluctuation and short-term fluctuation. However, the very bright stimulus of the ST EVFT has the potential to mask some of the fluctuation, thereby making long-term fluctuation of little significance.

Another well documented factor to variability is the learning effect (Birch *et al*. 1995) (section 1.7.8.) whereby repeat testing can improve short-term fluctuation (Tattersall *et al*. 2007) and hence with practice patients can improve their perimetry result (Hitchings. 1994).

A driver found to have reduced visual fields, in as much as not meeting the DVLA criteria, can lead to them losing their licence. The current figures for having a licence revoked are very small as outlined in section 1.13.1. These figures never exceed 1% and impact on just under 8,000 people annually. However, for each of these individuals, losing a licence can be considered a significant life event impacting on the practicalities of travelling to work, shopping, attend appointments and socialise (Owen *et al*. 2008) and providing a loss of independence (Manji & Plant. 2000). Reducing a person's space to around their home results in isolation (Racette e*t al*. 2005) which is a contributing factor to depression (Bradley & Mitchell. 2006). People who lose a driving licence can suffer feelings of inadequacy and low self-esteem (Owen e*t al*. 2008) and a reduction in quality of life (Medeiros e*t al*. 2012, Ramulu e*t al*. 2014, Matza *et al*. 2008, Trento e*t al*. 2013, Alqudah *et al*. 2016) also contributing to depression (Racette e*t al*. 2005, Ragland *et al*. 2005, Kaleem e*t al*. 2012).

Due to the authority the EVFT possesses in determining whether a person is fit-to-drive or not fit-to-drive, it holds a responsibility to avoid the results inappropriately being the cause of a vehicle licence being revoked when there is evidence of impact upon the

individual. It also holds a responsibility to ensure those who are unsafe to drive are not on the road leading to an at-fault MVC or a pedestrian collision. The RCO do state that accidents caused by a poor level of vision is not all that common (Elliot & Newman. 2016) and some evidence does suggest that those with VFL can be safe to drive (Wood e*t al*. 2009, Kubler e*t al*. 2015, Parker e*t al*. 2010, Szlyk e*t al*. 2002, Lamble e*t al*. 2002, Bowers *et al*. 2005) mainly due to individual adaption (Sandin *et al*. 2014, Haan e*t al*. 2014, Kanesci *et al*. 2014, Dowers e*t al*. 2010, Papageorgiou e*t al*. 2012, Vega e*t al*. 2013, Rauscher e*t al*. 2007, Hamel e*t al*. 2012, Coekelburgh e*t al*. 2004. Coekelburgh e*t al*. 2002). However, other evidence demonstrates that VFL leads to unsafe driving (Bowers e*t al*. 2009, Alberti e*t al*. 2013, Bronstad e*t al*. 2013, Bhorade e*t al*. 2016, Cheung e*t al*. 2011, Krader. 2014, Szylk *et al*. 2005, Glen e*t al*. 2015, Bronstad e*t al*. 2015, Alberti e*t al*. 2014, Kunimatsu-Sanuki *et al*. 2017) and that there is a link between MVCs and VFL (McGwin *et al*. 2013, Kwon *et al*. 2016, Rubin *et al*. 2007, Cross e*t al*. 2008. Sotimehin & Ramulu. 2018). With conflicting evidence, and variable methodologies to establish the evidence, a link with MVCs and field loss is difficult to establish. However, this conflict does not lessen the importance of a careful measurement of visual fields in those who are visually impaired when determining their legal status of driving (Nowakowski. 1994). It is highly important that the field test that has this authority possesses good retest reliability, producing repeatable results upon retest in those with VFL to avoid a pass on one examination and a fail on a subsequent examination, or vice-versa, when there has been no change in pathology. Failure to do so would have a significant impact on the driver. McKendrick (2005) reviewing automated perimetry, stated that a perimetric test should be four things: accurate, efficient, reflect the extent of any damage and be ‘repeatable’ (McKendrick. 2005).

4.2. Primary Aim.

Although the EVFT, VFL and driving have been subject to much research, the repeatability of the EVFT has not been investigated in those with VFL. This study wished to address this by investigating the repeatability of the EVFT in those with VFL. Secondary aims have previously been outlined in section 2.1.1.1.

4.3. Methods.

To evaluate the repeatability of the EVFT a case-control evaluation study was performed. Instrumentation used in this study has been outlined in section 3.2.

4.3.1. Participants.

Participant recruitment and details have been previously outlined in section 3.1. Those with VFL had a variety of presenting conditions and were representative of patients who should inform the DVLA they have a diagnosed eye condition and hence, represent the population that would be affected by current driving standards. Having a selection of heterogeneous VFL conditions within the sample allows evaluation over a wide spectrum of participants that could present in clinical practice.

Age and gender matched controls were used in order to distinguish effects of retest variability of the EVFT. A Mann-Whitney test confirmed there was no statistically significant difference between ages between the study and control participants (p=0.661). A Pearson's chi-squared test confirmed there was no statistical difference between gender between the study and control participants (p=1.000)

4.3.2. Procedure.

The procedures for all studies have been previously outlined in section 3.3. For this study, three visits were chosen to minimise the perimetry learning effect. Main improvements in FT visual field testing performance occur between visit 1 and visit 2 (Heijl & Bengstsson. 1996) and for those who have no experience in visual field testing the second test should be used as the baseline (Horani *et al*. 2002). All visits were used in the analyses in order to represent patients attending for visual field tests within high street practice. Visits were spaced one week apart to limit changes in results due to progression or due to cognitive decline that occurs with age and has been apparent on tests such as the results of the UFOV (Rao *et al*. 2013).

Duration between visits were of non-normal distribution as confirmed by Shapiro-Wilk tests (study: SW(68)=0.464; p=<0.005; controls: SW(80)=0.544; p=<0.005). A Mann-Whitney test found that there was no statistical differences between the elapse of time between visits for the study group or the controls (*U*=1639.5; z=-1.061; p=0.289). Neither were there any differences between the elapse of time between visit 1-to-visit 2 compared to the elapse of time between visit 2-to-visit 3 for either the study group (z=-0.356; p=0.722) or the control group (z=-0.372; p=0.710) as confirmed by Wilcoxon tests.

Each visual field test varied upon duration between participants, but was within 8'19" for each individual study participant and 4'55" for each control participant. The average completion time for all study participants was 5'01" (SD=0.985) and 4'12" (SD=0.28) for the control sample.

4.3.3. Data Analysis.

Data analysis has been previously outlined in section 3.4. The primary analysis was for the repeatability of the EVFT in those with VFL. The first prediction would be that EES would be significantly less repeatable in participants with VFL. The second prediction would be that the location of defect would also be significantly less repeatable in participants with VFL.

To determine the pass/fail on first or second visit, the three visits were separated into paired classes (table 4-1).

Frequency	First pair set	Second pair set
Pass/pass/fail	Pass/pass	Pass/fail
Fail/pass/fail	Fail/pass	Pass/fail
Fail/pass/pass	Fail/pass	Pass/pass
Pass/pass/pass	Pass/pass	Pass/pass
Fail/fail/fail	Fail/fail	Fail/fail

Table 4-1. The paired frequency equivalents across visits. Paired sets for frequencies across three visits.

Data for those with VFL were further analysed in the sub-categories of those with NFD and those with CFD. Analysis for PFD is not presented due to the very small sample size. This was also the case for those with Un defects. In addition, the variance in the conditions would provide difficulty establishing any meaningful result. Data were only analysed where a statistical difference was established in the pooled data in those with VFL but could not be established within the sub-categories of NFD or CFD. This was to investigate where the difference was located

4.4. Results.

The EES were confirmed to have a trend in the overall significant difference between study and control groups (T_{J}=9455.500, z=7.751, p=<0.005) with those with VFL scoring lower than the controls (t_b=0.444, p=<0.005) confirming the nature of the participants.

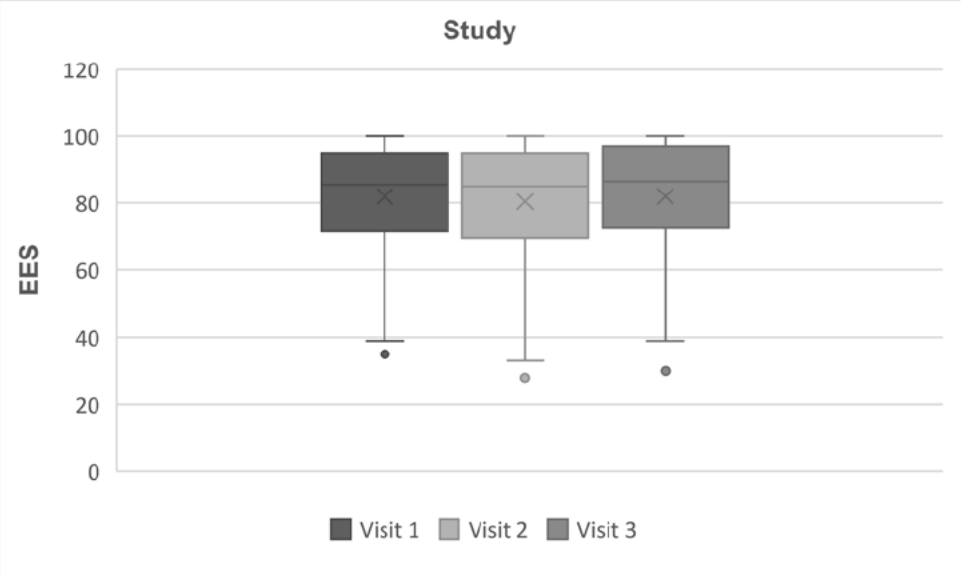
4.4.1. Repeatability of EES.

Table 4-2 provides a summary of the recorded EES, presenting the median and the interquartile range (IQR) for all participants and the participant sub-categories. Figure 4-1 presents the EES for each visit for those participants with VFL (a) and the controls (b). Figure 4-2 presents the EES for each visit for those participants with NFD (a) and CFD (b). Figure 4-3 presents the EES scores plotted per visit illustrating the test-retest correlation between visits for those with VFL (a) and the controls (b) and figure 4-4 presents the EES plotted per visit illustrating the correlation between visits for those with NFD (a) and CFD (b). Bland and Altman plots (Figure 4-5) present the levels of agreement for those with VFL and the normal controls. Figure 4-6 presents the levels of agreement for those with NFD and CFL. The plots illustrate agreement of scores between visits 1-to-visits 2, visits 2-to-visits 3 and visits 1-to-visit 3. Table 4-3 provides the values of the bias, standard deviation along with the upper and lower limits of agreement for each Bland and Altman plot for those with VFL (a), the controls (b), NFD (c) and CFD (d)

Participant category.	**Visit**	**EES Median**	**EES IQR**	**Participant category**	**Visit**	**EES median**	**EES IQR**
All	1	93	13	**NFD**	1	85	23
	2	95	12		2	85	24.5
	3	95	12		3	88	26
Study	1	85	24	**CFD**	1	94.5	11
	2	85	22		2	94.5	11.5
	3	86	22		3	96.1	12.5
Control	1	96	7.5	**PFD**	1	65	19.5
	2	96	5		2	68.5	23.5
	3	96	6		3	64.5	20.5
				Un	1	78	23
					2	85	31
					3	80	26

Table 4-2. Summary table of EES, presenting median and IQR for all participants and participant sub-categories. EES= Esterman efficiency score. IQR=interquartile range.

(a).



(b).

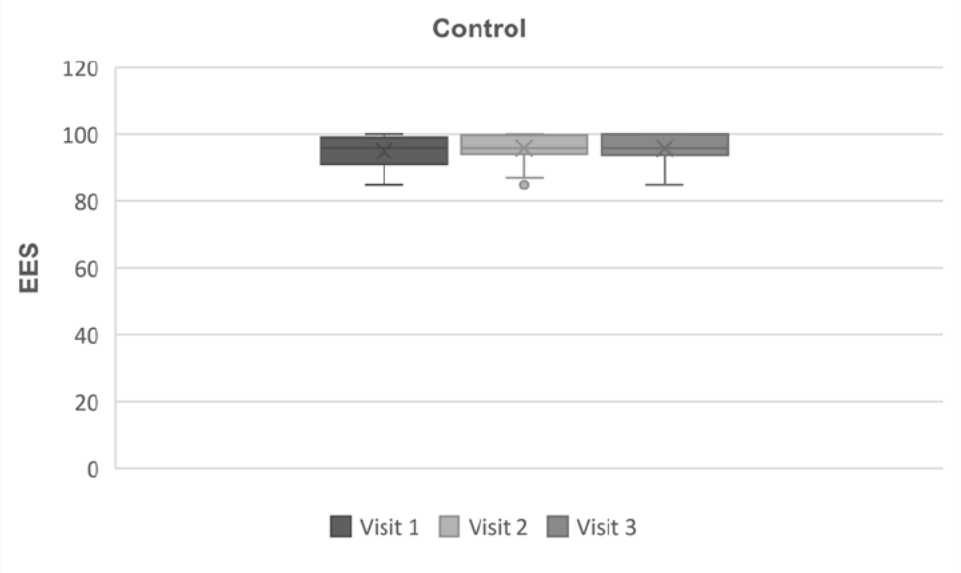
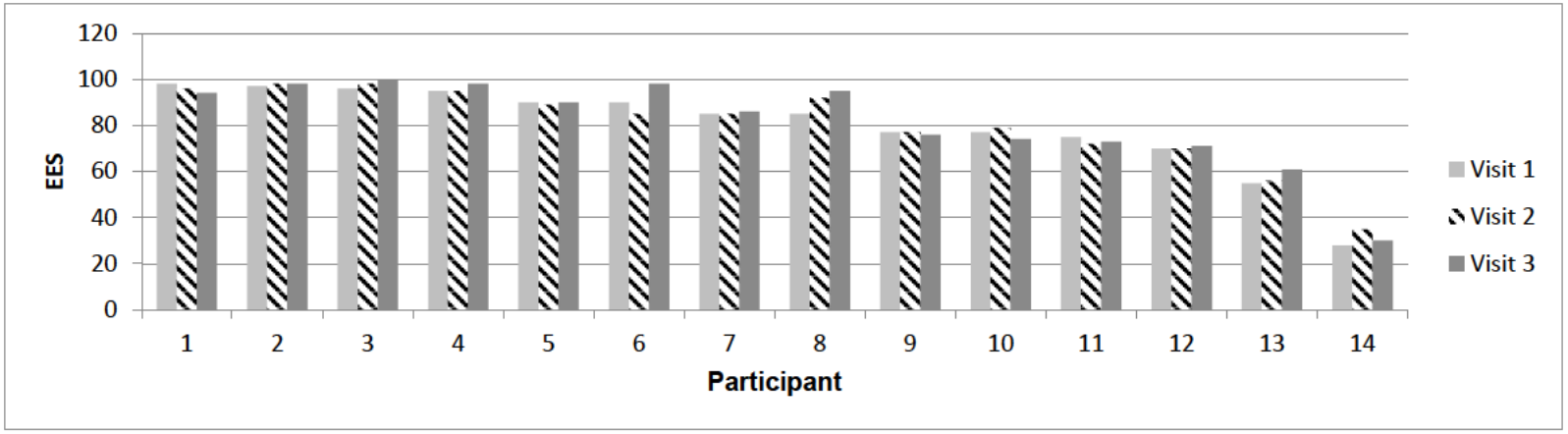


Figure 4-1. EES per visit. The thick vertical bars indicate the interquartile ranges. The thin vertical lines indicates maximum and minimum values. Outliers are represented as dots. Median indicated by thin horizontal line. Mean indicated by x. Data shown for (a) the VFL participants and (b) the controls.

(a).



(b).

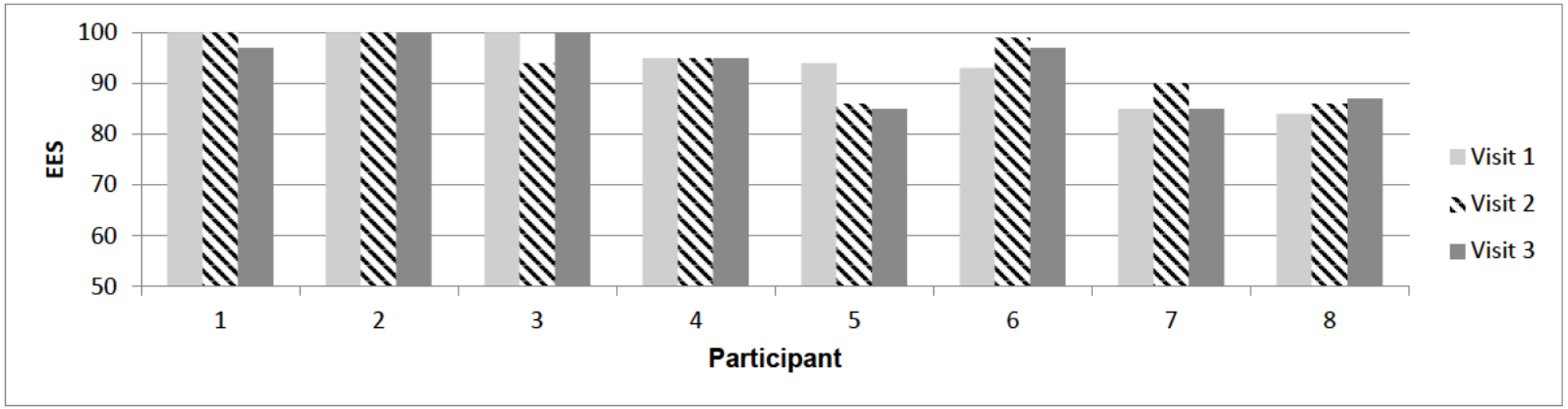
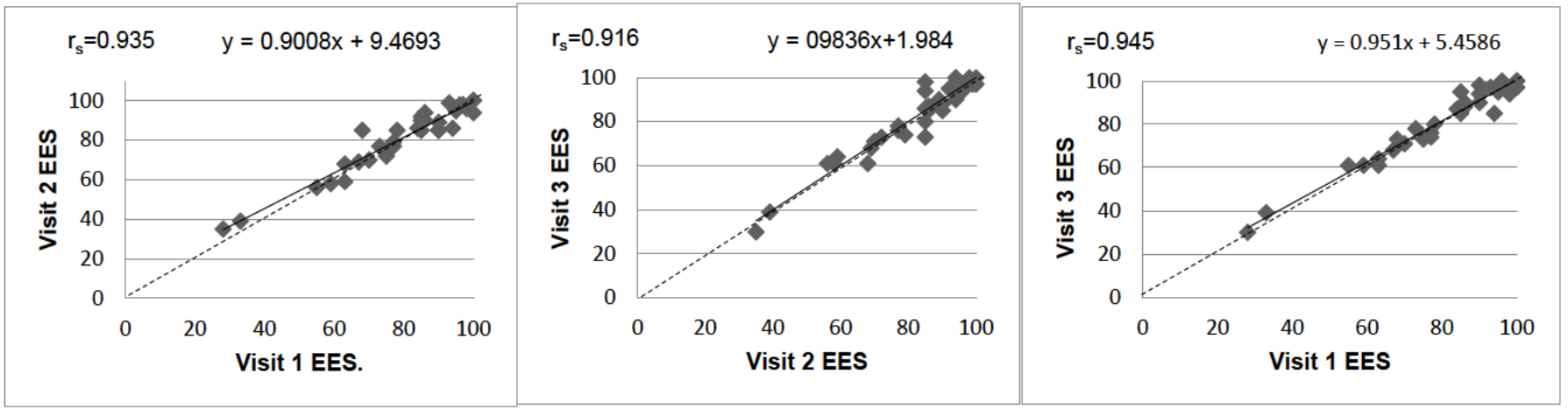


Figure 4-2. EES scores per visit for those with NFD and CFD. Bars in order of visit. 1st, 2nd, 3rd visit for (a) participants with NFD (b) and participants with CFD.

(a)



(b)

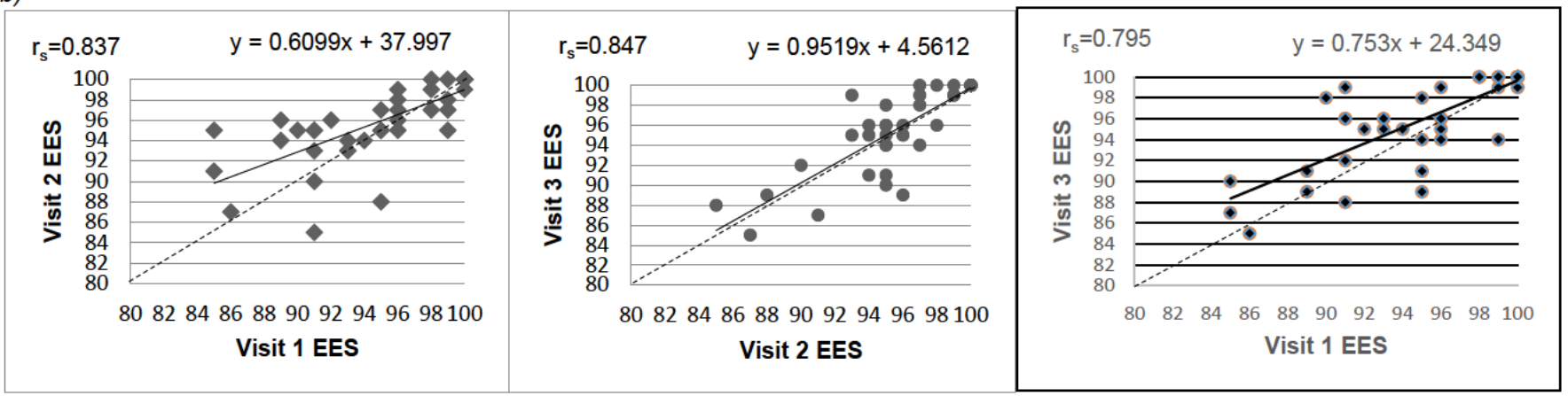


Figure 4-3. EES scores plotted for each visit and their test-retest coefficient (Spearman's rho (r_s)) for those with VFL (a) and controls (b). Dashed line represents the line of equality. Linear equation shown.

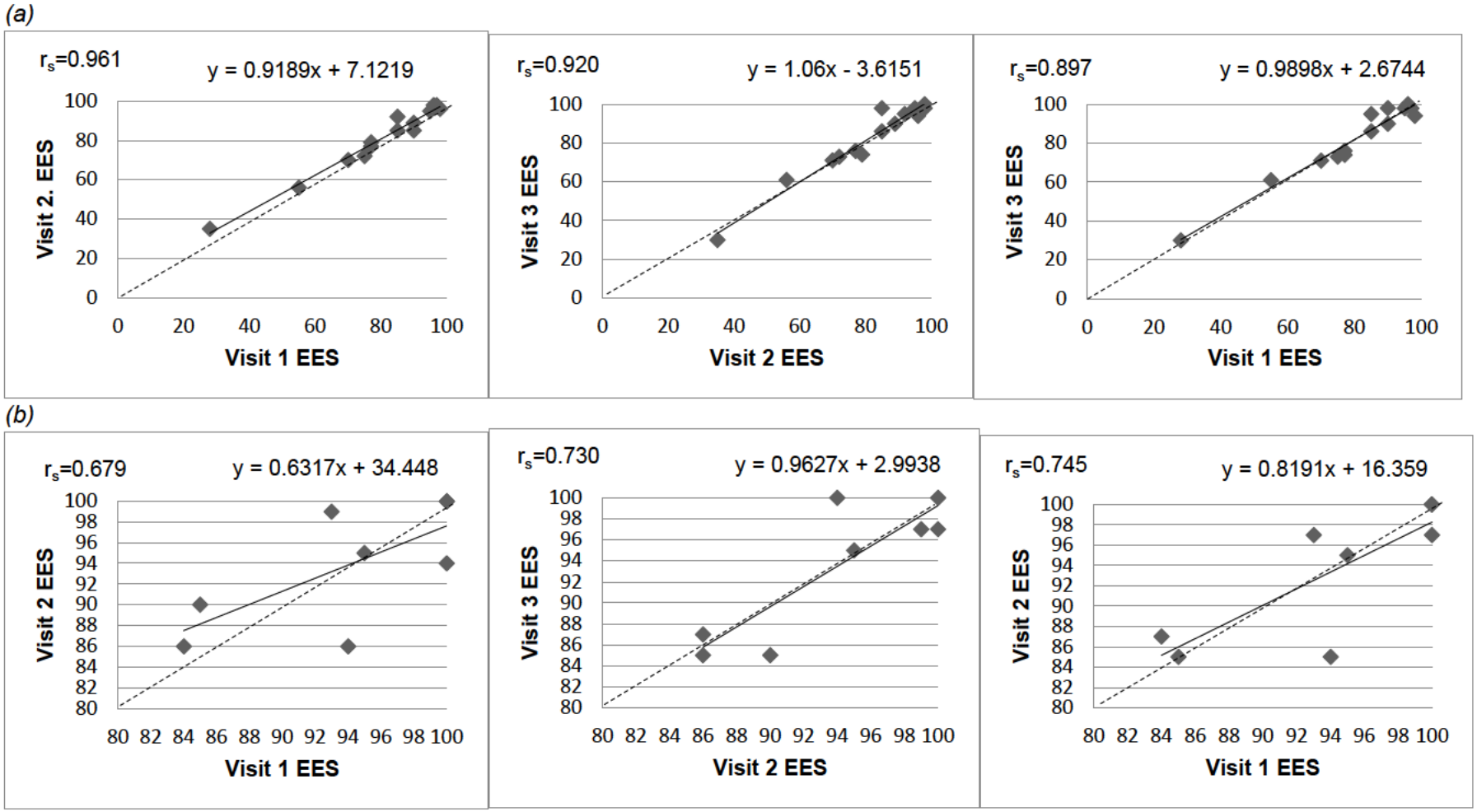


Figure 4-4. EES scores plotted for each visit and their test-retest coefficient (Spearman's rho (r_s)) for those with NFD (a) and for those with CFD (b). Dashed line represents line of equality. Linear equation shown.

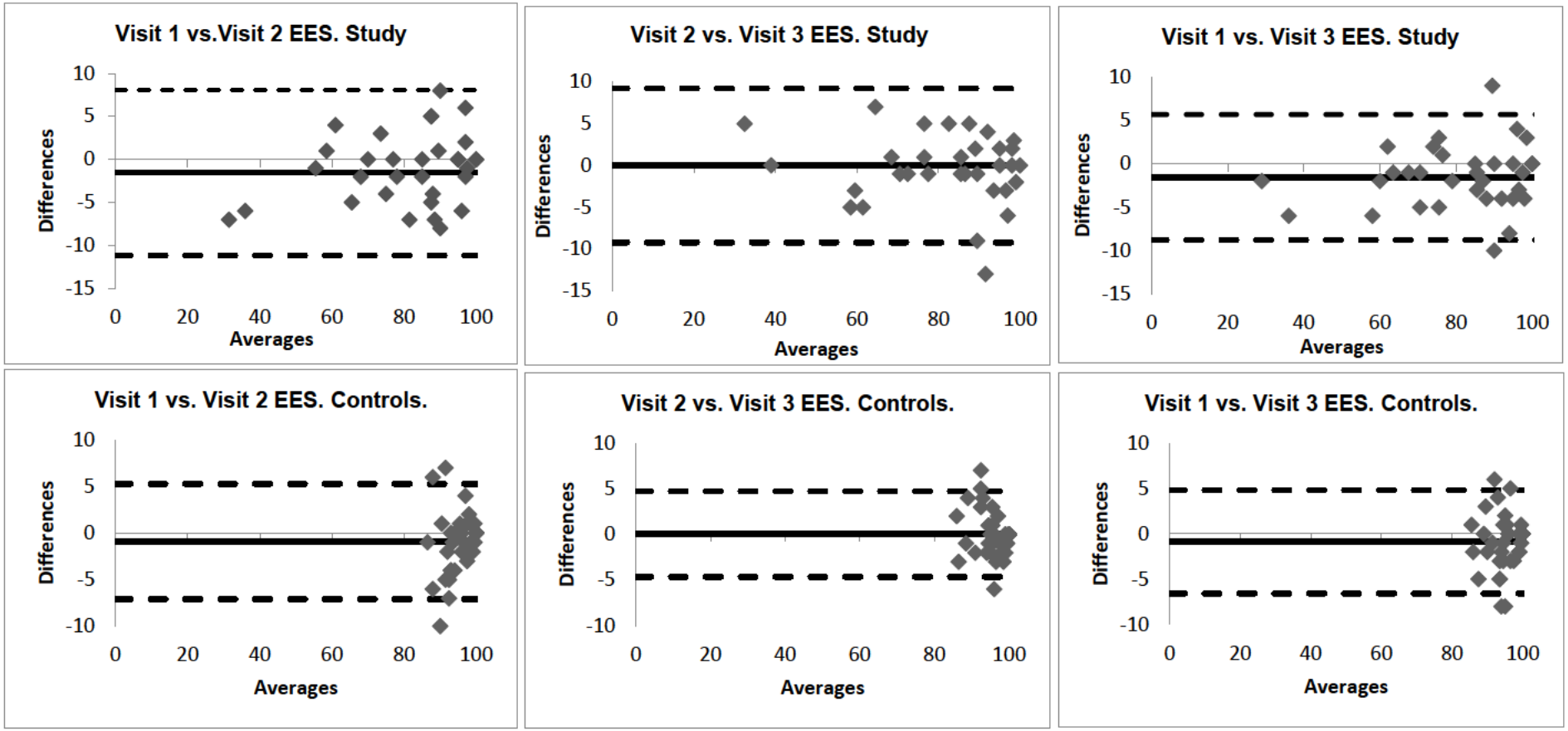


Figure 4-5. EES total reliability for those with VFL (n=33) and controls (n=40). Solid lines indicate mean test-retest difference and dashed lines indicate 95% limits of agreement.

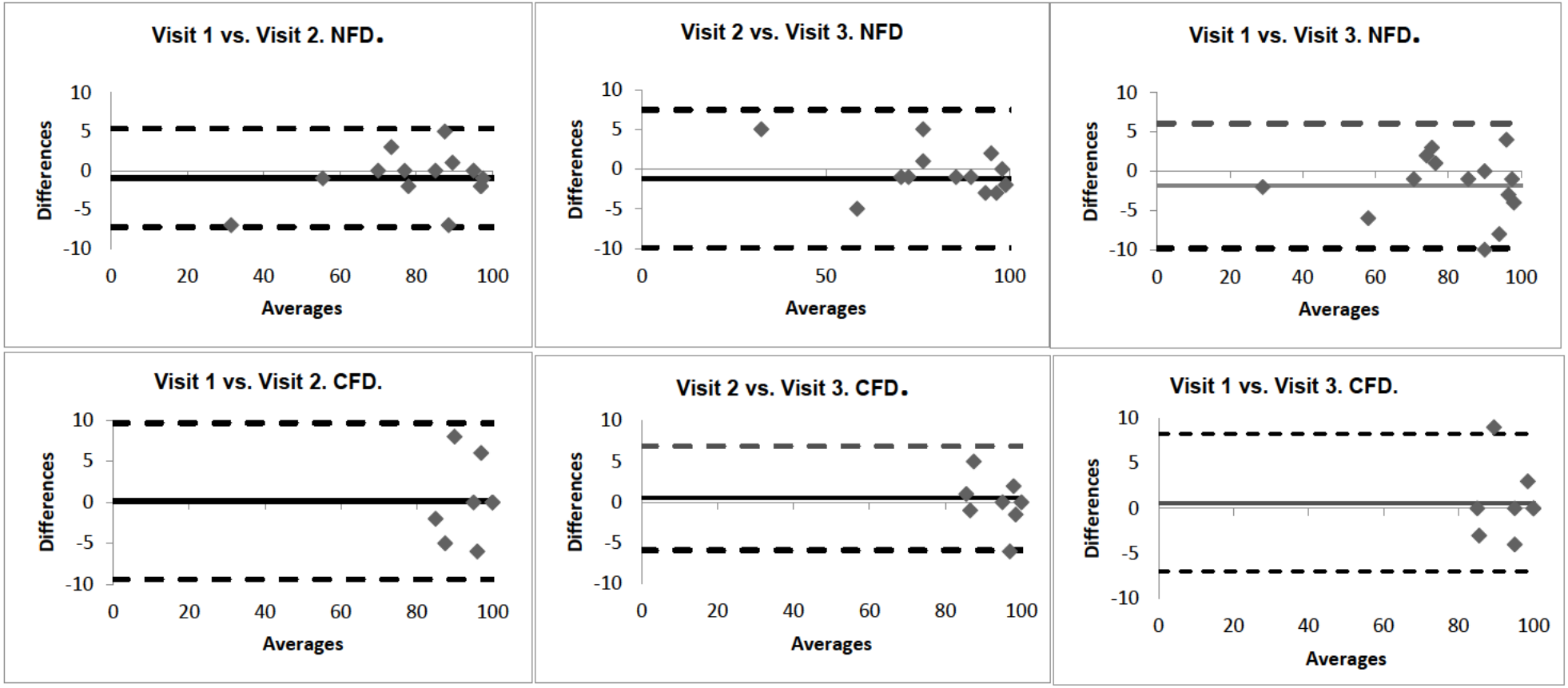


Figure 4-6. EES total reliability for those with NFD (n=14) and those with CFD (n=8). Solid lines indicate mean test-retest difference and dashed lines indicate 95% limits of agreement.

(a)

	Visit 1 vs. Visit 2. Study participants	Visit 2 vs. Visit 3. Study participants	Visit 1 vs. Visit 3. Study participants
Bias	-1.546	0.00	-1.546
STDEV	4.919	4.697	3.684
Lower LOA	-11.186	-9.206	-8.765
Upper LOA	8.095	9.206	5.674

(b)

	Visit 1 vs. Visit 2. Control	Visit 2 vs. Visit 3. Control	Visit 1 vs. Visit 3. Control
Bias	-0.925	0.050	-0.875
STDEV	3.157	2.396	2.910
Lower LOA	-7.113	-4.646	-6.580
Upper LOA	5.263	4.746	4.830

(c)

	Visit 1 vs. Visit 2. Nerve fibre defects	Visit 2 vs. Visit 3. Nerve fibre defects	Visit 1 vs. Visit 3. Nerve fibre defects
Bias	-0.929	-1.214	-1.857
STDEV	3.222	4.423	4.055
Lower LOA	-7.243	-9.884	-9.804
Upper LOA	5.386	7.455	6.090

(d)

	Visit 1 vs. Visit 2. Central field defects	Visit 2 vs. Visit 3. Central field defects	Visit 1 vs. Visit 3. Central field defects
Bias	-0.125	0.500	0.625
STDEV	4.853	3.251	3.888
Lower LOA	-9.387	-5.873	-6.995
Upper LOA	9.637	6.873	8.245

Table 4-3. The agreement between EES between visits. The bias, standard deviation (STDEV), lower limits of agreement (LOA) and the upper LOA for the Bland and Altman plots for those with VFL (a), the controls (b), those with NFD (c) and those with CFD (d)

The EES measured for each visit for those with VFL were tested for normality and were of non-normal distribution (SW(33): Visit 1: 0.833, p=0.002; visit 2: 0.875, p=0.001; visit 3: 0.879, p=0.002). The EES median for those with VFL was 85 for both visits 1 (IQR=24) and visit 2 (IQR=22). For visit 3 the EES median was 86 (IQR=22).

The definition of agreement based on the correlation coefficient is defined as follows: 0= no agreement; +/-0.1 to +/- 0.2= poor agreement; +/-0.3 to +/-0.5= fair agreement; +/-0.6 to +/-0.7 = good agreement; +/-0.8 to +/-0.9= very strong agreement; +1 to -1= perfect agreement (Akoglu. 2018).

Bland and Altman (Bland and Altman. n.d.) stated that correlation does not assess agreement. Therefore, in addition to correlation, Bland and Altman plots were used to determine agreement. No previous studies have attempted to determine agreement in the EES. Consequently, the normal variance of EES has not been previously established to compare results against. Therefore, for this study, the normal variance expected was established from the control group to enable comparison of the Bland and Altman plots generated from the study participants EES across their visits. The upper and lower limits of agreement along with the bias for the control group are detailed in table 4-3.

The median EES for the controls was 96 for all three visits (visit 1 IQR=7.5; visit 2 IQR=5; visit 3 IQR=6).

The test-retest correlation demonstrates a very strong correlation between EES on visits 1-to-visits 2 (r_s=0.837; p=<0.005), visits 2 to 3 (r_s=0.847; p=<0.005) and good correlation between visits 1-to-visits 3 (r_s=0.795; p=<0.005) for the controls.

Bland and Altman plots demonstrated closer agreement in EES between visits in the controls compared to those with VFL. The closest agreement was between visits 2-to-visits 3 with the lower limit of agreement being closer to the bias.

A Friedman two-way analysis of variance found there was no statistical significance between the scores for the three visits for the control group ($\chi^2(2)$=5.196; p=0.074) with a small effect size (W=0.07) Post hoc testing established power of 1-β=0.24 with α=0.05.

The test-retest correlation demonstrated a very strong correlation between scores on visits 1-to-visits 2 (r_s=0.935; p=<0.005), visits 2-to-visits 3 (r_s=0.916; p=<0.005) and visits 1-to-visits 3 (r_s=0.945; p=<0.005) in those with VFL. However, the limits of agreement determined by Bland and Altman plots do not illustrate agreement between

visits. Demonstrating that they are further from the bias from visit 1-to-visit 2 and narrowing towards visit 3. The narrowest limits of agreement are provided from visit 1-to-visit 3.

A Friedman two-way analysis of variance found there was a statistically significant difference between the scores for participants with VFL for the three visits ($\chi^2(2)=6.649$; p=0.036). Using pair-wise Wilcoxon analyses and using a Bonferroni correction factor of α=0.017, The scores between visit 1-to-visit 3 were statistically different (z(1)=-2.410; p=0.016; r=-0.29). No statistical difference was found between visits 1-to-visits 2 (z(1)=-1.705; p=0.088; r=-0.21), or between visits 2-to-visits 3 (z(1)=-0.120; p=0.905; r=-0.02). A post-hoc test provided statistical power of 1-β=0.50 for results of differences in EES from visit 1-to-visit 2 and 1-β=0.07 with α=0.05 for results of visit 2-to-visit 3.

The median EES for those with NFD was 85 for both visits 1 (IQR=23) and visit 2 (IQR=24.5) and the median EES for visits 3 was 88 (IQR=26).

Test-retest correlation demonstrates a very strong correlation between scores on visits 1-to-visits 2 (r_s=0.961; p=<0.005), visits 2 to 3 (r_s=0.920; p=<0.005) and between visits 1-to-visits 3 (r_s=0.897; p=<0.005) for those with NFD. Bland and Altman plots illustrate that the limits of agreement for visit 1-to-visit 2 are similar to that of the control group, but the limits of agreement increased away from the bias for visit 2-to-visit 3 and departed from those found in the control group. The limits of agreement are however narrower from the pooled study data.

A Friedman two-way analysis of variance found there was no statistical significance difference between the scores for the three visits in those participants with NFD ($\chi^2(2)=3.160$; p=0.206) with a small effect size (W=0.11). Post hoc testing provided power of 1-β=0.68 with α=0.05.

The median EES for those participants with CFD was 94.5 for both visits 1 (IQR=11) and visits 2 (IQR=11.5) and the median EES for visits 3 was 96 (IQR=12.5).

Test-retest correlation demonstrates a moderate correlation (r_s=0.679; p=<0.064) which was not found to be significant between scores on visit 1-to-visit 2 and a moderate correlation for visit 2-to-visit 3 (r_s=0.730; p=0.040) and Between visit 1-to-visit 3 (r_s=0.745; p=0.034) for participants with CFD. Bland and Altman plots illustrate limits of agreement that fall further away from the bias than the control and NFD groups for visit 1-to-visit 2. The limits of agreement narrow towards the bias for visit 2-

to-visit 3, albeit larger than the controls, they are narrower than both the NFD and the pooled study group.

A Friedman two-way analysis of variance found there was no statistical significance difference between the scores for the three visits in those participants who had CFD ($א^2(2)=0.667$; p=0.717) and minimal effect size (W=0.04). Post hoc testing provided statistical power 1-β=0.06 with α=0.05.

In those without VFL the upper and lower limits of agreement range from 5.26 to -7.11 respectively. Those with VFL exceed these limits of agreement with the upper and lower limits of agreement ranging from -11.18 to 9.21 respectively. The lack of agreement demonstrated by the Bland and Altman plots compared to the limits of agreement of the control participants, and the significant difference found in EES between visits 1-to-visits 3 inform that the EES on the EVFT is not repeatable in those with VFL.

Figure 4-7 shows the EES plotted for each visit for participants with PFD and Un. The median EES for those participants with PFD was 65 (IQR=19.5) for visit 1, 68.5 (IQR=23.5) for visit 2 and 64.5 (IQR=20.5) for visit 3. For those participants in the Un category the median EES was 78 (IQR=23) for visit 1, 85 (IQR=31) for visit 2 and 80 (IQR=26) for visits 3.

A Friedman two-way analysis of variance found there was no statistically significant difference between the scores for the three visits in those participants who had PFD ($א^2(2)=5.733$; p=0.057). A large effect size was found (W=0.72). There was also no statistically significant difference between the scores for the three visits in those participants who were in the Un category ($א^2(2)=4.571$; p=0.102) with medium effect size (W=0.33). Post hoc testing provided power of 1-β=0.23 and 0.11 respectively when α=0.05.

The difference in EES found in the VFL participants between visits demonstrates the EES of the EVFT is not repeatable in these participants. However, the type of VFL that drove this difference is not clear.

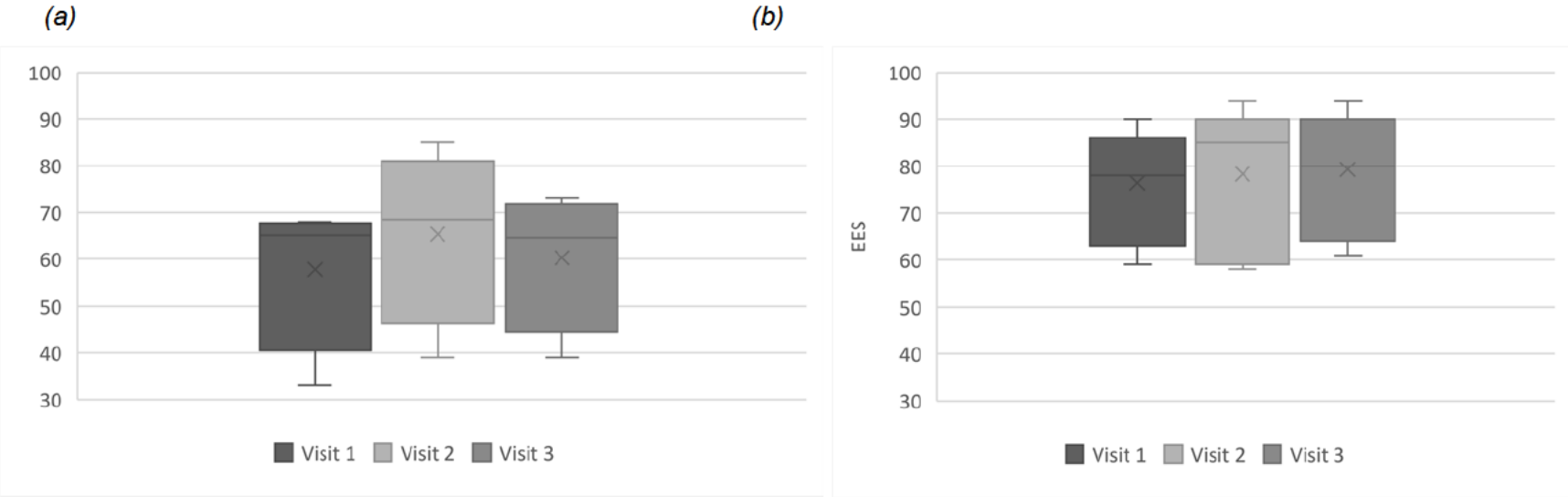


Figure 4-7. EES for PFD (a) and Un defects (b) for each visit. The thick vertical bars indicate the interquartile ranges. The thin vertical lines indicates maximum and minimum values. Median indicated by thin horizontal line. Mean indicated by x.

4.4.2. Range of EES Variance. Between Group.

To compare the range of variance between groups each participant's mean variance between all three visits was taken. The mean variance was normally distributed for the study group (SW(33)=0.966 p=0.690), those with NFD (SW(14)=0.959; p=0.702) and those with CFD (SW(8)=0.852; p=0.100). The mean variance for the controls had a non-normal distribution (SW(40)=0.945; p=0.050).

Figure 4-8 presents the mean range of variance over the three visits plotted against the percentage of participants. Comparisons of the mean range of variance is presented for the controls and the study group and the study sub-groups and table 4-4 presents the results for mean range of variance between visits; between groups.

All results, for all the categories of study participants, had confirmed homogeneity of the variance when compared to the controls. There was no statistical significance between the range of variation means between visits for any of the study participant sub-groups when compared to the range of variance means of the controls.

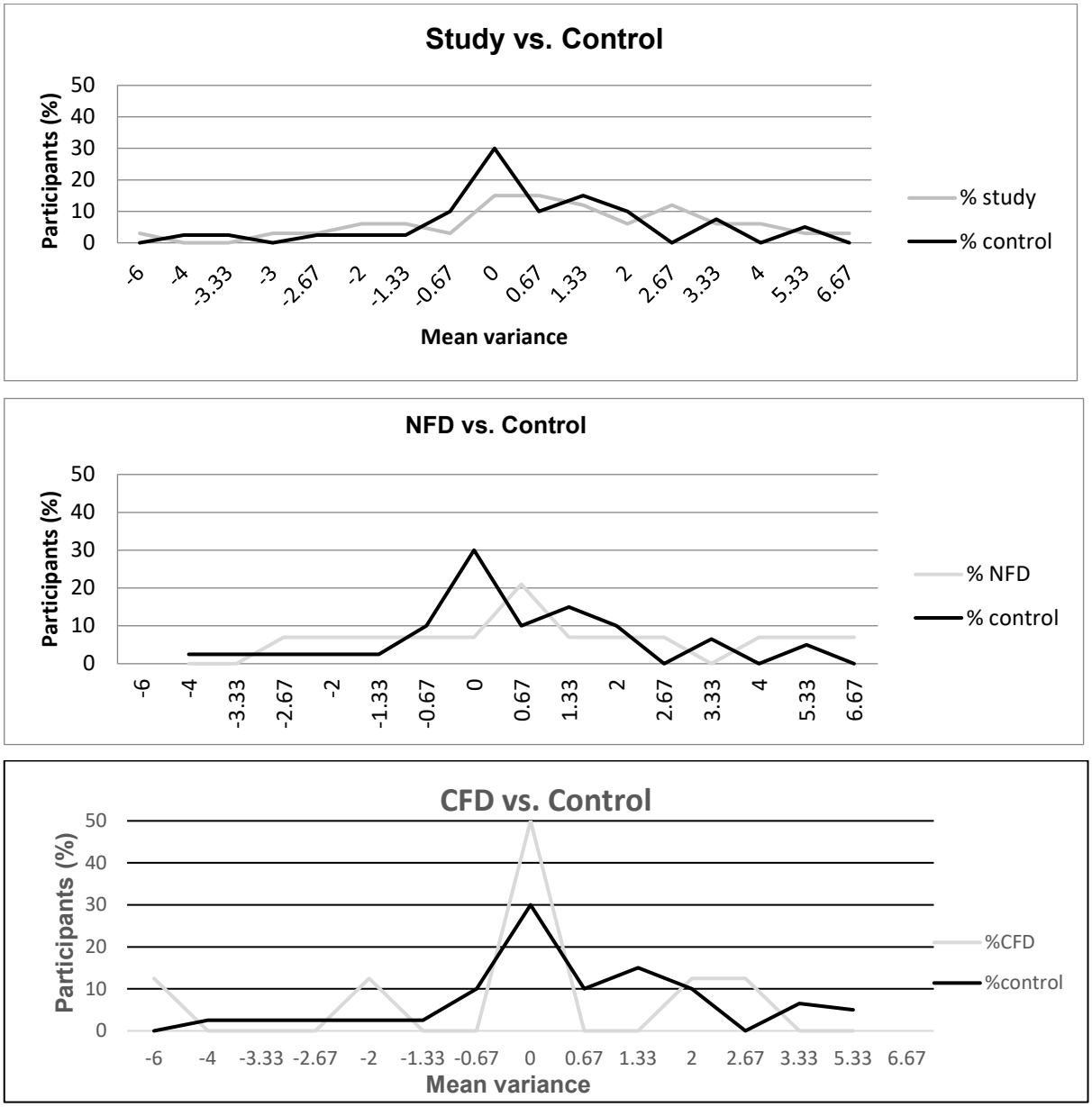


Figure 4-8. The mean range of variance over the three visits plotted against frequency of participants (%). Top: Comparing the range of mean variation in EES between those with VFL and the controls. Middle: Comparing the range of mean variation in EES between those with NFD and the controls. Bottom: Comparing the range of mean variation in EES between those with CFD and the controls. Negative and positive values indicate direction of EES variance from baseline.

Participant category; Comparison with controls.	Result: Levene's test.	Homogenity present?	Result: Mann-Whitney U test.	Range of variance significantly different between groups?	Control Median	Control IQR	Median of group under test.	IQR of group under test.	Power when α=0.05.
Established visual field loss	F(1)=1.667; p=0.201.	Confirmed.	*U*=541.000; z=-0.999; p=0.318.	Unconfirmed.	0	1.33	0.67	2.67	1-β=0.12; r=-0.12.
Nerve fibre defect.	F(1)=2.387; p=0.128	Confirmed	*U*=245.500; z=-0.687; p=0.492.	Unconfirmed.	0	1.33	0.67	3.34	1-β=0.09; r=-0.09
Central field defect.	F(1)=0.486; p=0.483.	Confirmed	*U*=131.500; z=-0.805; p=0.438.	Unconfirmed	0	1.33	0	2	1-β=0.09; r=-0.12

Table 4-4. Results for mean range of variance between visits; between groups.

4.4.3. Repeatability of Pass and Fail Frequencies.

Table 4-5 presents the frequencies in percentage of pass or fail episodes for the study group and table 4-6 presents comparison of pass/fail frequency episodes in 2x2 tables across visits for those with VFL. As expected, all the control participants passed each visit. Table 4-7 provides the frequencies of pass/fail results in their combinations for each of the three visits for both the study and control participants. Pass and fail visual fields were defined using the DVLA criteria.

Visit 1		**Visit 2**		**Visit 3**	
Pass(%)	**Fail(%)**	**Pass(%)**	**Fail(%)**	**Pass(%)**	**Fail(%)**
48.50	51.50	57.60	42.40	48.50	51.50

Table 4-5. Frequencies of pass and fail rates for each visit. Pass/fail frequencies provided in percentages. Data for participants with VFL.

	Visit 1		
Visit 2		Pass	Fail
	Pass	16	3
	Fail	0	14

	Visit 2		
Visit 3		Pass	Fail
	Pass	16	0
	Fail	3	14

	Visit 1		
Visit 3		Pass	Fail
	Pass	15	1
	Fail	1	16

Table 4-6. Pass/fail frequencies across visits. Comparing pass/fail rates between visit 1-to-visit 2, visit 2-to-visit 3 and visit 1-to-visit 3. Data provided= frequency of participants.

Frequencies study (n=33)									
PPP	**FFF**	**PFP**	**PPF**	**PFF**	**FPF**	**FFP**	**FPP**	**Consistent result**	**Inconsistent result**
15	14		1		2		1	29	4
(%)									
45	42		3.33		6.67		3.33	87	12

Frequencies control (n=40)	
40	40
(%)	
100	100

Table 4-7. The combination of pass/fail results. Combinations provided in order of visit along with the amount of consistent and inconsistent results. P= Pass result. F= Fail result.

Figure 4-9 presents the study subgroups and frequency of pass, pass/fail and fail results as defined by the DVLA criteria.

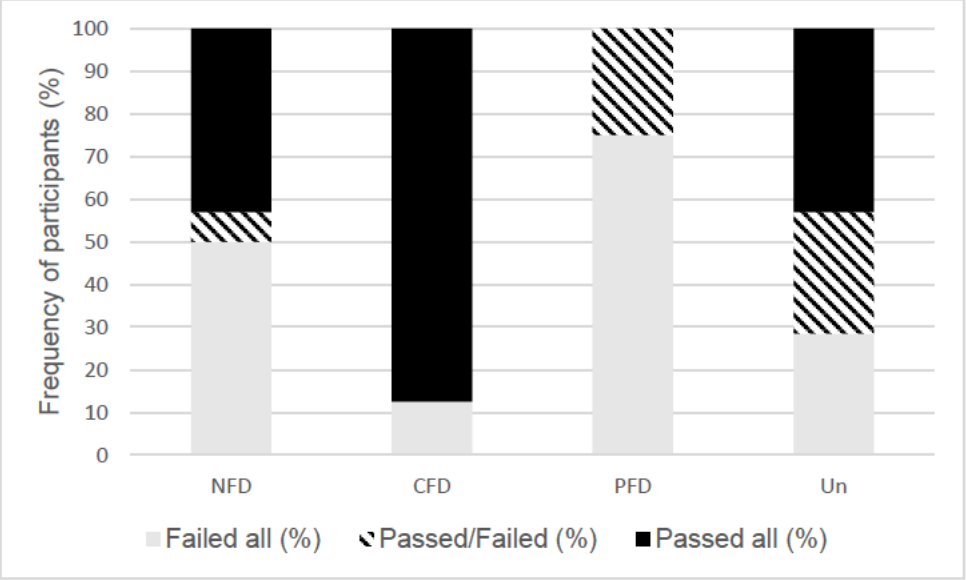


Figure 4-9. Frequencies of passed, failed and passed/failed on all visits (%). Data for study participant subgroups.

The pass/fail frequencies are a measure of variance. Variability in fitness-to-drive arose in 12% of participants with VFL.

A McNemar chi-squared test was used to compare the frequencies and change between visit 1-to-visit 2 (p=0.250); visit 2-to-visit 3 (p=0.250); visit 1-to-visit 3 (p=1.000). None of the changes in frequencies between visits were found to be

statistically significant. No chi-square value was provided by SSPS due to a correction factor it conducted with the test, the chi-squared value was sourced by conducting the chi-squared test on Excel (X^2=0.750) the p-values from SSPS are recorded above. A post hoc test provided power of 1-β=0.75 with α=0.05.

4.4.4. Overlap Zone. Pass/fail Frequencies.

Table 4-8 provides the scores for overlap whereby a participant may pass on one visit or fail on another visit for all the study participants. Along with the minimum and maximum scores and the extent of the variance in EES that resulted in inconsistent results. To calculate sensitivity and specificity from the results of three visits, the results from paired visits were employed as outlined in table 4-1.

Study participants									
Test	**Number in overlap one**	**Extent of overlap**		**Variance in overlap**		**False positive rate(%)**	**False negative rate(%)**	**Sensitivity (%)**	**Specificity (%)**
		Min score	Max score	Min	Max				
EVFT	4	68	94	1	17	6.67	6.67	**93.33**	**94.12**
Control participants									
Test	**Number in overlap one**	**Extent of overlap zone**		**Variance in overlap one**		**False postive rate (%)**	**False negative rate (%)**	**Sensitivity (%)**	**Specificity (%)**
		Min score	Max score	Min	Max				
EVFT	0	0	0	0	0	0	0	**100**	**100**

Table 4-8. Overlap zone whereby participants passed on one visit and failed on another. False negatives indicate a pass first visit but a fail on second visit. False positives indicate a fail on first visit but a pass on second visit. True negatives= pass on both. True positive= fail on both. Sensitivity= true positives/(true positives+false negatives). Specificity=true negatives/(true negatives+false positives)

Table 4-9 provides the EES regions for definite pass (white area) definite fail (dark grey area) and could be either pass or fail (light grey area) creating the overlap zone for those with inconsistent results across visits in those with VFL.

Table 4-10 provides the frequencies of pass/fail results per visit for those results that were inconsistent.

EES (%)	Pass. Number of participants.	Fail. Number of participants.
94	1	0
90	1	0
86	0	1
85	2	0
80	0	1
78	0	1
77	2	0
76	0	1
73	0	1
68	0	1

Table 4-9. Regions of EES for definite pass, definite fail and either pass or fail. Definite pass (white), definite fail (dark grey) and could be either pass or fail creating the overlap zone for those with inconsistent results across visits in those with established VFL (light grey).

	Visit 1	Visit 2	Visit 3
P	1	4	1
F	3	0	3

Table 4-10. Frequencies of pass/fail results for each visit where results were inconsistent. Data provided= number of participants. P= Pass result. F= fail result as defined by the DVLA criteria.

A Shapiro-Wilk test found the EES were of normal distribution ($SW(12)=0.974$; $p=0.950$). For the participants with VFL that presented with inconsistent results, the overall mean change in EES was 1.67% (SD=7.39; CV=443.31%). From visit 1-to-visit 2 all scores increased with a mean of 8% (SD=6.98; CV=87.20%) From visit 2-to-visit 3 all scores decreased with a mean of 5.5% (SD=4.67; CV=84.81%). From visit 1-to-visit 3 the scores increased by 10% (SD=2.65; CV=26.46%). A one-way Anova found that EES did not alter significantly ($F(2)=1.277$; $p=0.325$). However, a large effect size ($d=1.01$) was found between the change in EES from visit 1-to-visit 2. (Visit 2-to-visit 3: $d=0.80$; visit 1-to-visit 3: $d=0.29$). $1-\beta=0.73$ with $\alpha=0.05$ and $d=1.01$.

4.4.5. Range of Variance in EES for Pass/fail Frequencies.

Figure 4-10 presents the range of variance in EES (average between visits taken) for those with pass/fail frequencies compared to study participants who had consistent frequencies between visits.

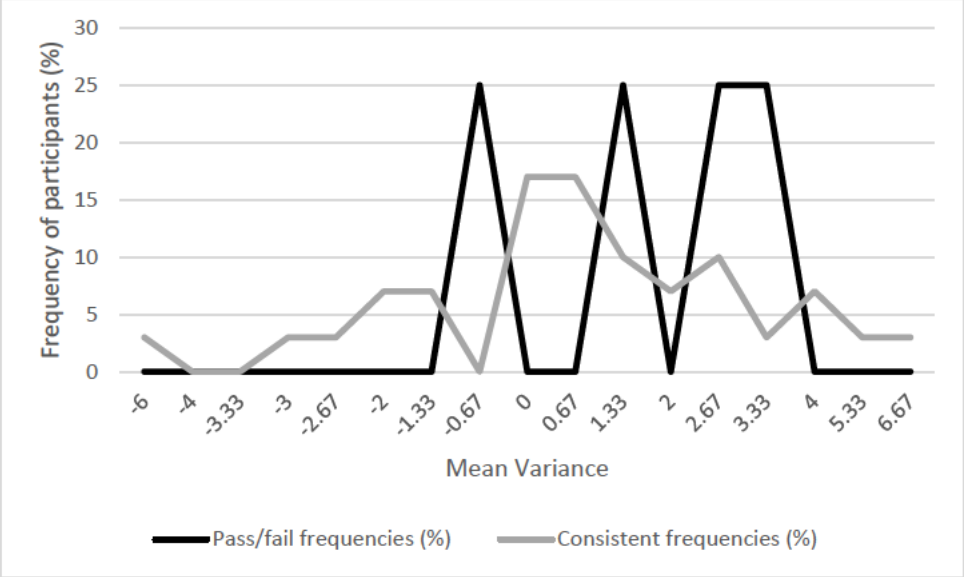


Figure 4-10. Range of average variance of EES between visits for those with inconsistent frequencies compared to those with consistent frequencies. Data for all study participants. Negative indicates mean average lower than baseline. Positive value indicates mean average higher than baseline.

A Shapiro-Wilk test confirmed normal distribution for the variances of those with inconsistent frequencies (SW(4)=0.945; p=0.685) and those with consistent frequencies (SW(29)=0.980; p=0.821).

A Levene's test of homegenity confirmed there was no significant difference between the mean variance of those with inconsistent results and those study participants with consistent results (F=0.812; p=0.375).

An independent samples t-test demonstrated there was no significant difference in average variances between visits between the study participants with inconsistent results (mean=1.67; SD=1.78; CV=106.00%) and study participants with consistent results (mean=13.00; SD=52.39; CV=402.98%) (t(31)=-0.429; p=0.671). A medium effect size was found (d=0.30). Post hoc testing revealed power of 1-β=0.55.

Study participants were also considered separately depending on whether they would be legal to hold a driving licence if the visual field criteria were excluded. Therefore, basing driving licensure on VA and eye condition alone. Of the 33 participants with

VFL, 17 participants would be allowed a driving licence if the visual field criteria were excluded from the assessment.

Table 4-11 presents the pass/fail frequencies dependent upon visit for the 17 participants that would be allowed a driving licence when the criteria for visual field assessment is excluded. Table 4-12 presents the frequencies of pass/fail in their combinations and presents the percentages for each presented combination for the 17 study participants who would qualify for a driving licence if the requirement for visual field assessment was excluded.

Frequencies between visits			
		Visit 1	
		Pass	Fail
Visit 2	Pass	10	1
	Fail	0	6

		Visit 2	
		Pass	Fail
Visit 3	Pass	9	0
	Fail	2	6

		Visit 1	
		Pass	Fail
Visit 3	Pass	9	0
	Fail	1	7

Table 4-11. The pass/fail frequencies when criteria for visual field is excluded. Comparing results for visit 1-to-visit 2, visit 2-to-visit 3 and visit 1-to-visit 3 for those with VFL that would be allowed a driving licence when the criteria for visual field assessment is excluded. Frequency data provided= number of participants.

PPP	**FFF**	**PFP**	**PPF**	**PFF**	**FPF**	**FFP**	**FPP**	**Consistent result**	**Inconsistent result**
9	6	0	1	0	1	0	0	15	2
(%)									
56.25	35.29	0	5.88	0	5.88	0	0	88.24	11.76

Table 4-12. Frequencies of pass/fail results for those with VFL with visual field criteria excluded. (n=17). P= passed. F= fail. Combinations provided in order of visit.

A McNemar Chi-Squared test found no significant difference in the frequencies from visit 1-to-visit 2 (p=1.000), visit 2-to-visit 3 (p=0.500) and visit 1-to-visit 3 (p=1.000) in those study participants who would be able to hold a licence if the visual field criteria was ignored. A chi-squared value was not performed on SPPS due to an automatic correction of the program using binominal distribution. Chi-squared value was obtained considering all three visits on Excel at a value of $X^2(4)=0.900$ (critical $x^2=9.488$). Therefore, the frequencies are independent of visit and the variance in EES and range of EES variance does not impact on pass/fail frequencies.

4.4.6. Influence of Age on EES.

Age and EES demonstrated a fair correlation ($r_s=0.445$; p=<0.005) for the study participants and a poor correlation ($r_s=-0.227$; p=0.013) for the controls. Therefore, the EES is weakly correlated with age in the normal group and there is a fair correlation with age and EES in the study group.

A Kruskal-Wallis test found a significant difference ($X^2(1)=30.121$; p=<0.005) in EES due to age in those with VFL. Those aged 41-50 (EES median=80.00; IQR=17.50) and 51-60 (EES median=59.00; IQR=35.00) scored lower than those aged 61-70 (EES median=85.50; IQR=17.50). This was significantly different for both age ranges (41-50 vs 61-70: $X^2(1)=4.501$, p=0.034; 51-60 vs 61-70: $X^2(1)=18.351$, p=<0.005). Those aged 71-80 (EES median=89.00; IQR=32.50) were also found to have a significant difference in scores ($X^2(1)=5.020$; p=0.025) scoring lower than those aged 81-90 (EES median=97.50; IQR=6.00). Significant differences were not found between other age ranges.

For the control group a Kruskal-Wallis test found a significant difference between age groups and scores ($X^2(1)=10.995$; p=0.027). With those aged 31-40 scoring significantly higher (EES median=100.00; IQR=0.00) than all other age groups (41-90 years: EES median=96.00; IQR=7.00) ($X^2(1)=5.045$, p=0.025) and those aged 81-90 scoring significantly ($X^2(1)=4.233$, p=0.040) lower (EES median=95.00; IQR=5.00) than those aged 31-80 (EES median=97.00; IQR=7.00). Scores for those aged 51-80 were not significantly different ($X^2(2)=1.724$, p=0.422). There were no participants aged between 41-50 in the control group.

4.4.7. Repeatability of Defect Location. Pointwise Analysis.

Taking the HFA grid with points from left to right and top to bottom, in numerical order (figure 4-4), Figure 4-12 presents the change (%) in defect or no defect status from visit 1-to-visit 2 and from visit 2-to-visit 3 for those with VFL (top) and for the controls for all test locations. Figure 4-13 presents the change in defect status (%; rounded to 0

decimal places) per location presented on the EVFT grid for all visits in those with VFL. Figure 4-14 presents the change in defect status (%; rounded to 0 decimal places) per location on the EVFT grid for all visits for the controls and figure 4-15 presents the difference of the change in defect status (%; rounded to 0 decimal places) per location on the EVFT grid, for all visits, comparing those with VFL and the controls.

The change in defect status (%) per location had non-normal distribution. For study participants between visit 1-to-visit 2 (SW(120)=0.883; p=<0.005), between visit 2-to-visit 3 (SW(120)=0.895; p=<0.005) and when the data were pooled for all visits (SW(120)=0.725; p=<0.005). The data for the control participants were also found to have non-normal distribution between visit 1-to-visit 2 (SW(120)=0.725; p=<0.005), visit 2-to-visit 3 (SW(120)=0.650; p=<0.005) and when the data were pooled for all visits (SW(120)=0.704; p<0.005).

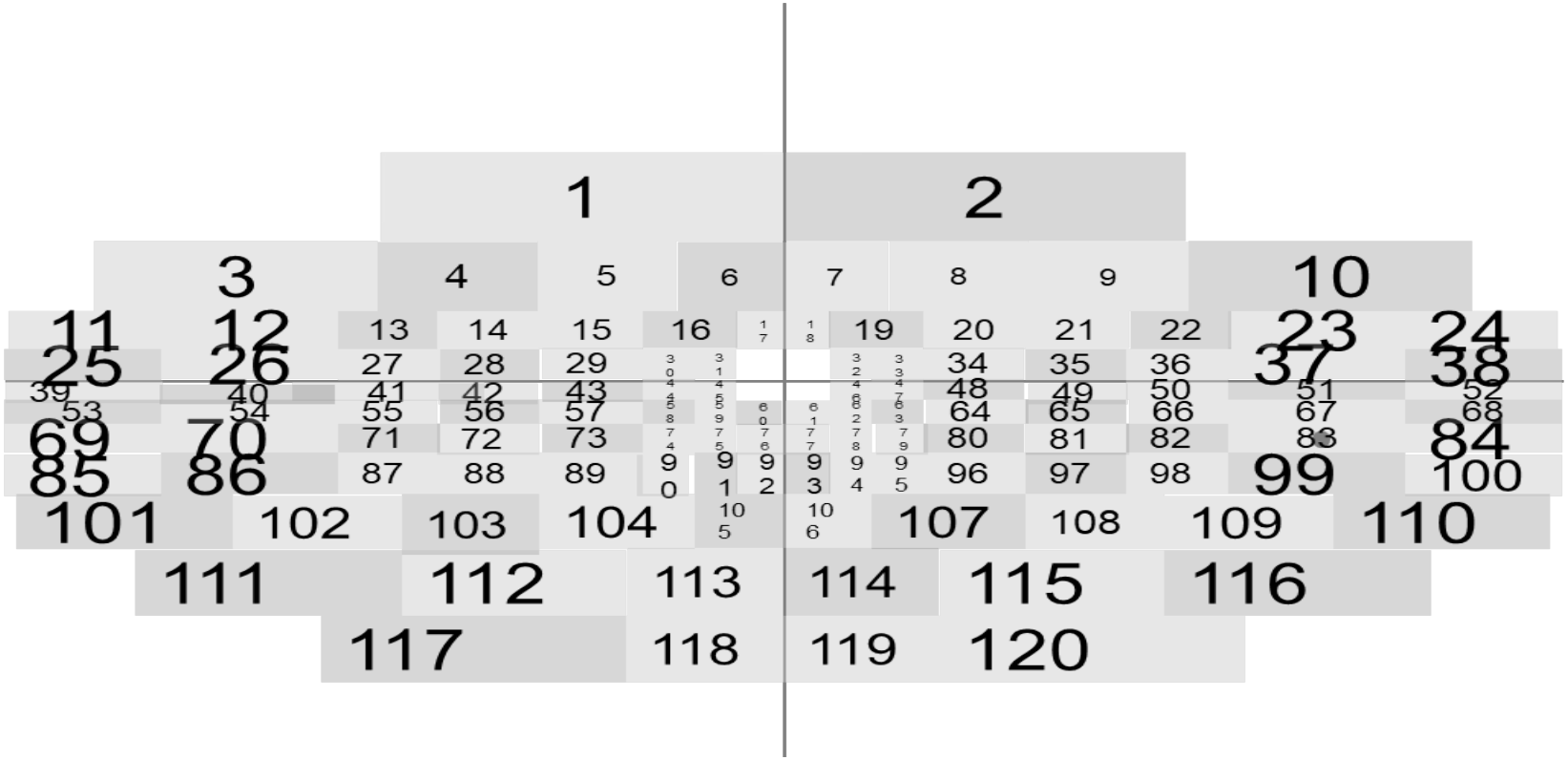


Figure 4-11. Assigned numerical locations of the EVFT.

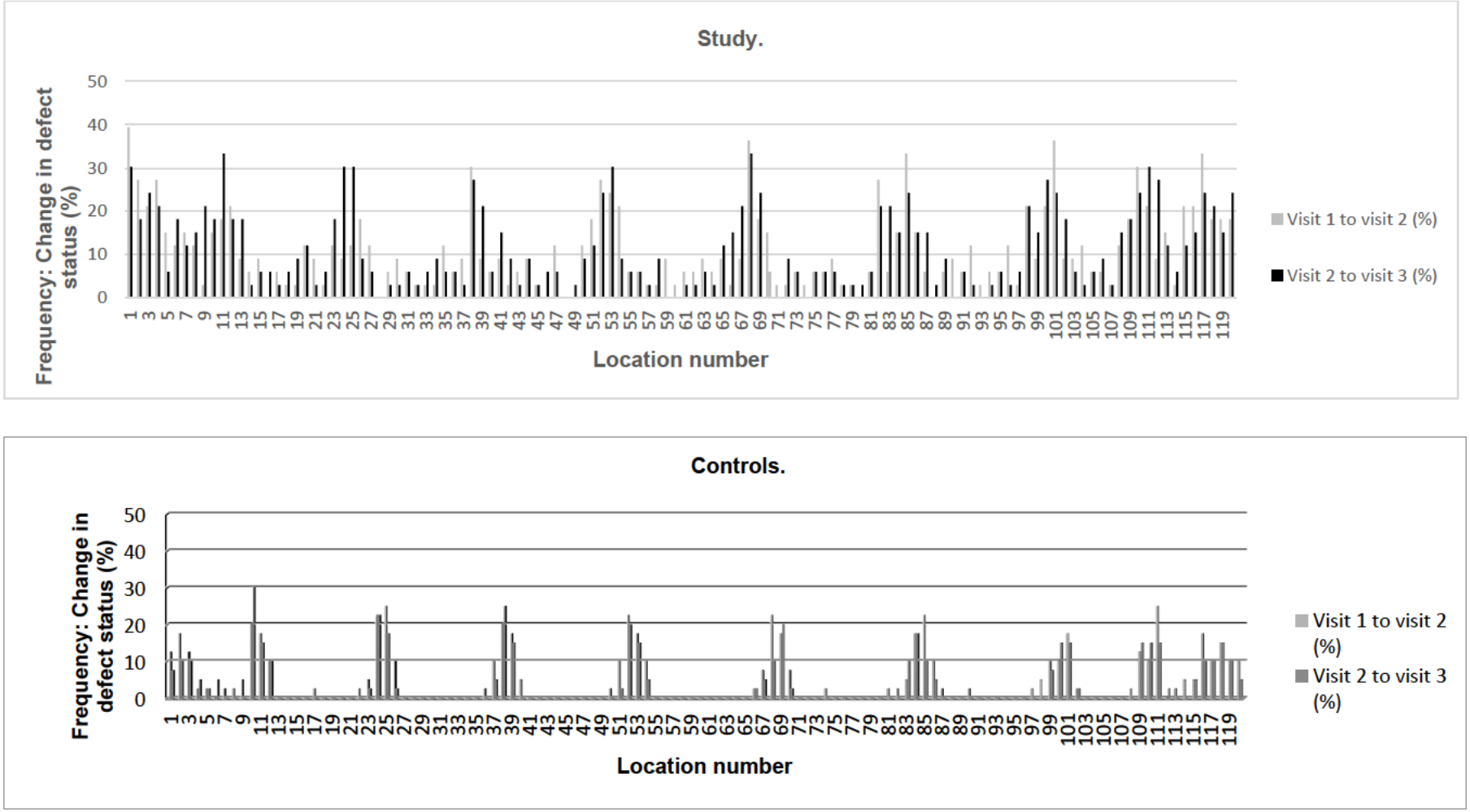


Figure 4-12. Change in defect status between visits; within group. Data presents the percentage of change in defect status for each location on the EVFT between visits for those VFL (top) and controls (bottom).

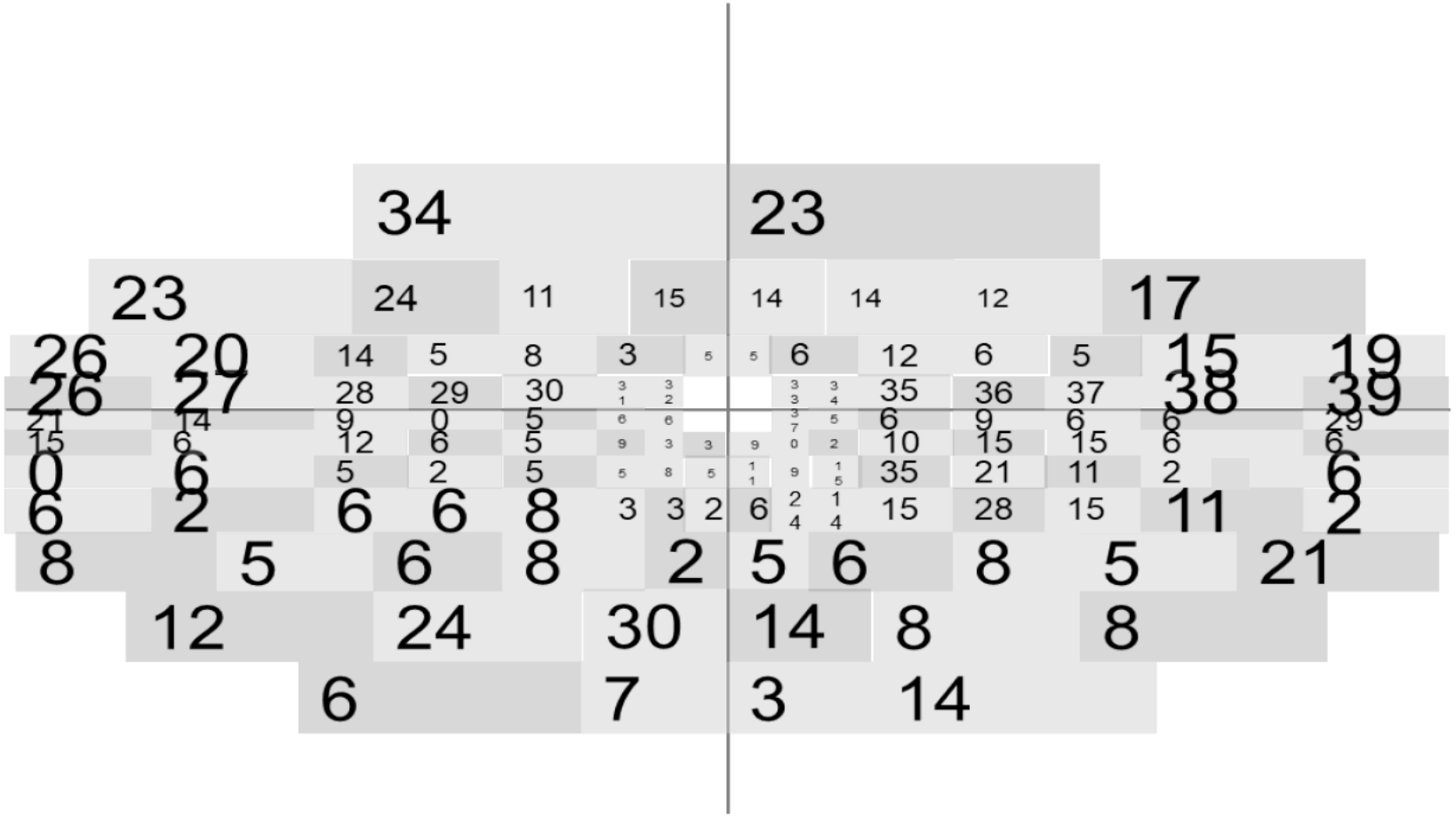


Figure 4-13. The change in defect status per location on the Esterman grid for all visits. Study participants. Data presented is percentage of defect status change in those with VFL. Figures are rounded to 0 decimal place.

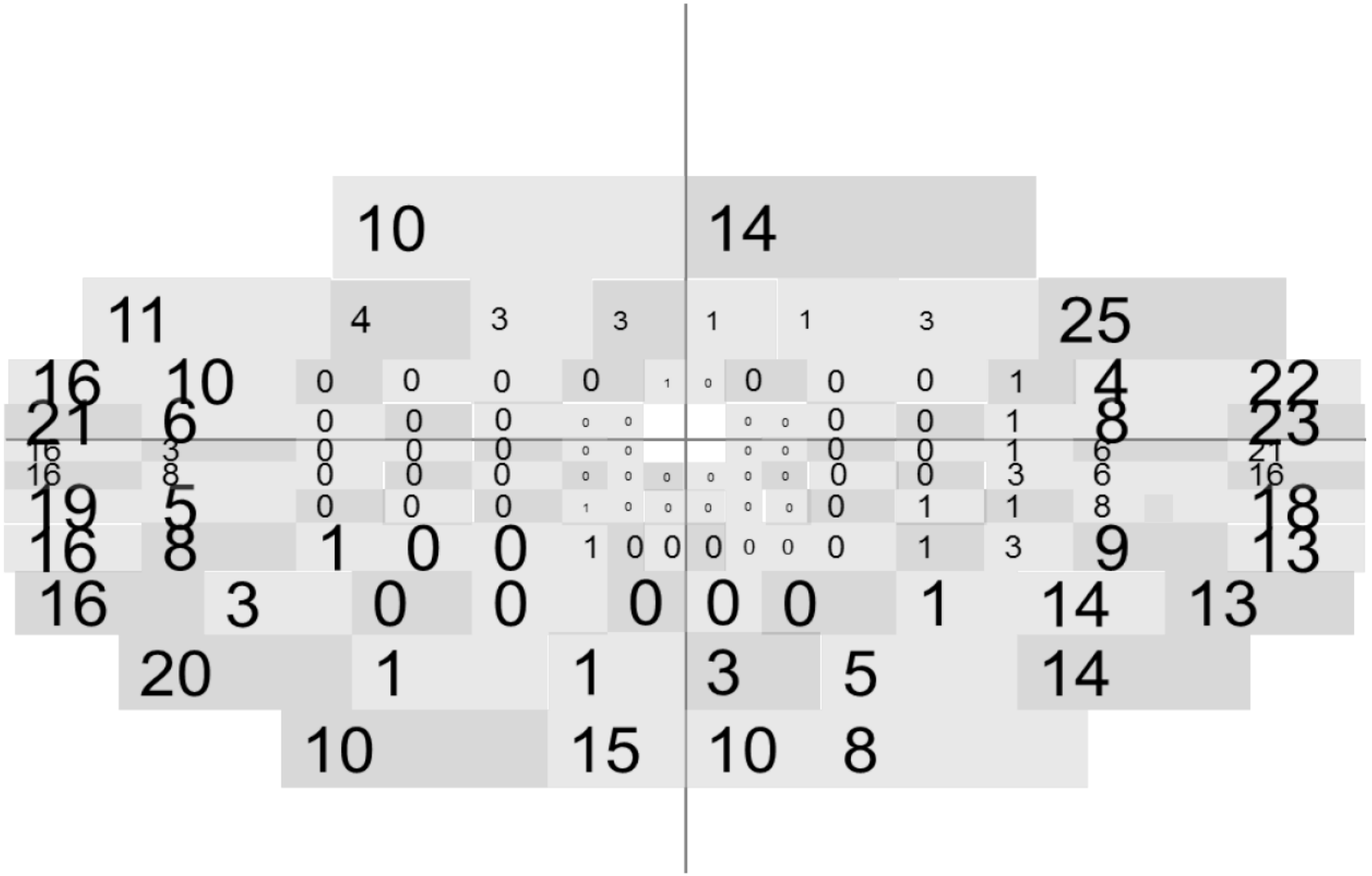


Figure 4-14. The change in defect status per location on the Esterman grid for all visits. Control participants. Data presented is percentage of defect status change for the controls. Figures are rounded to 0 decimal place.

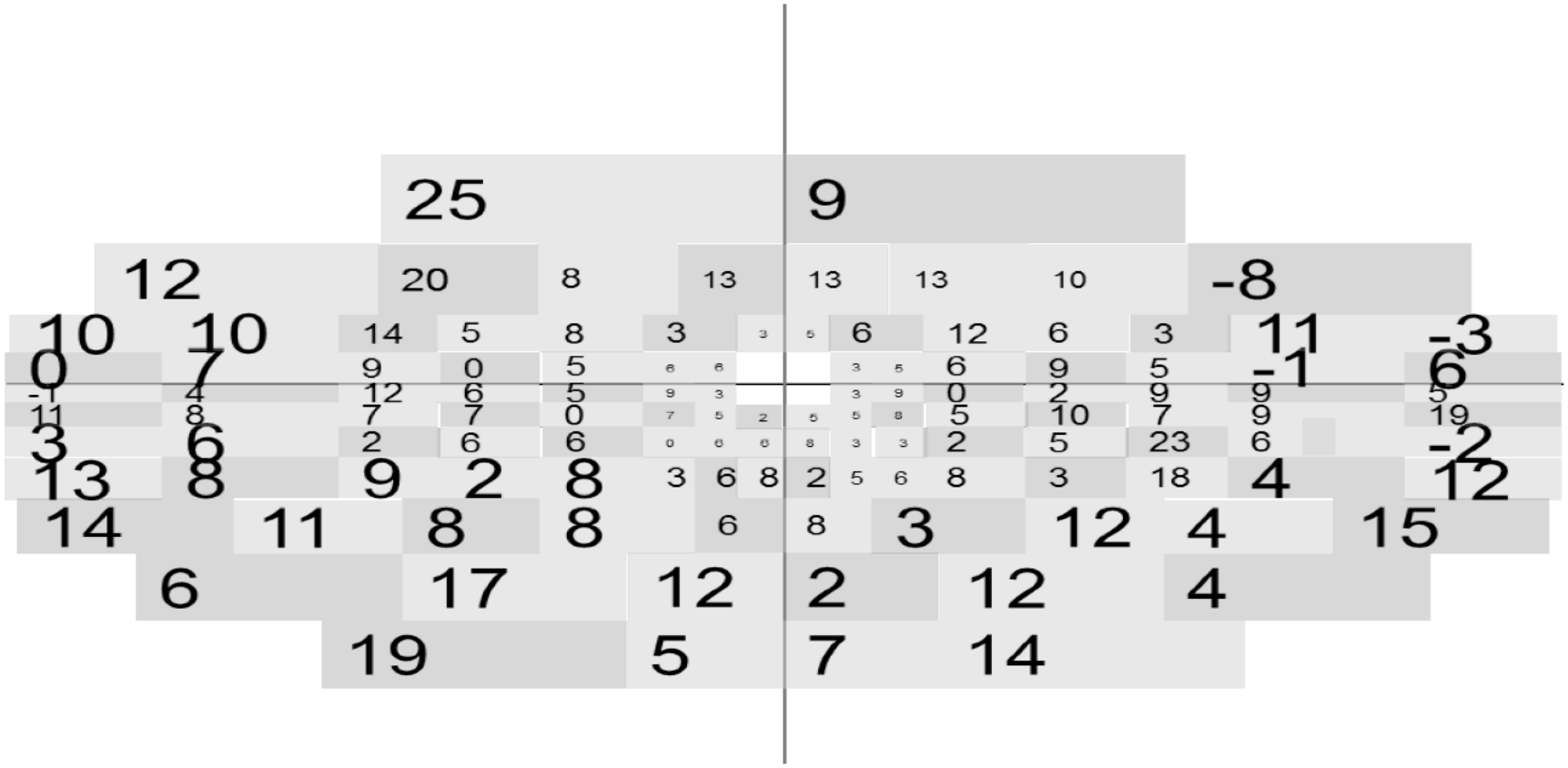


Figure 4-15. The difference in the mean change in defect status per location on the Esterman grid for all visits comparing those with VFL with the controls. Data is the percentage difference between study participants and controls rounded to 0 decimal place. A negative value indicates the defect status change of the study participants was less than that of the controls. A positive value indicates the defect status change of the study participants was more than that of the controls.

A Mann-Whitney test (one-tailed) found that there was a significant difference between the change in defect status (%) per location (pooled data for all visits) between the study participants (median=7.58; IQR=10.60) and the control participants (median=1.25; IQR=7.50) with the study participants having a higher percentage of change per location than the control participants (*U*=2967.500; z=-7.945; p=<0.005). There was a large effect size (r=-0.51). Post hoc calculations provided power of 1-β=0.99 when α=0.05.

The results demonstrate that those with VFL present with more variability than the controls and the defect locations of the EVFT are not repeatable in these participants.

Considering eccentricity, the EVFT was separated into zones of increasing eccentricity. Up to 20º from fixation (zone 1), >20º and up to 40º from fixation (zone 2) and >40º from fixation (zone 3). Shapiro-Wilks tests for normality found that all mean differences within the separated zones were of non-normal distribution for those with VFL (zone 1: SW(42)=0.770, p=<0.005; zone 2: SW(38)=0.880, p=0.001; zone 3: SW(40)=0.912, p=0.004) and the controls (zone 1: SW(42)=0.222, p=<0.005; zone 2: SW(38)=0.575, p=<0.005) except for zone 3 of the controls (SW(40)=0.963; p=0.212). A Friedman two-way analysis of variance determined there was no significant difference in any defect status changes with eccentricity (zone 1: median=7, IQR=10.00; zone 2: median=11.00, IQR=9.00; zone 3: median=11.50, IQR=15.00) in those with VFL ($\chi^2(2)=5.169$; p=0.075) and a large effect size (W=0.56). Post hoc testing provided power of 1-β=0.81 when α=0.05. A Friedman two-way analysis of variance determined that there was a significant difference between areas for the controls ($\chi^2(2)=63.895$; p=<0.005). Using a Bonferroni correction factor of 0.0017 Wilcoxon tests found that there was significantly more change in defect status with increasing eccentricity. Zone 3 (median=10.50; IQR=10.00) had significantly (z=-5.515; p=<0.005) more change in defect status than zone 1 (median=0.00, IQR=0.00) with a large effect size (r=-0.60), and zone 2 (z=-5.172; p=<0.005) with a large effect size (r=-0.56). There was also a significant difference in changes of defect status when comparing zone 2 (median=0.00; IQR=1.00) and zone 1 (z=-3.667; p=<0.005) with a medium effect size (r=-0.41).

4.4.7.1. Repeatability of Peripheral Defect Location. Pointwise Analysis Comparing Spectacle Wearers with Non-spectacle Wearers.

Figure 4-16 presents the change in defect status (%; rounded to 0 decimal places) per peripheral location, beyond 40º of fixation, presented on the EVFT grid for all visits in those with VFL, comparing the change in defect status for those who wore spectacles

and those who did not wear spectacles. Figure 4-17 presents the change in defect status (%; rounded to 0 decimal places) per peripheral location, beyond 40º of fixation, on the EVFT grid for all visits for the controls, comparing the change in defect status for those who wore spectacles and those who did not wear spectacles. The change in defect status (%) per location beyond 40º of fixation, had normal distribution for the study participants who wore spectacles (SW(40)=0.975; p=0.503), and also for those who did not wear spectacles (SW(40)=0.955; p=0.114), when the data were pooled for all visits. The data for the control participants were found to have non-normal distribution for those that wore spectacles (SW(40)=0.944; p =0.048) and for those who did not wear spectacles (SW(40)=0.423; p <0.005) when the data were pooled for all visits.

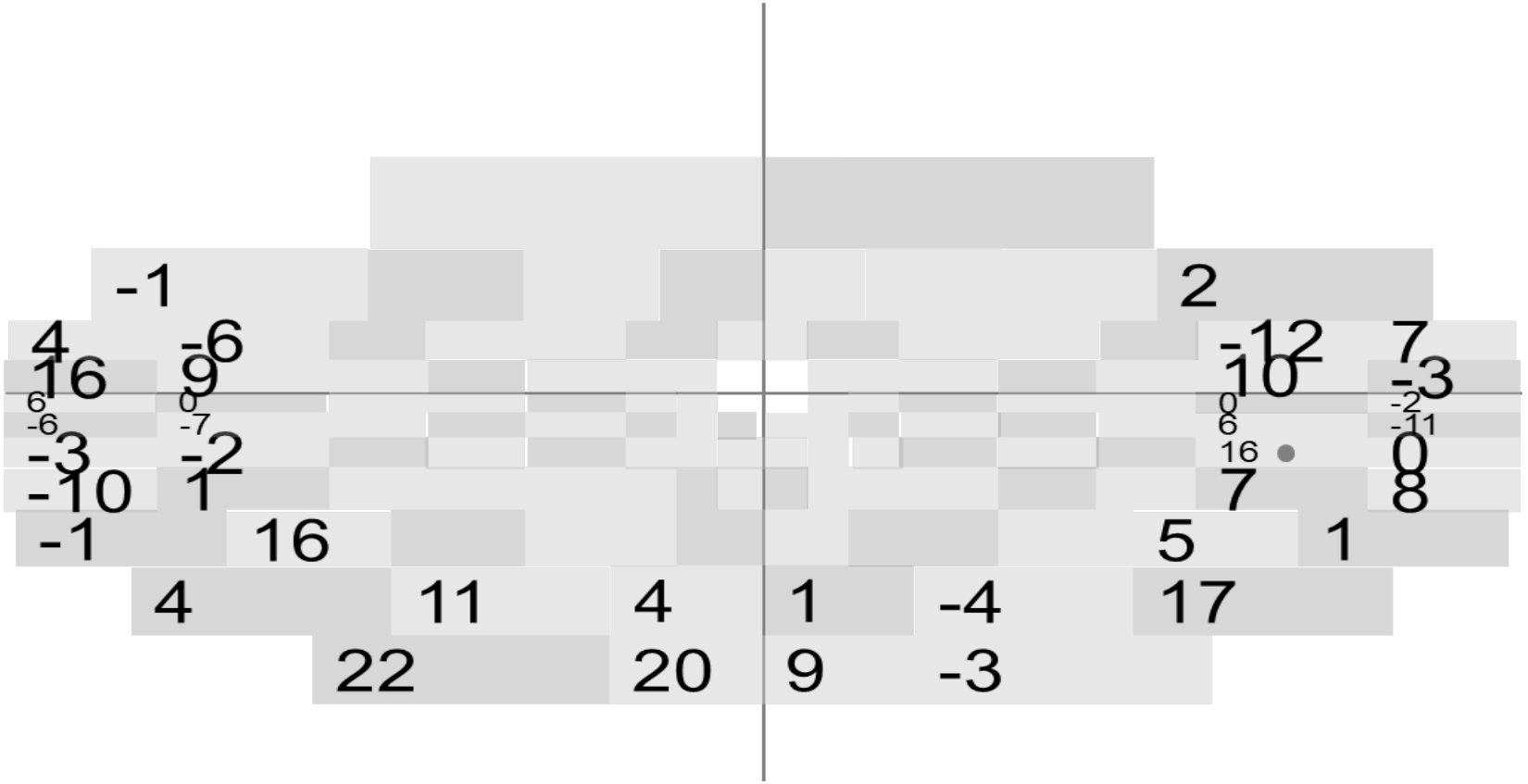


Figure 4-16. The difference in the mean change in defect status per peripheral location on the Esterman grid for all visits comparing those with VFL who wore spectacles, and those with VFL who did not wear spectacles. Data is the percentage difference between study participants who wore spectacles, and study participants without spectacles, rounded to 0 decimal place. A negative value indicates the defect status change of the spectacle wearers was less than that of the non-spectacle wearers. A positive value indicates the defect status change of the spectacle wearers was more than that of the non-spectacle wearers.

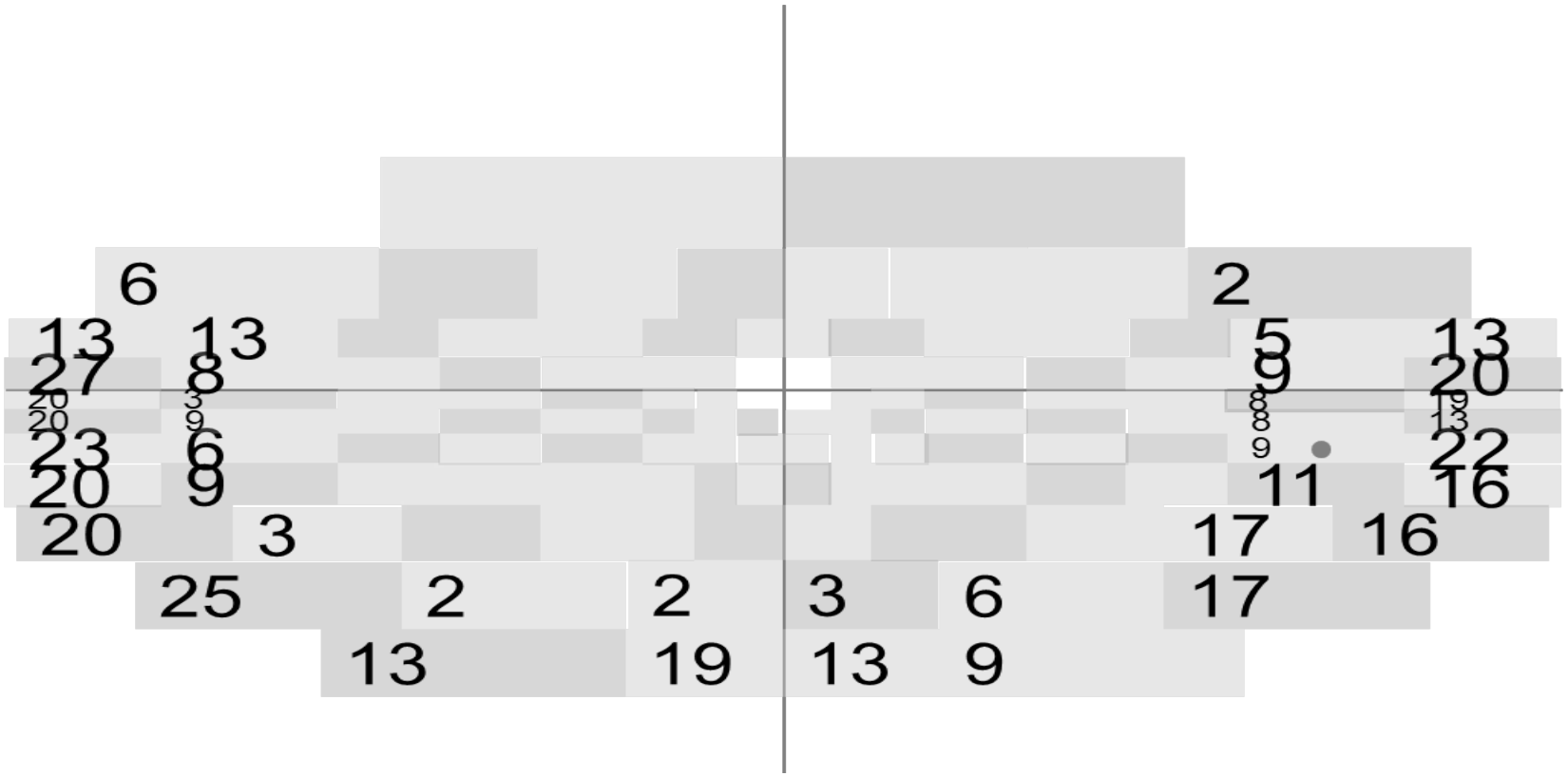


Figure 4-17. The difference in the mean change in defect status per peripheral location on the Esterman grid for all visits comparing those controls who wore spectacles, and those controls who did not wear spectacles. Data is the percentage difference between control participants with spectacles, and control participants without spectacles, rounded to 0 decimal place. A negative value indicates the defect status change of the spectacle wearers was less than that of the non-spectacle wearers. A positive value indicates the defect status change of the spectacle wearers was more than that of the non-spectacle wearers

A Levene's test for homogeneity found that there was a significant difference in the variance of data for the study participants who wore spectacles and those study participants who did not wear spectacles (p=0.034). An independent samples t-test with equal variance not assumed found that there was a significant difference between the change in defect status (%) per peripheral location (pooled data for all visits), between the study participants who wore spectacles (mean=20.63; SD=6.79) and the study participants who did not wear spectacles (mean=16.64; SD=9.43) with the study participants who wore spectacles having a higher percentage of change per peripheral location than the study participants who did not wear spectacles (t(70.852)=2.167; p=0.034). There was a medium effect size (d=0.47). A Mann-Whitney U test found a significant difference between the change in defect status (%) per peripheral location (pooled data for all visits), between the control participants who wore spectacles (median=12.50; IQR=12.50) and the control participants who did not wear spectacles (median=0; IQR=0) with the control participants who wore spectacles having a higher percentage of change per peripheral location than the study participants who did not wear spectacles (*U*=87.000; z=-7.120; p=<0.005). There was a small effect size (r=-0.18).

Results demonstrate that variability in the normal visual field is driven by eccentricity. However, for those with VFL the variability is not driven by eccentricity. The variability of those with VFL can be explained by the various types of VFL included within this cohort and the variability is driven by the nature of the defect itself. However, it is found that spectacle wear can cause variability in the peripheral field beyond 40º of fixation for participants with and without VFL.

4.5. Discussion

The current perimetry test determining a person's fitness-to-drive, the EVFT, is most likely to be undertaken by those who represent the visually impaired population. This examination is usually carried out at one visit. Failure on this examination can produce a life changing episode for an individual. Yet the repeatability of the EVFT is still to be established.

The primary aim in this study was to establish whether there is any test-retest variability by comparing results across three consecutive visits in participants with established VFL.

Certain factors were controlled for. The use of one clinician, to limit the impact on clinician conduct by providing clear instructions and encouragement uniform for all participants to promote reliable results (Haley. 1993) was implemented. However, it was considered important to replicate high street practice where patients of this population are likely to attend to perform the EVFT. Therefore, usual methodology was used, including the usage of habitual spectacles. The same correction used for each visit controlled for any differences caused by refractive error, which will take the form of single vision distance prescription or commonly progressive lenses which introduce a variable defocus profile across the field. Age and gender matched controls were used to limit the effect of individual variation. There was no significant difference for these factors between the study participants and the controls. No restriction on pathology was incorporated to replicate the cohort of different pathologies that may be seen within high street practice. The data were analysed for all the participants within this group and sub-groups of NFD and CFD were also analysed separately. Other sub-groups had too small a sample size or were grouped with too many variations to consider separately. However, analyses were undertaken for the smaller samples when significant differences were found within the pooled data with unclear location of the driving type of VFL within the larger sample sub-sets. The data from the smaller sub groups were included within the pooled data for analysis.

The overall trend of the EES in those with VFL (range 28–100) was significantly lower ($p=<0.005$) than the controls (range 85-100). Confirming the nature of the study and the control group. Those participants who scored an EES of 100 had CFD and a possible explanation of the high scores will be due to the sampling of the EVFT. The EVFT does not examine the central 7.5º of the visual field.

For those with VFL there is a significant ($p=0.036$) change of the measured EES across the three visits. This however, presented with a small effect size. There was a small increase in EES between 1%-3% occurring at visit 3 for those with VFL, including the sub-groups of NFD and CFD. The EES median for visit 1 and visit 2 remained at 85 with an alteration of the median to an EES of 86 at visit 3 (Fig 4-2) in those with VFL. Considering CFD and NFD separately, these sub-groups also had a stable EES median for visits 1 and visits 2. This was 94.50% for CFD with a slight increase in median at visit 3 to 96%, and 85% for NFD with a slightly higher increase to 88% at visit 3. The control participants had a stable median EES of 96% across all three visits. The increase in EES for those with VFL could be indicative of a learning effect. However, no effect was evident within the controls. To evaluate the presence of the learning effect it would be usual to look at the control population where the variability

cannot be due to a defective field. However, at such high scores within the controls, including participants scoring 100% on visit one, the presence of learning effect is difficult to determine. It is not possible to increase a score of 100% on subsequent visits. Therefore, it can be ascertained that those with VFL indeed possess variability in EES across visits, which can be a consequence of variability due to the defect with a possibility of a slight learning effect.

The EES scores across visits were very strongly correlated in those with VFL and there is a similar find for the NFD participants. The use of correlation is not always appropriate determining if there is a relationship rather than the agreement within scores (Armstrong & Eperjesi. 2005, Bland & Altman. n.d). However, in these two groups the EES clusters around the 45º line of equality. This correlation was higher than that of the controls who possessed moderate correlation. The high correlation of scores was not found within the CFD participants, but this may be explained with the use of a smaller sample size within this group. Hence, caution is practiced in interpreting these results (Siegal & Castellan. 1988) and further methods utilised to establish agreement.

The use of Bland and Altman plots strictly speaking are used when there is normality of the data. However, they are used here to enable visualisation of the agreement between the scores across the visits. As there are no previous studies establishing the expected variance in EES across visits, the control group for this study was utilised as the standard of expected variance to compare the study participant's variance against. The upper and lower limits of agreement for the controls ranged from 5.26 to -7.11 respectively. Although the EES were very strongly correlated they did not determine agreement of EES across visits for those with VFL, CFD and NFD demonstrating test-retest variability with the 95% limits of agreement being wider than that of the controls (figures 4-5 & figure 4-6).

In those with VFL the 95% limits of agreement were furthest from the bias when analysing agreement for visit 1-to-visit 2 and were similar to that of the controls. The limits of agreement significantly ($p=0.002$) narrowed towards the bias for visit1-to-visit 3. The limits of agreement moved slightly closer to the bias when comparing scores from visit 2-to-visit 3 and are closer than all those for all groups except for the controls. However, no significant difference was found between the EES of visit 1-to-visit 2 or visit 2-to-visit 3. The 95% limits of agreement also narrowed towards the bias comparing EES from visit 1-to-visit 3 for CFD participants.

As with a previous study looking at the repeatability of the UFOV by Bentley *et al* (2014), those with glaucoma demonstrated test-retest variability with wider 95% limits of agreement compared to the non-glaucomatous controls. However, the variability in those with VFL is unpredictable. In this study the NFD demonstrated more agreement comparing the EES of visit 1-to-visit 2 with the limits of agreement being close to that of the controls and widening when comparisons were made with visit 3. The differences in EES between visits for those with NFD were of no significance (p=0.206). For those with PFD and Un there was no significant difference found in either the PFD (p=0.057) or the Un (p=0.102) participant groups.

The significant results for those with VFL are in agreement that there is a need for repeat testing to establish an accurate result. The results suggest that at optometric practice level there should be a retest where a participant fails the EVFT to account for the variability.

One of potential limitations of the EES was the cluster of scores around 87% in those with glaucoma. (Jampel *et al.* 2002a, 2002b). The studies here utilised those under observation for glaucoma as well as those who were suspected with glaucoma. In this study utilising people diagnosed with glaucoma including those participants at a very advanced stage, the median score agrees at 85%. However, there was a broad range of EES within those with VFL of 30% to 100%.

To establish the test-retest reliability within group the variance across the 3 visits was analysed. The use of a week between visits limited the possibility for a significant change in pathology (Gardiner. 2003) and hence a change in pathology would not be expected to contribute to test-retest variability.

Due to the well documented test-retest variance of those with VFL, more variance in EES was anticipated in participants with VFL than controls. Furthermore, those with VFL are likely to have longer test durations increasing the fatigue effect (Wall *et al*. 2001). However, there is also the potential that an amount of variability may be masked by the very bright ST stimulus. The mean variance of EES for each participant was calculated. The amount of participants (%) was plotted against the EES variance value (figure 4-8). There was no significant (p=0.318) difference found between the retest variability in those with VFL, NFD (p=0.492) or CFD (p=0.438) when compared to the test-retest variance of the controls. Suggesting that the EES is resistant to the variability caused by lower sensitivity. This resistance to variability may be explained by the brightness and suprathreshold nature of the stimulus used in the EVFT which is 10 dB. Inspection of Duane's hill of vision (figure 1-2) informs that the normal threshold

value at 60º from fixation is in the region of 20 dB. The presenting stimulus of the EVFT is 10 times brighter. Variation is more likely to be exhibited when a stimulus is close to threshold. The measurement of threshold is not a function of the EVFT. The ST nature will underestimate the VFL and only determine deep scotomas. Threshold variation can be up to 15 dB, so some variation is expected but the majority will be masked by the 10 dB stimulus. Furthermore, it limits variation caused by a participants uncertainty in decision making, allowing an easier choice for the participant of seen and unseen, as opposed to making a decision of just seen at threshold.

Those with VFL do exhibit more variance when comparing the location of the defect. Each individual location on the EVFT was compared across the three visits for all participants. There is a significant difference between those with VFL performing an exact repeatable test across a series of visits compared to the controls (p=<0.005). The percentage of change occurring is mapped for each individual location (figure 4-13). Those with VFL have a mean chance of change in defect status for each location of 6.93% compared to the controls. Only 3% of participants with VFL had an exact repeat of test on all three visits compared to 20% of the controls. Ninety-seven percent therefore did not have an exact replication of their visual field test based upon location if presenting with VFL compared to 80% of the controls. This will impact on how the person is determined as pass/fail when the criteria used is based upon location of defect. A limitation on the variance in location is the subjective measurement of fixation. The fixation monitoring is a manual task and is dependent upon clinician conduct. One clinician was utilised to limit variability, but human influence is not robust, being subjective to fatigue and lack of attention. However, this is in-line with the usual procedure of the EVFT and hence is representative of usual practice.

To assess variability with eccentricity the points on the EVFT grid were categorised into zones of up to 20º from fixation (zone 1), 20-40º from fixation (zone 2) and >40º from fixation (zone 3). The control participants presented with significant changes between zone 3 compared to zone 1 (p=<0.005) and zone 2 (p=<0.005) and when comparing zone 2 to zone 3 (p=<0.005). The detection of peripheral target stimuli decreases with eccentricity (Crundall *et al*. 1999) and uncertainty increases (Raj *et al*. 2005). The results are in agreement that variability increases with eccentricity (Chauhan & Johnson. 1999, Phu e*t al*. 2017). There was no significant difference found due to eccentricity for those with VFL (p=0.075) This may be explained by the mix of conditions within the cohort which included those who would have defects within the central, peri-central and peripheral field as well as participants with patchy visual field defects. Increased variability was however, demonstrated in the peripheral field

beyond 40º in those participants who wore spectacles, compared to those who did not wear spectacles with (p=0.034) and without (p=<0.005) VFL. This variability may have arisen from rim artefacts. Of the Esterman visual fields for the controls, 19 of the fields with defective locations in the peripheral fields may have arisen due to rim artefacts and cannot be ruled out as a cause of variability. Another cause of variability with eccentricity arising from the use of habitual spectacles may include the use of progressive power lenses. Of the fields that had defects within the periphery, 10 of these were examined with the participants own progressive power lens spectacles and this also cannot be ruled out as a cause of variability. The protocol of wearing the same spectacles at each visit was expected to limit this, but vertex distances of spectacles can alter which was not measured on each visit. A difference in vertex distance will impact the available field of view.

In real-life it is not the EES score that determines fitness-to-drive but the criteria outlined by the DVLA. Four (12%) of the 33 study participants had inconsistent results when analysed with the DVLA criteria whereby they either passed or failed dependent upon visit. The frequency of an inconsistent result arising across visits was 12.12% in those with VFL but was not found to be significant (Visit 1-to-visit 2 & visit 2-to-visit 3: p=0.250; visit 1-to-visit 3: p=1.000). An overlap zone (figure 4-9) found the range of EES scores that can give rise to an inconsistent result to be 68-94% with a total variance of EES between 1-17% and a mean of 1.67% giving rise to a change in driving status. Within this range, scores of 90% or above led to a pass and those below 77% led to a fail. Scores of 77-86% could be either pass or fail with sensitivity of 93.33% and specificity of 94.12%. Those who had consistent results whose mean change in EES was 13%, falls across this range of variance, and can be explained by the inclusion of those with consistent fails who would normally possess higher test-retest variability due to the significant loss of sensitivity. Creating a link between the presenting EES and the possibility of pass/fail frequencies has therefore proven difficult and the frequency of inconsistent results are of no significance (visit 1-to-visit 2: p=0.250; visit 2-to-visit 3: p=0.250; visit 1-to-visit 3: p=1.000). For those who could hold a driving licence when eliminating the visual field criteria (n=17) 2 of the participants had an inconsistent result, lessening the amount of impact of an inconsistent result on the cohort. The change in driving status was also of no significance (p=1.000). The inability to generate a defined area whereby participants would fail and subsequently pass, and vice versa is down to the criteria of pass/fail itself. It is not determined by EES but by location. One missed location within the central 20 degrees can give rise to a fail if contiguous with three other missed points. This one missed location would

account for 1%. Whereas the peripheral points at the extremities of the EVFT grid are beyond the required 120 degrees and hence numerous of these can be missed and will not impact upon a change in outcome. Therefore, the actual presenting EES cannot predict who will have an inconsistent result.

Where there was a failure in fitness-to-drive on one visit, there was an increase in EES on average of 8% on visit 2 from baseline and a reduction of an average of 5.5% on visit 3. The difference in EES had a large effect size, but the difference in EES was also not of any significance (p=0.325) and further complicated by the wide range of variation in EES an individual can exhibit and remain consistent, the variance exhibited by participants with inconsistent results is not significantly different from the variance exhibited by those with consistent results (p=0.671). Therefore, the variability presented by an individual can also not be predictive of an inconsistent result.

A confounding factor in determining a significant difference within perimetry results is age. Age is a factor that contributes to a decline in functional vision (Wood & Black. 2016) and fatigue increases contributing to small decreases in sensitivity found to be in those aged over 60+ for SITA Standard SAP. (Wall *et al*. 2001). Failures occur on the UFOV at 57+, which also examines attention, both divided and selective (Rauscher *et al*. 2007). In those with VFL there was a fair correlation (p=<0.005) with age. When analysing in age groups, those aged 60+ scored significantly higher (p=<0.005) than those under 60, Furthermore, those aged 80+ had a significantly higher score than those aged 71-80 (p=<0.025). EES increased with age. The controls demonstrated a weak correlation (p=0.013) with age and the EES was significantly lower with advancing age (p=0.027). Those aged 31-40 score significantly higher (p=0.025) and those aged 81-90 score significantly lower (p=0.040) compared to all the other age groups providing an expected downward trend in EES with advancing age. Those with VFL would not be immune to the fatigue effect. Perimetry takes longer to complete in those with VFL, which increases fatigue. There are also declines in sensitivity and attention with age that it can be assumed to affect all participants within this study. The results indicate that the pathology in the study participants overshadows these effects and subsequently leads to lower scores in the younger population.

To an individual who fails on one visit and passes on another, although not statistically significant, it can be considered clinically significant to that individual. In this study this was 12% (4 out of 33 participants) and it is argued that the chance of failing on a visit is all that is needed for an individual, which is the equivalent of a statistically non-significant result, to undergo a life changing event. This life changing event can impact

on the practicalities of daily life (Owen *et al*. 2008), independence (Racette *et al*. 2005, Manji & Plant. 2000) and travel for work. Losing a licence can result in social isolation (Racette e*t al*. 2005) and contributing to depression (Mitchell & Bradley. 2006). It can cause psychological trauma, feelings of low self-esteem (Owen e*t al*. 2008) and reduces quality of life (Medeiros *et al*. 2012, Ramulu *et al*. 2014, Alqudah *et al*. 2016) which also can result in depression (Racette *et al.* 2005).

Therefore, statistical significance aside, it is recommended that within optometric practice where a person fails the EVFT on their first visit, that a repeat examination occurs to account for the variability in those with VFL and a possible learning effect.

Repeat tests are recommended in particular if a participant presents with an EES of 77-90% where there is a possibility they could have a fail/pass change on a subsequent visit. These results show that variability in the pass/fail status of the EVFT can occur across three visits. All participants who had inconsistent pass/fail results on the EVFT who had failed on visit 1, passed on visit 2. All participants who had failed on both visit 1 and on visit 2, did not pass on visit 3.

Consequently, it should be clinically recommended that where a person fails the EVFT on their first test, they are retested, particularly when their score is within the 77-90% EES range, as within this range they are more likely to pass on a second examination.

These recommendations are to limit the adverse consequences that losing a driving licence can have on an individual and to provide greater certainty in the fitness-to-drive result.

5. The Reproducibility of the Esterman Visual Field Test in Those with Established Visual Field Loss.

Summary.

The EVFT is not instrument specific and it can be conducted on any visual field screener. The primary aim of this study was to investigate the reproducibility of the EVFT by performing the examination on the HFA and the Henson Pro 5000 Perimeter in thirty two participants with VFL (mean age 66.00; SD 15.70) along with 31 age and gender matched controls (mean age 68.23; SD 8.54). There was a significant lack of agreement in EES between perimeters, with the EES on the Henson being significantly lower than the EES on the HFA for both those with VFL ($z=-4.612$; $p=<0.005$) and controls ($z=-2.553$; $p=0.011$). The difference in EES is driven mostly by NFD ($z=-3.297$; $p=0.001$). There was significantly ($t(43.839)=-3.782$; $p=<0.005$) more range of variability in those with VFL compared to the controls. The EVFT performed on the Henson records more points that the test considers defective than the EVFT on the HFA and the change in location of defect is found to be significantly more ($U=2558.000$; $z=-7.205$; $p=<0.005$) in those with VFL compared to the controls. No participants with VFL had an exact replication of defective locations between perimeters and lack of replication was also found in 90.32% of the controls. Variability was driven by eccentricity in both those with VFL ($z=-3.921$; $p=0.002$) and the controls ($z=-4.546$; $p=0.002$). The variance in both, EES and location of defective points, does not significantly impact on a persons fitness-to-drive status ($p=0.454$). It is however recommended that the EVFT is performed on the HFA to avoid unnecessary difficulty to an already stressful examination.

5.1 Introduction.

Perimetry assesses the eyes ability to determine just noticeable differences of luminance changes. How luminance contrast is defined and measured has been previously discussed in sections 1.3.2. and 1.3.3. The decibel is dependent upon the maximum intensity of the stimulus available (Imaging & Perimetry Society. 2010, Kalloniatis and Khuu. 2016) and hence, can vary between perimeters.

The EVFT is currently the visual field test conducted to determine whether drivers have a visual field (DVLA. 2014) that complies with the DVLA standards. The criteria of which has been previously outlined in section 1.10. The EVFT is a ST test, the methodology of which has previously been outlined in section 1.6.1. To examine fitness-to-drive the stimulus presented is Humphrey size III at 10 dB white (Heijl e*t al*. 2012, Crabb e*t al*. 2004, Ayala. 2012) against a background luminance of 31.5 asb. This relates to the Goldman size III4e. On automated perimeters the ½ degree white standard of kinetic perimetry relates to 4mm^2 white at 1000 asb presented with a background luminance of 31.5 asb (Esterman. 1983).

5.1.1. One Test. Different Instruments.

The EVFT is included within the test menu of the HFA (Ayala. 2012, Jampel e*t al*. 2002) and other standard automated perimeters (Owen *et al*. 2008). Of these perimeters the EVFT is most commonly performed on the HFA (Rauscher *et al*. 2007).The DVLA (2014) states that the interpretation of the visual field charts for the given criteria relate to tests performed on the HFA (DVLA. 2014). However, the current standard is not specific to the instrument. The EVFT is also included in the test menu of the Henson Pro Perimeter, a bowl perimeter instructed via a computer (Artes *et al*. 2002). Table 5-1 details comparative aspects of the HFA and Henson Pro 5000 Perimeter. The Henson Pro 5000 Perimeter will be referred to as Henson throughout the majority of this chapter and subsequent chapters.

Item	Humphrey Field Analyser II	Henson Pro 5000 Perimeter
Stimulus of Esterman visual field test.	10 dB (1000 asb)-cannot be altered.	31.80 asb.
Maximum intensity	Bulb=10,000 asb (0db)	Light emitting diodes (LED)=1000 cd/m2=3140 asb (1 cd/m2=3.14 asb)
Target	III4E (4 mm^2 white). Subtense at the eye 0.50° approximately. Trigonometry calculation provides 0.69°	3 mm @ 25 cm. Subtense at the eye 0.50º approximately. Goldman size III. Trigonometry calculation provides 0.69°
Fixation target	Central amber/warm orange target. Fixation target is stationary.	Central red stimulus. Moves position, subject to fixate on new position.
Presentation	Projected onto bowl with a projection device	Back projection (LED)
Bowl luminance	Uniform background luminance of 31.50 asb.	Background luminance 3.15 cd/m^2/10 asb
Bowl radius	33 cm	25 cm
Distance of eye to centre of the bowl	30 cm	25 cm
Spectral output of stimuli	White light. Halogen CRI=100.	530-600nm (LED). Green/yellow (nearing to orange)
Presentation time	200 ms	200 ms
Number of stimuli	120	112
Location of stimuli	Appendix 1 and figure 1-6.	Appendix 4 and figure 5-3.

Table 5-1. Comparative aspects between the HFA II and the Henson Pro 5000 Perimeter.

Retinal adaption and the impact of background luminance, stimulus type, size and intensity has been previously discussed in sections 1.15.1-1.15.3 and collated in table 1-10.

At different levels of illumination there will be a different response from the photoreceptors of the retina. Cones mediate when exposed to bright background levels and rods mediate at dim background levels. The shifting of retinal adaption to scotopic levels will increase the sensitivity of the rods and lower the sensitivity of the cones (Argus & Brenton. 1986). Hence, dim backgrounds will raise the sensitivity of the rods

(Sharpe *et al*. 1992) and under mesopic light levels there is rod-cone interaction (Gloriani e*t al*. 2016). How brightness is distributed within the visual field has a direct impact on vision processing (Dorosz e*t al*. 2002).

The retina undergoes both luminance and contrast adaption. The retina will adjust to the mean light sensitivity within the visual field. The average light level that a human eye is exposed to influences the eye's sensitivity (Rasengane *et a*l. 2001. Freeman *et al*. 2010). Variations in ambient lighting, spectral distributions and angular subtense (Cengiz *et al*. 2015) are adapted to by the visual system with adjustment to its sensitivity (Sharpe e*t al*. 1992, Virsu & Lee. 1983) and results in a change in the hill of vision profile (Henson. 2001). Hence, detection thresholds are affected by luminance and contrast of the background amongst other various factors (Sebastion *et al*. 2017). The detection of a bright flash of light is dependent upon the background luminance. There is a rise in threshold as the luminance of the background rises (Lennie. 1979). The higher the luminance, the higher the likelihood of shallow defects being undetected (Johnson *et al*. 2014) and consequently reduced luminance results in reduced sensitivity and increases within-subject and between-subject variability (Swanson e*t al*. 2014). It has been found that using neutral density filters in an attempt to lower the background luminance of a perimeter resulted in the production of significant visual field defects (Klewin & Radius. 1986). If the background varies between perimeters, the state of retinal adaption is different and consequently so is the state of retinal sensitivity.

It can be inferred that differences in stimuli and background parameters will make an impact on the comparative performance of perimeters. The state of retinal adaption will differ. There was an incident in 2015 reported in the press (The Guardian. 2015) whereby people had their licenses revoked due to failing the EVFT, due to a fault of the equipment used between 2010 to 2015. The reported account claimed that 600+ drivers had licence revocation. On re-examination of the visual field the interviewee's licence was re-instated (The Guardian. 2015). The DVLA (Phillip. 2016, personal communication, 04 May) has not been able to disclose the model or make of the machine that was at fault.

5.1.2. Comparison of the Sensitivity for the HFA and Henson EVFT.

Any impact caused by differences in stimuli and background parameters due to utilising different perimeters has not been quantified for the EVFT. The HFA background luminance matches that used by the Goldmann perimeter and the original Esterman examination and is the recommended standard by the International

Perimetric Society. The background luminance at this level requires less adaptation time for the patient when they are examined after exposure to daylight or a bright room (Haley. 1993). The background luminance of the HFA at 31.5 asb is at the lower end of the photopic range (Heijl e*t al*. 2012). The background of the Henson in some texts is also considered to fall within the lower photopic range (Henson. 2001). However, it is also considered that photopic luminance commences at 15.7 asb when cones dominate and the transition from here until the rods dominate can be considered mesopic (15.7-0.02 asb) (Eloholma *et al*. 2005, Cengiz *et al*. 2014, Halonen & Bizjak. n.d.)

The EVFT test is uniformly conducted at 10 dB. Luminance is measured in candelas/m^2 (cd/m^2) and 1 cd/m^2 is equal to 3.14 asb (Rowe. 2016). Table 5-2 records the background and target luminance of the EVFT for both the HFA and the Henson.

	Perimeter	**HFA**	**Henson Pro 5000**
Parameter			
Background luminance		31.50 asb=10.03 cd/m^2	10 asb=3.15 cd/m^2
Target luminance		1000 asb=318.47cd/m^2	31.8 asb=10.13 cd/m^2

Table 5-2. Background and target luminance for the EVFT. Data for the HFA and Henson Pro 5000 Perimeters.

Using known formulae for both perimeters provides theoretical differences between the perimeters which are provided in Appendix 3.

Utilising these calculations alone provides differing values between perimeters. Ricco's law informs that there will be equal visibility of stimuli if their products of surface and intensity are identical (Rijn. 2002). Where not identical, it can be assumed to have an impact on the results of visual field tests. Using these calculations alone would indicate that a participant would perceive the EVFT stimulus on the Henson harder to detect than the stimulus presented on the HFA. However, the EVFT is performed at a standard of 10 dB and hence this should provide identical performances. However, presenting at differing background luminance will impact on retinal adaption. The impact of increased background luminance has been previously collated in table 1-10 and discussed in section 1.15.1. There is a rise in threshold as the illumination of the background rises (Lennie. 1979).

A study by Manji and Plant (2000) demonstrated the effect of increased contrast. The EVFT on the HFA passed more people as fit-to-drive (passed 75%) than the Goldmann

(passed 58%). Unlike the Henson and HFA comparisons, the background luminance was uniform at 31.50 asb. The difference in contrast arose from the difference in the stimulus presented which differed by 2150 asb (EVFT=3150 asb; Goldmann=1000 asb).

Whether differences in driving status occurs due to the differences in background luminance when using the HFA or the Henson is currently unknown.

5.1.3. Stimulus Size.

Light adaption has a strong dependence on the size of the stimulus as well as the eccentricity and wavelength of the stimulus (Virsu & Lee. 1983). The differing physical sizes of the stimuli between perimeters is shown via trigonometry to subtend the same visual angle and hence this is not expected to have an impact on the results between the two perimeters.

5.1.4. Variability in Those with Established Visual Field Loss.

There are many incidental factors that can cause variability in perimetry results as outlined in section 1.7. Perimetry itself is subjective and considered highly variable (Kim *et al*. 2005) and areas of damage have shown to increase variability in visual field testing (Wall e*t al*. 2008, Haley. 1993, Crabb e*t al*. 1996, Crabb *et al*. 1995, Henson e*t al*. 2000, Viswanathan e*t al*. 1997, Birch e*t al*. 1995, Heijl e*t al*. 2012, Henson. 2001, Heijl *et al*. 1989) with increased retest variability in areas of reduced sensitivity (Turpin *et al*. 2007, Gardiner. 2003, Gardiner e*t al*. 2006, Miranda & Henson. 2008, Artes e*t al*, 2003. Artes e*t al*. 2002, Bentley *et al*. 2012) which can reach up to 15 dB (Nouri-Mahdavi *et al*. 1997, Swanson e*t al*. 2014). VFL on same day testing can range from quadrantanopic to hemianopic (Wall *et al*. 1998). Variability in perimetry in those with VFL has been previously discussed in 1.8. Patients with areas of damage in their visual field are those representative of people who would be expected to undertake the EVFT to determine fitness-to-drive. Participants with VFL were anticipated to present variance in the EES between perimeters.

In addition, the nature of the EVFT can be a further cause of variability due to not lending itself to objective fixation monitoring (Chisholm. 2008b, Crabb *et al*. 2016, Ayala. 2012).

The impact a licence revocation can have on an individual has been previously discussed in section 1.13.1 and the importance of this aspect along with the importance of a fitness-to-drive examination correctly identifying those fit and unfit-to-drive, has been outlined in section 4.1. There is some evidence to suggest that those

with VFL can be safe to drive (Hamel e*t al*. 2012, Wood e*t al*. 2009, Haan e*t al*. 2014, Kasneci e*t al*. 2014, Kubler e*t al*. 2015, Parker e*t al*. 2010, Szlyk e*t al*. 2002, Lamble e*t al*. 2002, Bowers *et al*. 2005, Sandin *et al*. 2014, Haan e*t al*. 2014, Kanesci *et al*. 2014, Dowers e*t al*. 2010, Papageorgiou e*t al*. 2012, Vega e*t al*. 2013, Rauscher e*t al*. 2007, Hamel e*t al*. 2012, Coekelburgh e*t al*. 2004, Coekelburgh e*t al*. 2002). However, other evidence demonstrates that VFL leads to unsafe driving (Bowers e*t al*. 2009, Alberti e*t al*. 2013, Bronstad e*t al*. 2013, Bhorade e*t al*. 2016, Cheung e*t al*. 2011, Krader. 2014, Szylk *et al*. 2005, Glen e*t al*. 2015, Bronstad e*t al*. 2015, Alberti e*t al*. 2014, Kunimatsu-Sanuki *et al*. 2017) and that there is a link between MVCs and VFL (McGwin *et al*. 2013, Kwon *et al*. 2016, Rubin *et al*. 2007, Cross e*t al*. 2008, Sotimehin & Ramulu. 2018). The evidence previously discussed in section 1.13.3 demonstrates that a link with MVCs and field loss is difficult to establish. However, this conflict does not lessen the importance of a careful measurement of visual fields in those who are visually impaired when determining their legal status of driving (Nowakowski. 1994). A test determining someone's fitness-to-drive should possess high sensitivity and high specificity (Coeckelbergh *et al*. 2005). It is therefore important for the EVFT to produce the same result regardless of the instrument being utilised for patients with VFL.

5.2. Primary Aim.

To date no studies have looked at the reproducibility of the EVFT. The clinical significance to a person would be whether the result could produce a change of driving licence status dependent upon the instrument used. Secondary aims have been previously outlined in section 2.1.1.2.

5.3. Methods.

The instrumentation used within this study has previously been outlined in section 3.2.

5.3.1. Participants.

Participant details were outlined in section 3.1. Age and gender matched controls were used in order to distinguish effects of the repeatability of the EVFT. The age ranges were of non-normal distribution for both study (SW(32)=0.926; p=0.030) and control participants (SW(31)=0.853; p=0.001). A Mann-Whitney test confirmed there was no statistically significant difference between ages between the two groups (p=0.940). Pearson Chi-squared confirmed that there was no statistically significant difference in gender between groups (x^2=0.243; p=0.622).

5.3.2. Procedure.

The procedure has been previously detailed in section 3.3.

Each visual field test varied upon duration between participants (figure 5-1), but was within 8'17" for the EVFT performed on the HFA and within 8'36" when performed on the Henson. The average completion time for all participants performing the EVFT on the HFA was 4'52" (SD=0.86), and on the Henson was 4'6" (SD=1.01). The test durations for the HFA were found to have non-normal distribution (SW(63)=0.795; p=<0.005). Non-normal distribution was also established for the Henson (SW(63)=0.817; p=<0.005). A Wilcoxon test established that there was no significant difference between the durations of the EVFT between perimeters (z=-1.913; p=0.056).

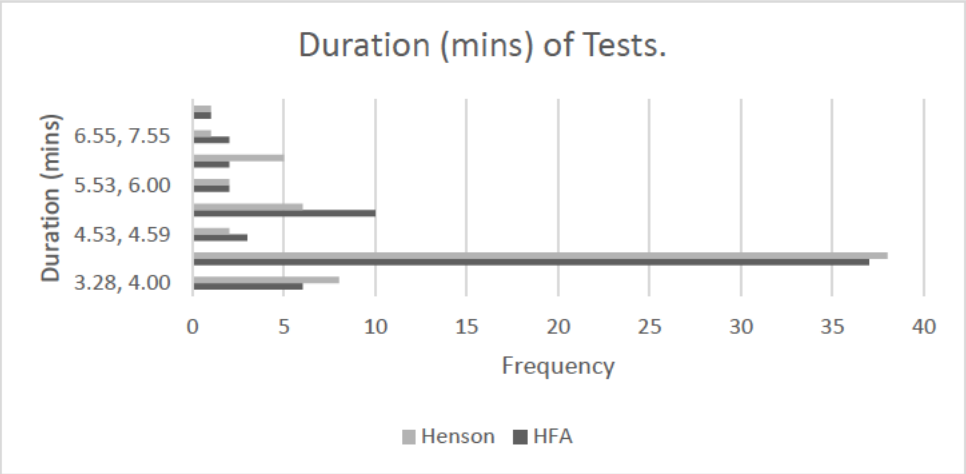


Figure 5-1. Bar chart showing the distribution of visual field test duration of the EVFT for both the HFA and Henson. Duration= minutes and seconds. Y values indicate sections of duration from-and-to.

5.3.3. Data Analysis.

Data analysis has been previously outlined in section 3.4. The primary analysis was to determine the reproducibility of the EVFT in those with VFL. The first prediction would be that the EES scores would be lower when the EVFT was taken on the Henson in those with VFL. The second prediction would be that there would be more variance in EES between each perimeter in those with VFL.

5.3.3.1. Pointwise Analysis. Comparative Test Locations Between Perimeters.

The EVFT sampling between perimeters differs (Figure 5-2). The coordinates of the EVFT on the HFA and Henson do not coinicide. This potentially makes pointwise comparison difficult. In order to perform pointwise analysis the individual coordinates from the Henson EVFT plot (figure 5-3) were measured (Appendix 4). Each Henson EVFT coordinate was mapped to the nearest HFA coordinate and a mid-value between plots was generated as their combined location (Appendix 5 and figure 5-4). The coordinates of the combined location and the original Henson coordinates were then

manually checked to confirm if they fell within the same EVFT functional zone (figure 5-5) as the original EVFT coordinates. The resulting combined stimuli grid (figure 5-4) provided a coordinate base to perform pointwise analysis.

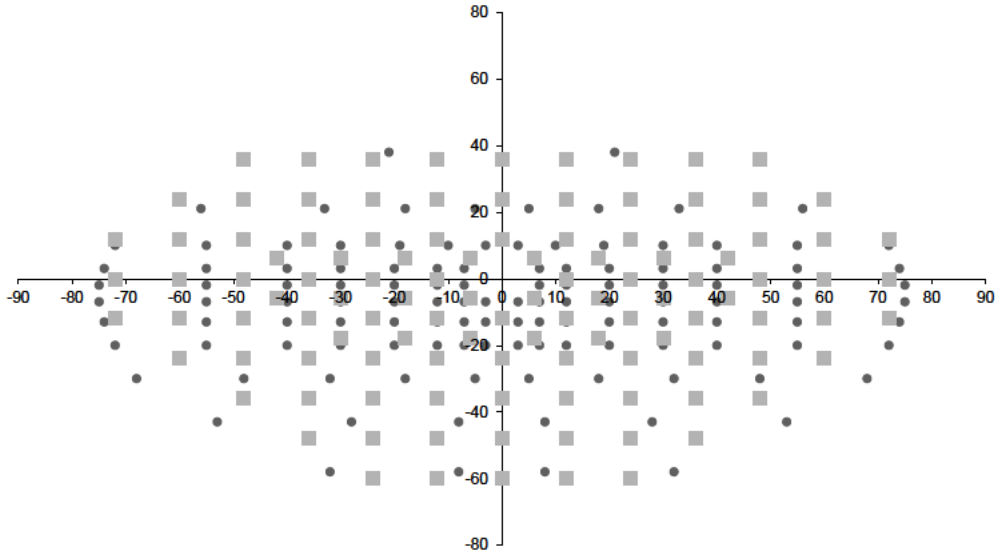


Figure 5-2. Sampling of both, the HFA and Henson EVFT. Stimuli plots from both perimeters superimposed. Black dot= HFA EVFT stimulus location. Grey Square= Henson EVFT Stimulus location. Spacing provided in degrees.

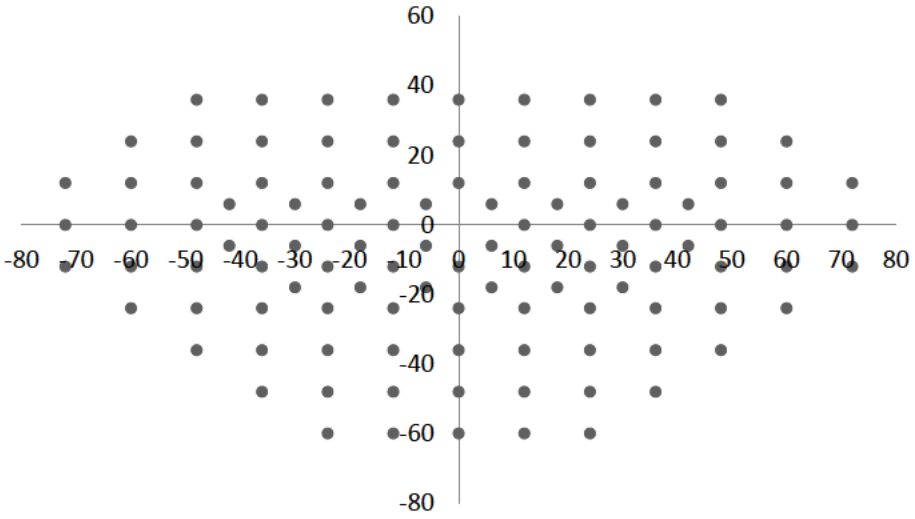


Figure 5-3. Henson EVFT stimuli plot coordinates. Each dot represents a stimulus position. Numerical spacing provided in degrees.

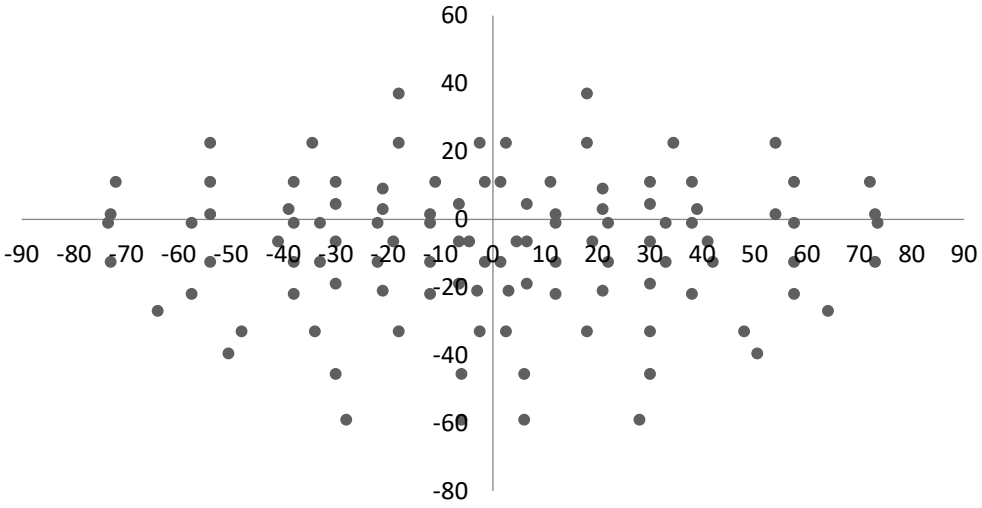


Figure 5-4. Plot of the combined HFA and Henson EVFT stimuli coordinates. Dots represent stimulus location. Numerical spacing provided in degrees. Numerical values of the combined grid are presented in table A5-1 within appendix 5.

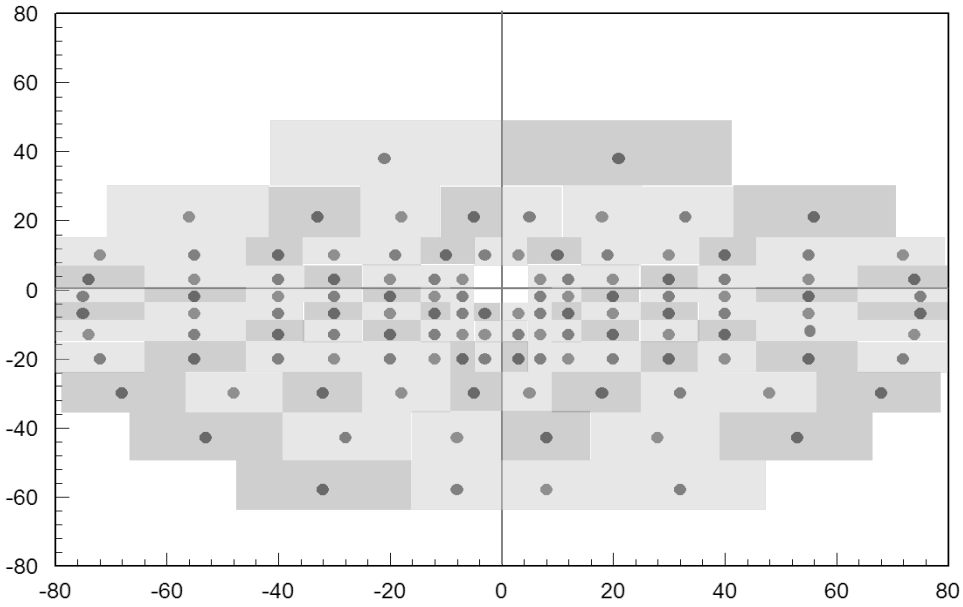


Figure 5-5. Functional zones of the EVFT. (Cubbidge 2012)**.** Each rectangle represents an EVFT functional zone a stimulus represents. Each matched coordinate of the combined stimuli grid was checked for correspondence to an original functional zone of the EVFT grid.

The plots of the combined grid vary from the original HFA or original Henson plot by a mean of 0.06º (SD=2.52) for the x coordinate and by a mean of 0.028º (SD=2.43) for a y coordinate. The variation range from either original EVFT plot is -4 to +4 degrees for the x coordinates and -3.50 to +3.50 degrees for the y coordinates.

Coordinates that did not correspond to a plot on the other perimeter within a suitable range, or when combined the location did not enable it to correspond within an original EVFT functional zone are listed in Appendix 6. These amounted to 2 stimulus points (1.67%) on the Henson EVFT and 12 stimulus points (10%) on the HFA EVFT. These points were excluded in the pointwise analysis.

5.4. Results.

5.4.1. Agreement Between Tests.

Table 5-3 presents the median and IQR of the EES for all participants, control participants. study participants and the sub-categories of the study participants.

Participant category.	Perimeter	EES Median	EES IQR	Participant category	Perimeter	EES median	EES IQR
All	HFA	95.00	14.00	**NFD**	HFA	88.00	25.00
	Henson	93.00	21.00		Henson	71.50	23.00
Study	HFA	86.00	6.50	**CFD**	HFA	96.00	12.50
	Henson	75.50	10.00		Henson	93.00	7.00
Control	HFA	98.00	5.00	**PFD**	HFA	61.00	39.00
	Henson	96.00	3.00		Henson	46.00	15.50
				Un	HFA	80.00	24.00
					Henson	71.00	32.00

Table 5-3. Summary table of EES for each perimeter presenting median and IQR for all participants and participant categories. EES= Esterman efficiency score. IQR=interquartile range. NFD=nerve fibre defect. CFD=central field defect. PFD=peripheral field defect. Un=Unclassifiable field defect.

The measured EES values were not normally distributed for the study group (Shapiro-Wilk(32)=0.903; p=<0.005) and the control group (Shapiro-Wilk(31)=0.804; p=<0.005). The variance between scores demonstrated normal distribution for both the study (Shapiro-Wilk(32)=0.987; p=0.940) and control group (Shapiro-Wilk(31)=0.954; p=0.376) and also for the NFD (Shapiro-Wilk(14)=0.925; p=0.258) and CFD (Shapiro-Wilk(8)=0.864; p=0.130) participants.

The EES from the HFA were confirmed to have a trend with an overall significant difference between study and control groups (T_{J}=799, z=4.193, p=<0.005) with those with VFL scoring lower than the controls (t_b=0.452, p=<0.005). The same trend was confirmed for the EES from the Henson (T_{J}=886.5, z=5.381, p=<0.005) with those with VFL scoring lower than the controls (t_b=0.573, p=<0.005).

Figure 5-6 presents the EES performed from both perimeters for the study participants, the control participants and the sub-groups of the NFD and CFD participants.

Figure 5-7 presents the correlation between measurements.

Bland and Altman (Bland & Altman. n.d.) have stated that correlation does not assess agreement. Figure 5-8 presents Bland and Altman plots comparing the ESS differences from the means of the measurements. As the measured values were not normally distributed the plots were solely generated to demonstrate a visual illustration of the differences from the means.

Spearman's correlation coefficient found a very strong level of association between the EES measurements on the HFA and the Henson for those with VFL. (r_s=0.874;

p=<0.005) and NFD (r_s=0.859; p=<0.005). A fair degree of reliability was found between the EES measurements on the HFA and the Henson for controls (r_s=0.568; p=0.001) and a moderate degree of association was found between the EES measurements on the HFA and the Henson for CFD participants, but without statistical significance for the CFD (r_s=0.640; p=0.087) participants.

Although the EES between perimeters for the study participants correlated highly. This is not the same as agreement (Bland & Altman. 2003). Bland and Altman plots illustrate a wide range from the mean in those with VFL. Wilcoxon tests confirmed deviation of the Henson EES from the HFA EES was of statistical significance (z=-4.612; p=<0.005) with a large effect size (r=-0.58) for those with VFL. The average deviation between scores was a reduction of 9.76% (SD=6.69) from the HFA EES to the Henson EES.

The limits of agreement were somewhat closer to the mean for the controls. However, the deviation of the Henson EES from the HFA EES was also shown to be statistically significant for the controls (z=-2.553; p=0.011). The average deviation was a reduction of 3.29% (SD=2.92) from the HFA EES to the Henson EES and provided an effect size of r=-0.32.

The limits of agreement for the NFD group were wider from the difference between the means than for all the study participants pooled. The deviation in Henson EES from the HFA EES for those with NFD were found to be statistically significant (z=-3.297; p=0.001). The average difference between scores was a reduction of 11.29% from the HFA EES to the Henson EES. Data provided a large effect size of r=-0.62.

No significant difference was found between the EES on the HFA and Henson Perimeter (z=-1.127; p=0.260) for those with CFD. (r=-0.28; 1-β=0.27 when α=0.05).

5.4.1.1. Smaller Sample Categories. Peripheral Retinal and Unknown/unclassifiable Defects.

In light of the significant differences found between EES for those with VFL between perimeters, that was driven by those with NFD, the smaller sub-groups were analysed with an aim to establish if other types of VFL also account for the differences in those with VFL.

The correlation was found to be entirely correlated for those with PFD (r_s=1.000; n.s) but the result had no meaning. The deviation in Henson EES from the HFA EES in

EES was not found to be statistically significant (W(3)=0.000; z=-1.604; p=0.109). Post hoc testing established power of 1-β=0.38 with an alpha level set at 0.05 (r=-0.65).

The scores were found to be strongly correlated for Un participants (r_s=0.955; p=0.001). Deviation in Henson EES from HFA EES was found not to be statistically significant for this group (W(7)=0.000; z=-2.371; p=0.180). Post hoc testing established power of 1-β=0.70 with α=0.05 and r=-0.63.

Results demonstrate that the EVFT EES is not reproducible in both those with VFL and the controls. Results also indicate that the lack of agreement in EES for those with VFL is be driven by those with NFD.

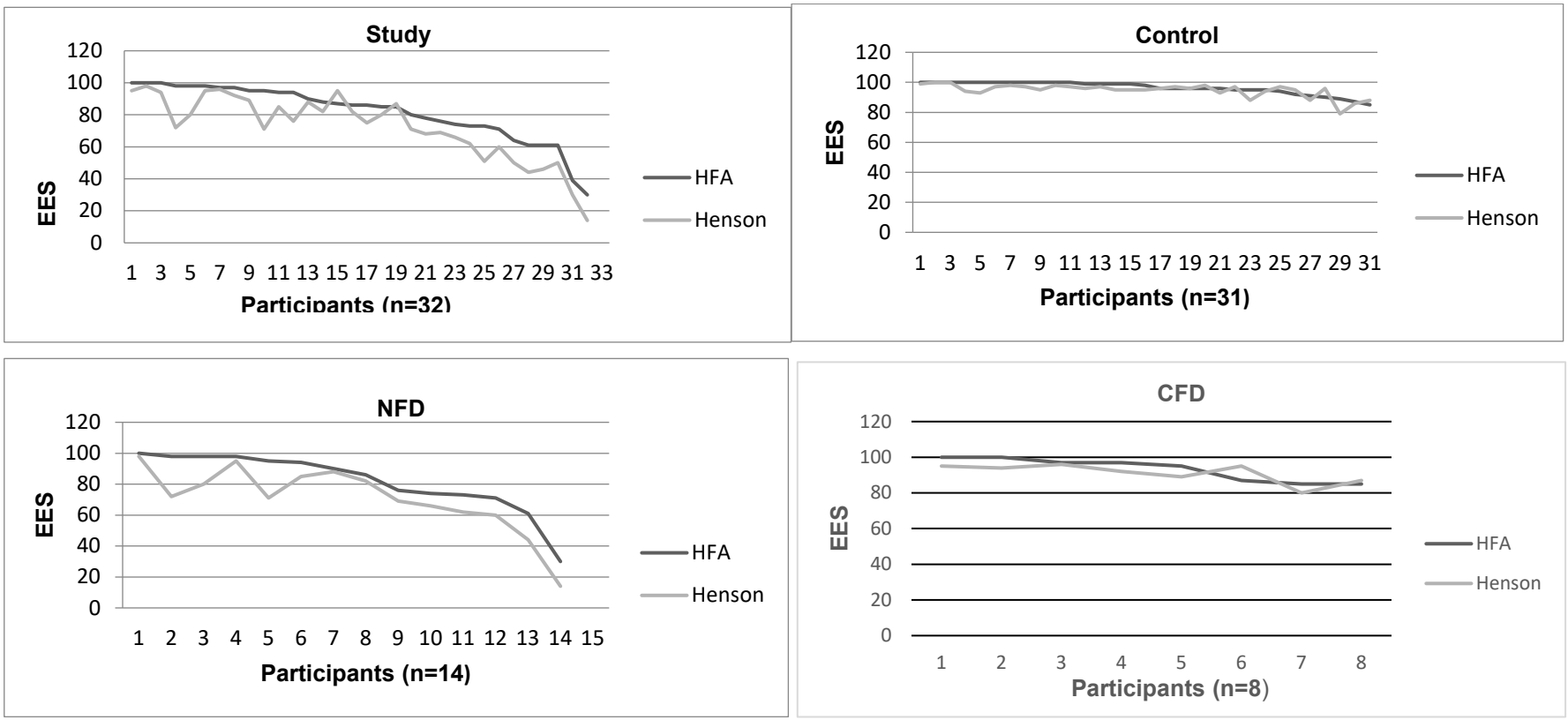


Figure 5-6. EES on HFA and EES on the Henson for each participant. Data presented for the VFL group (top left), control group (top right), participants with NFD (bottom left) and participants with CFD (bottom right). Data ranked in order of descending EES from the HFA.

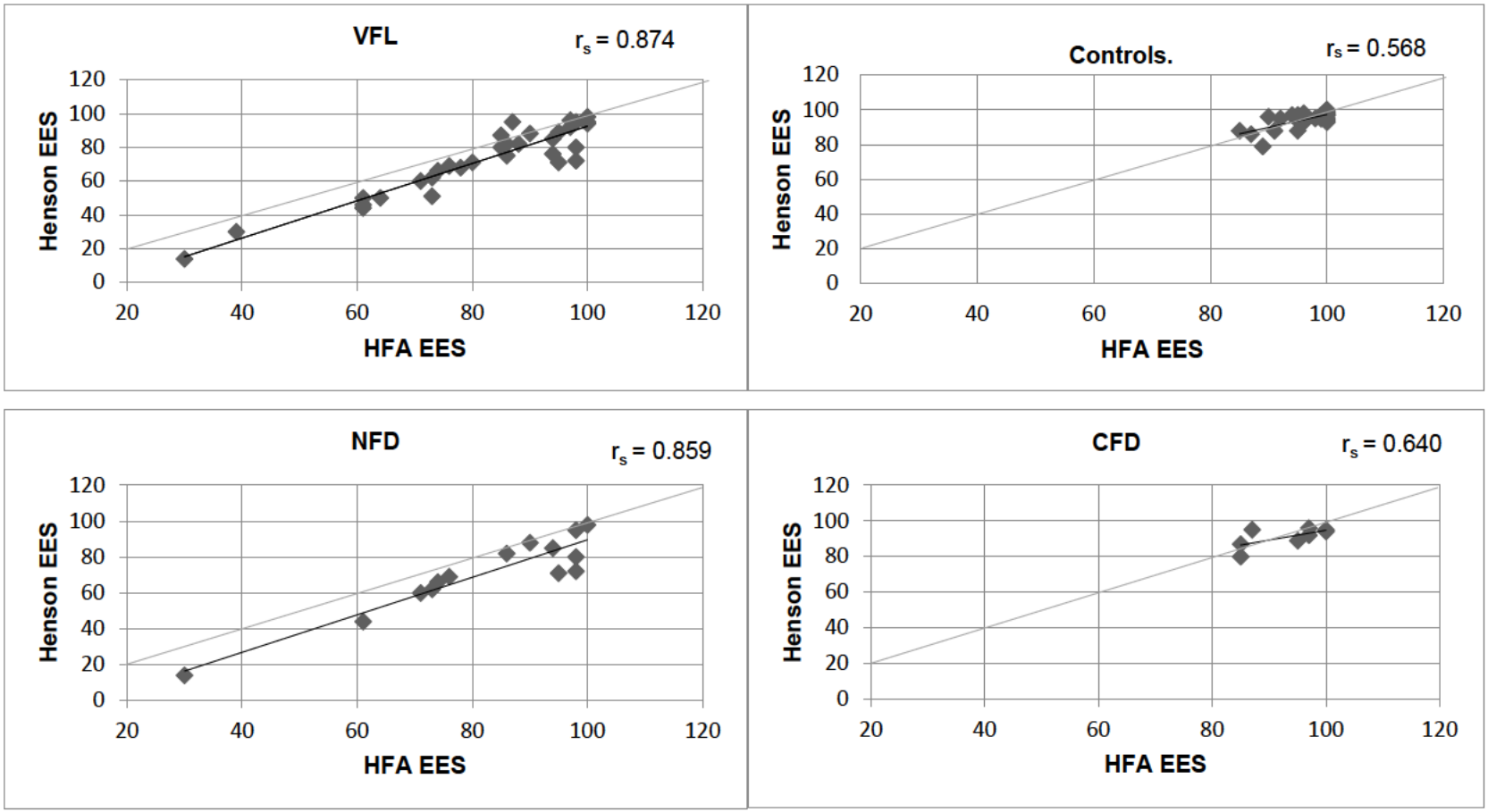


Figure 5-7. Correlation of EES. Presenting the correlation of the ESS from the HFA and Henson EVFT for those with VFL (top right), the control group (top left), NFD (bottom right) and CFD (bottom left). Diagonal line of equality (grey) and trend line (black) shown. Correlation coefficient shown (Spearman's rho (r_s)).

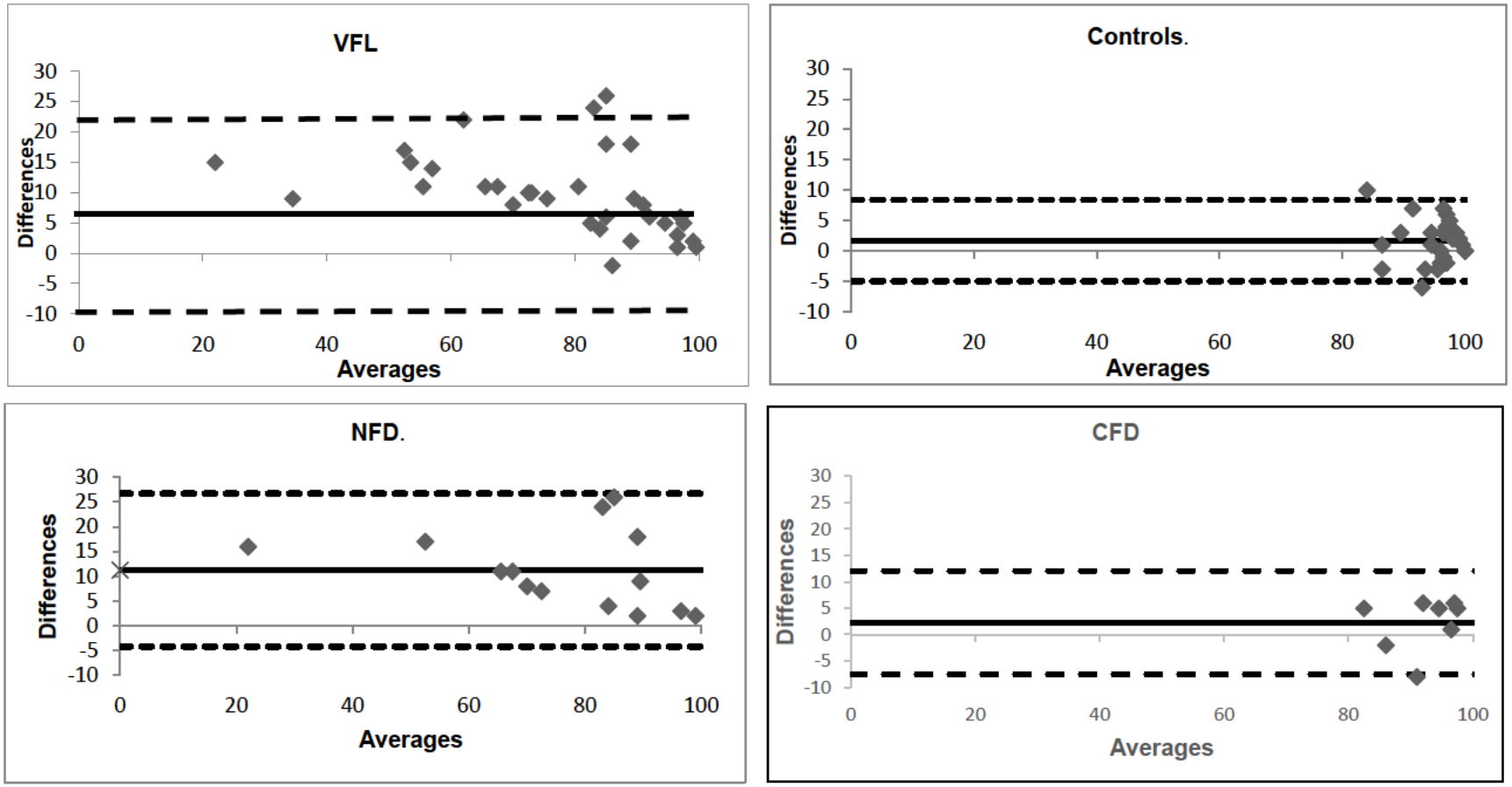


Figure 5-8. EES total reproducibility. Presented for those with VFL (n=32), controls (n=31), NFD (n=14) and CFD (n=8). Solid lines indicate mean test-retest difference between the EVFT performed on the HFA and the Henson. Dashed lines indicate the 95% limits of agreement.

Bland and Altman Parameter	All study participants	Control participants	NFD participants	CFD
Bias	9.700	1.710	11.286	2.250
STD DEV	6.830	3.418	7.878	5.007
Lower LOA	-3.691	-4.990	-4.156	-7.514
Upper LOA	23.084	8.408	26.727	12.064

Table 5-4. Parameters of Bland and Altman plots for agreement of EES between perimeters. Listing bias, standard deviation (STD DEV), lower limits of agreement (LOA) and upper limits of agreement.

5.4.2. False Positive Results.

Figure 5-9 presents the false positive results between perimeters for all included participants.

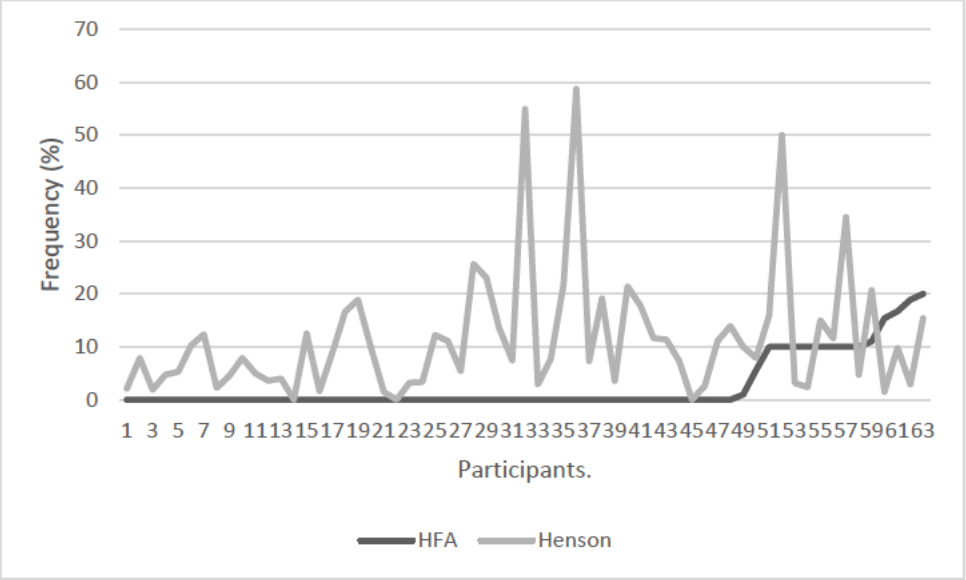


Figure 5-9. False positive rates. Data shows the frequency (%) of the false positive rates for each perimeter per participant. Data for all participants shown ranked in ascending HFA false positive rates.

The frequency data for the false positives were of a non-normal distribution for both the HFA perimeter (SW(63)=0.558; p=<0.005) and the Henson (SW(63)=0.747; p=<0.005). A Wilcoxon test found the frequency of the false positives results were significantly higher (z=-5.205; p=<0.005) for the Henson compared to the HFA. Data provided an effect size of r=-0.46.

Results indicate that participants have more difficulty determining if they have seen or not seen a target when a target has not been presented.

5.4.3. Range of Variance.

Figure 5-10 presents comparisons of the range of variance in EES between controls (n=31) and the study group (n=32), NFD group (n=14) and the CFD (n=8) group. Differences in EES between perimeters (HFA vs. Henson) was found and plotted for comparison between groups.

The variance of the ESS measured between instruments ranged from 1-26% for those with VFL. The control groups variance of ESS ranged from 0-13%.

Data of variability in EES were of normal distribution. Levene's test for homogeneity of variance revealed that there was significant difference in variability from the means between the control and the study participants (F=11.379; p=0.001).

As the samples were not of equal variance an independent-samples t-test was conducted with 'unequal variances not assumed', which is the correction to the t-test in such data sets, to compare variability in EES results from the HFA and Henson in those with VFL (n=32) and controls (n=31). There was a significant difference in the variability in the scores between those with VFL (M=-8.41; SD=8.64; CV=-97.30%) and the controls (M=-2.03; SD=3.97; CV=-195.42%); (one-tailed t(43.839)=-3.782, p=<0.005; lower CI=-9.771; upper CI=-2.977). Those with VFL having a greater range of variability than the controls with an effect size of d=0.94.

Data for the NFD group were considered normally distributed. Levene's test for homogeneity revealed that variances were significantly different between controls and those with VFL resulting from NFD (F=11.672; p=0.001).

An independent-samples t-test with 'unequal variances assumed' found there was a significant difference in the variability in the scores for those with NFD (M=-11.36; SD=7.94; CV=-69.9%) and the controls (one-tailed t(16.015)=-4.166, p=0.001; lower CI=-14.069; upper CI=-4.58), with those with NFD having a greater range of variability than the controls with a large effect size of d=1.83.

The Levene's test for homogeneity revealed that variance between those with CFD and the controls was also significantly different (F=6.201; p=0.018).

An independent-samples t-test (two-tailed) with 'equal variances not assumed' was conducted to compare variability in EES score results from the HFA and Henson in those with CFD (n=8) and controls (n=31). There was no significant difference in the variability in the scores for those with CFD (M=-1.00; SD=5.45; CV=-545.10%) and the controls; (two-tailed t(8.326)=0.188, p=0.855; Lower CI=-4.233; upper CI=4.992). Data provided a small effect size (d=0.24).Post hoc testing provided a power of 1-β=0.32 when α=0,05.

Results demonstrate that those with VFL present with more variability in EES than those without visual field defects and this is driven by those who present with NFD.

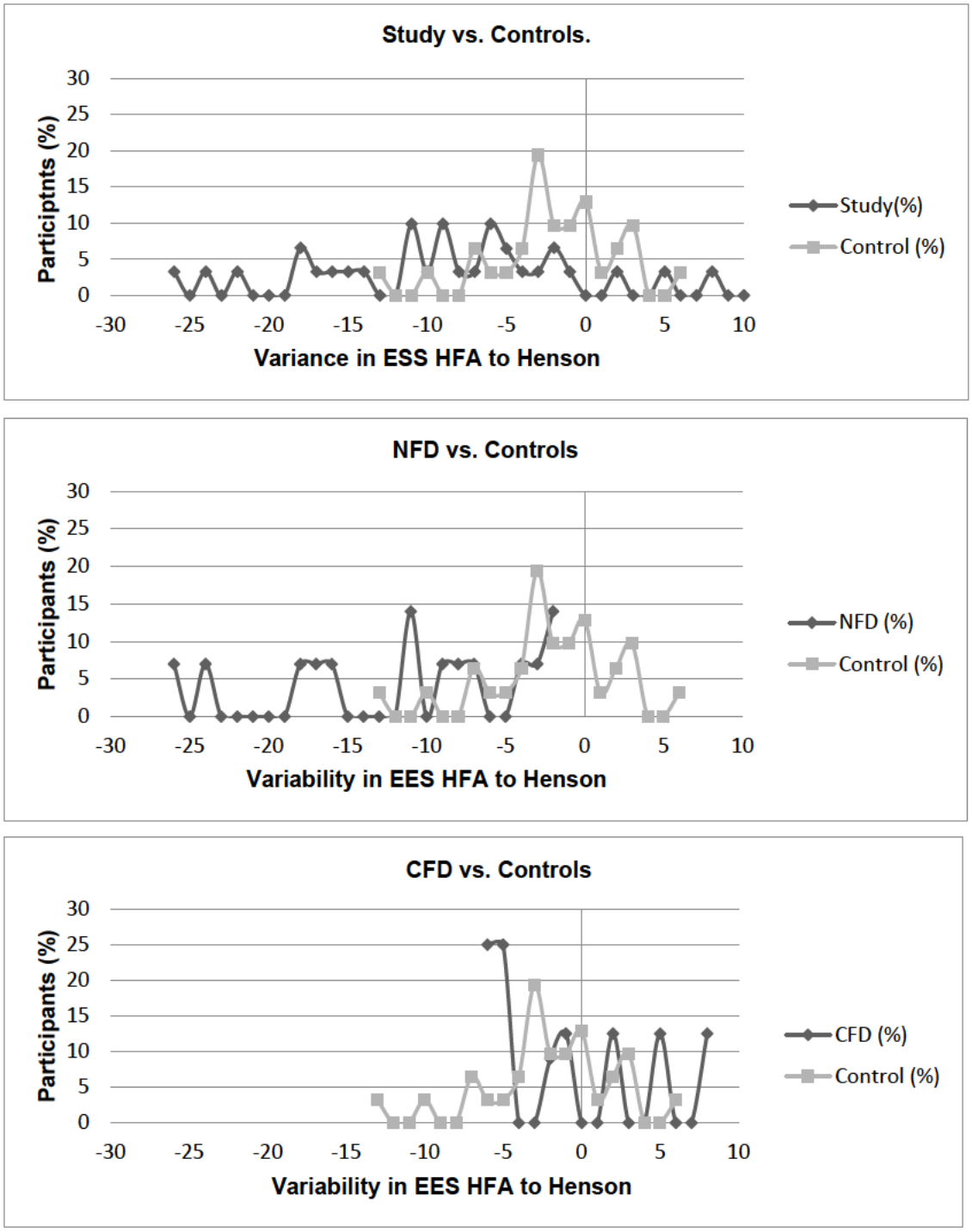


Figure 5-10. Range of variances in EES recorded on the HFA and Henson; Between groups. Range of variance in the EES plotted for the control participants compared to the VFL participants (top) the NFD participants (middle), and the CFD participants (bottom). Frequency of participants presented in percentages.

5.4.4. Correlation Between Perimeter EES.

Figure 5-11 presents the correlation of scores for both the study and control participants, along with the linear equation to predict the EES that would be found on the HFA when the Henson EES is known for a participant and vice-versa.

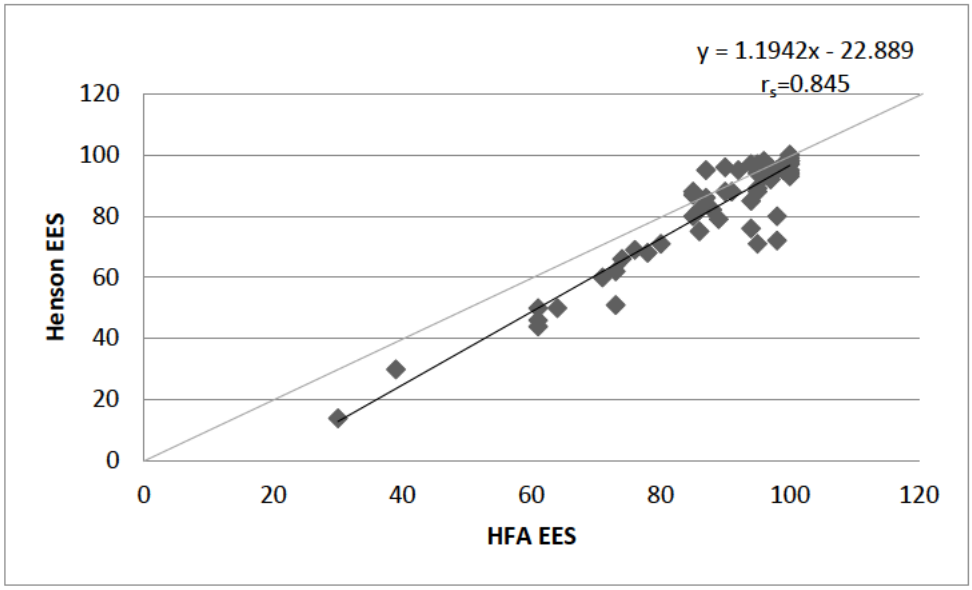


Fig 5-11. Correlation of EES for the HFA and Henson; All participants including both the study and the control participants. The linear regression line presents the prediction of the Henson and HFA EES and vice versa. Spearman's correlation coefficient ((rho) r_s) and linear equation provided. Grey diagonal line indicates line of equality.

The correlation coefficient for the EES on both perimeters is r_s=0.845 (p=<0.005) This demonstrates a very strong correlation between scores. The linear regression line however does not provide an accurate prediction of EES for the other perimeter in practice. Differences in the hill of vision profile and the variability presented in those with VFL means the use of the linear equation is flawed for real-life usage.

5.4.5. Agreement of Pass/fail Frequencies.

Table 5-5 presents the frequencies of pass and fail decisions for the EVFT when performed on both the HFA and the Henson for those with VFL and the controls.

	Frequency table		Study (n= 32)
		HFA	
		Pass	Fail
Henson	Pass	15	0
	Fail	1	16

	Frequency table		Control (n=31)
		HFA	
		Pass	Fail
Henson	Pass	31	0
	Fail	0	0

Table 5-5. Frequency of pass and fail results. Frequencies provided for the HFA and Henson EVFT. All participants with VFL and the controls.

All the control participants passed both tests. The participants with VFL either all passed or all failed except one participant. This alteration in failure result on the Henson was as expected, performing a binominal test, not found to be significant ($p=0.454$). The EVFT possesses good agreement in passing or failing individuals with the current criteria. However, post hoc testing established the power to be $1-\beta=0.03$ with $\alpha=0.05$.

To determine if a participant's MD from a SITA Standard examination on the HFA could allow a prediction of a participant who would pass on the HFA but fail on the Henson perimeter, the mean MD for all participants who passed both tests, failed both tests and passed on the HFA but failed on the Henson were determined. The mean MD from FT testing with the HFA of those with VFL who passed both tests was -8.67 (SD=8.72; CV=-100.58%) and for those who failed both tests this was -15.77 (SD=8.30; CV=-52.63%). For the participant who passed on one test but failed on another the MD mean was -10.13 (SD=2.12. CV=-20.93%) with the EES on the Henson being the lower value. As this was only one participant the mean and SD is not considered valuable.

Following the method by Latham *et al* (2014), looking for overlap zones where the recorded visual acuity would create uncertainty as to whether the participant would pass or fail the number plate test (Latham *et al*. 2014), this was adapted to consider if

the EES could create uncertainty on passing or failing on both perimeters. Table 5-6 looks for an overlap zone along with false positives, false negatives, sensitivity and specificity.

The zone whereby a participant can fail on one test or pass on another extends from 75-86% with sensitivity of 94.12% and specificity of 100%. A numerical zone whereby a participant can pass one test and is then likely to fail another cannot be established as the above variance value of 11% falls within the variance of 0-26% whereby a participant can still pass both or fail both tests.

Study participants									
Test	**Number in overlap one**	**Extent of overlap**		**Variance in overlap**		**False positive rate (%)**	**False negative rate (%)**	**Sensitivity (%)**	**Specificity (%)**
		Min score	Max score	Min	Max				
EVFT	1	75	86	11	11	0	2.94	94.12	100
Control participants									
Test	**Number in overlap one**	**Extent of overlap zone**		**Variance in overlap one**		**False postive rate (%)**	**False negative rate (%)**	**Sensitivity (%)**	**Specificity (%)**
		Min score	Max score	Min	Max				
EVFT	0	0	0	0	0	0	0	100	100
Study + Control									
Test	**Number in overlap zone**	**Extent of overlap**		**Variance in overlap**		**False positive rate (%)**	**False negative rate (%)**	**Sensitivity (%)**	**Specificity (%)**
		Min score	Max score	Min	Max				
EVFT	1	75	86	11	11	0	1.54	94.12	100

Table 5-6. Overlap zone: passed on one test, but failed on subsequent test. False negatives indicate a pass on the HFA but a fail on the Henson. False positives indicate a fail on the HFA but a pass on the Henson. True negatives=pass on both. True positive=fail on both. Sensitivity=true positives/(true positives+false negatives). Specificity=true negatives/(true negatives+false positives).

5.4.6. Agreement of Pass/fail Frequencies Excluding the Visual Field Criteria.

The following table 5-7 presents pass/fail frequencies for those study participants who would be able to hold a driving licence based on visual acuity and condition alone when the VF criteria is excluded.

Perimeter		**HFA**	
Henson	**Status**	Pass	Fail
	Pass	8	0
	Fail	0	5

Table 5-7. Study participants who would be able to hold a driving licence with visual field criteria excluded. Criteria based on visual acuity and condition (n=13).

Considering those participants who would be able to hold a driving licence status if they were not excluded by the visual field criteria further confirms that the EVFT has good reproducibility in fitness-to-drive status utilising the current criteria.

5.4.7. Agreement of Defect Location. Pointwise Analysis.

Figures 5-12 & 5-13 present the change in status (%) from defect present or not present and vice versa between the EVFT on the HFA and the EVFT on the Henson per location in those with VFL and the controls respectively. The illustration shows the actual locations making use of the combined points functional zones.

Using the same grid, figure 5-14 presents the change in status (%) whether a defect present or not present between the EVFT on the HFA and the EVFT on the Henson per location comparing those with VFL and the controls by presenting the difference between the two groups.

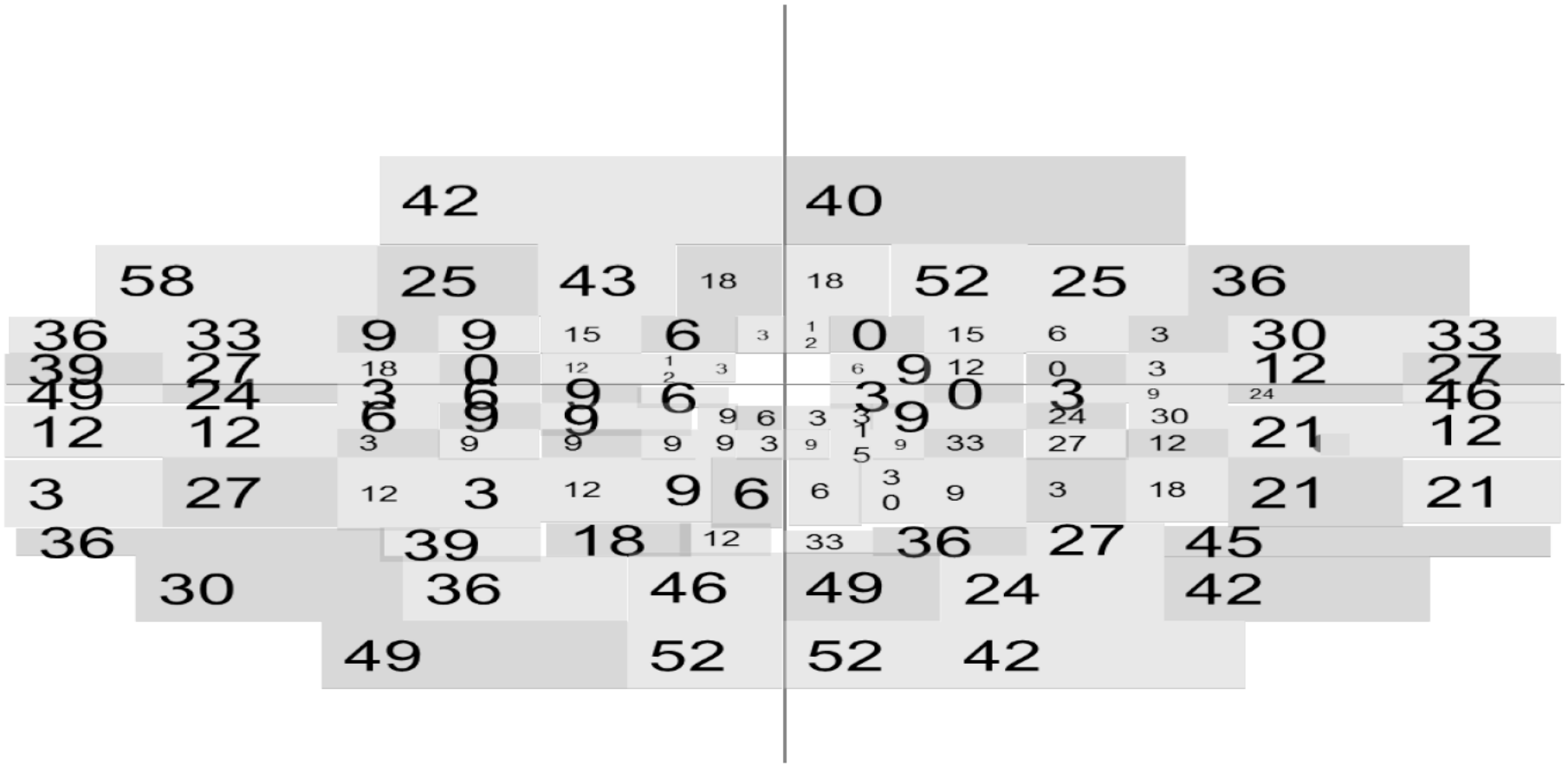


Figure 5-12. The change in status (%) of whether a defect present or not present between perimeters per location. Study group.
Change in defect status (%) per location for the EVFT on the HFA and the EVFT on the Henson in those with VFL. Percentage changes are shown for the combined grid.

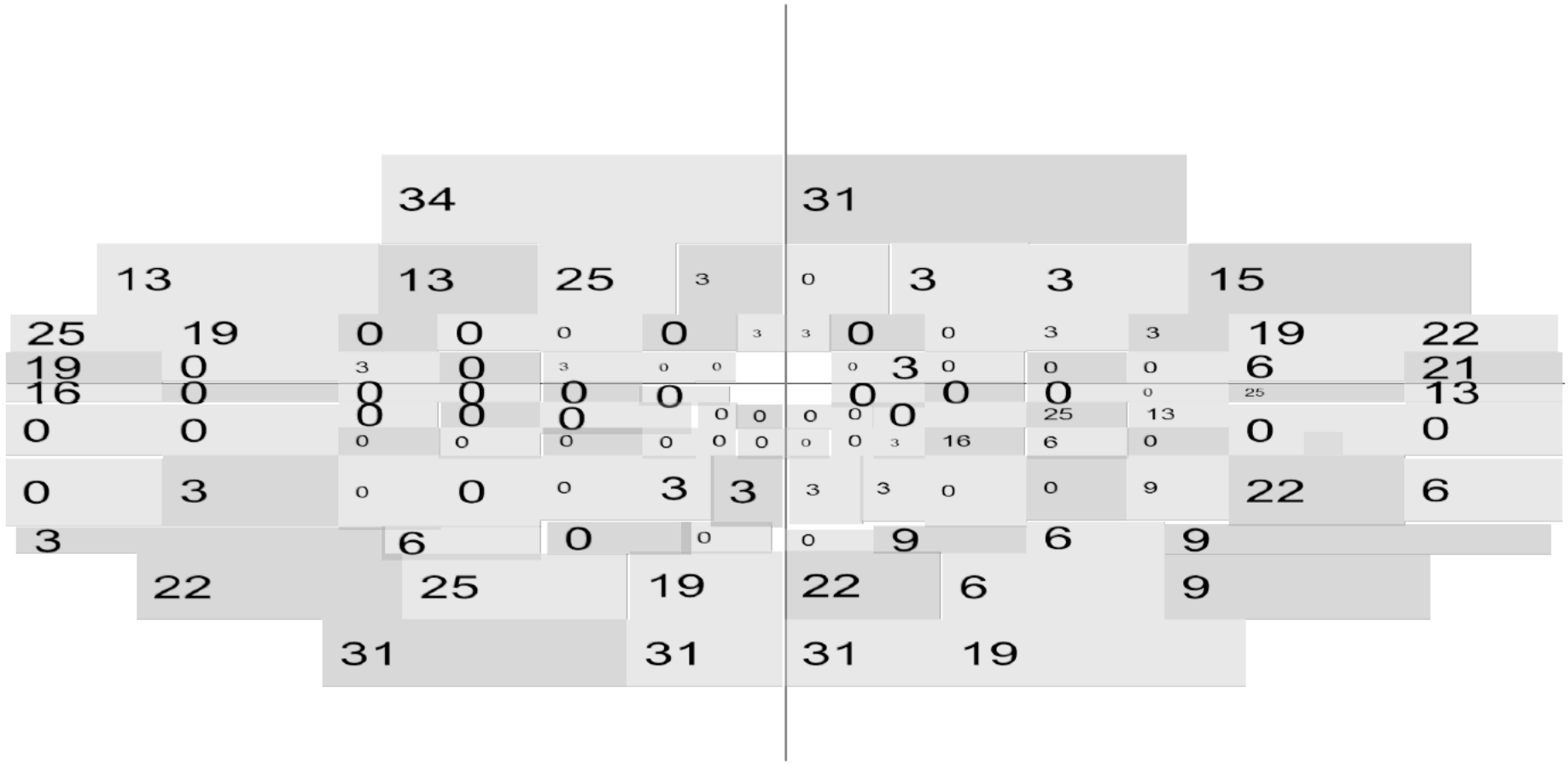


Figure 5-13. The change in status (%) of whether a defect present or not present between perimeters per location. Control group. Changes in defect status differences (%) per location in the controls. Percentage changes are shown on the combined grid.

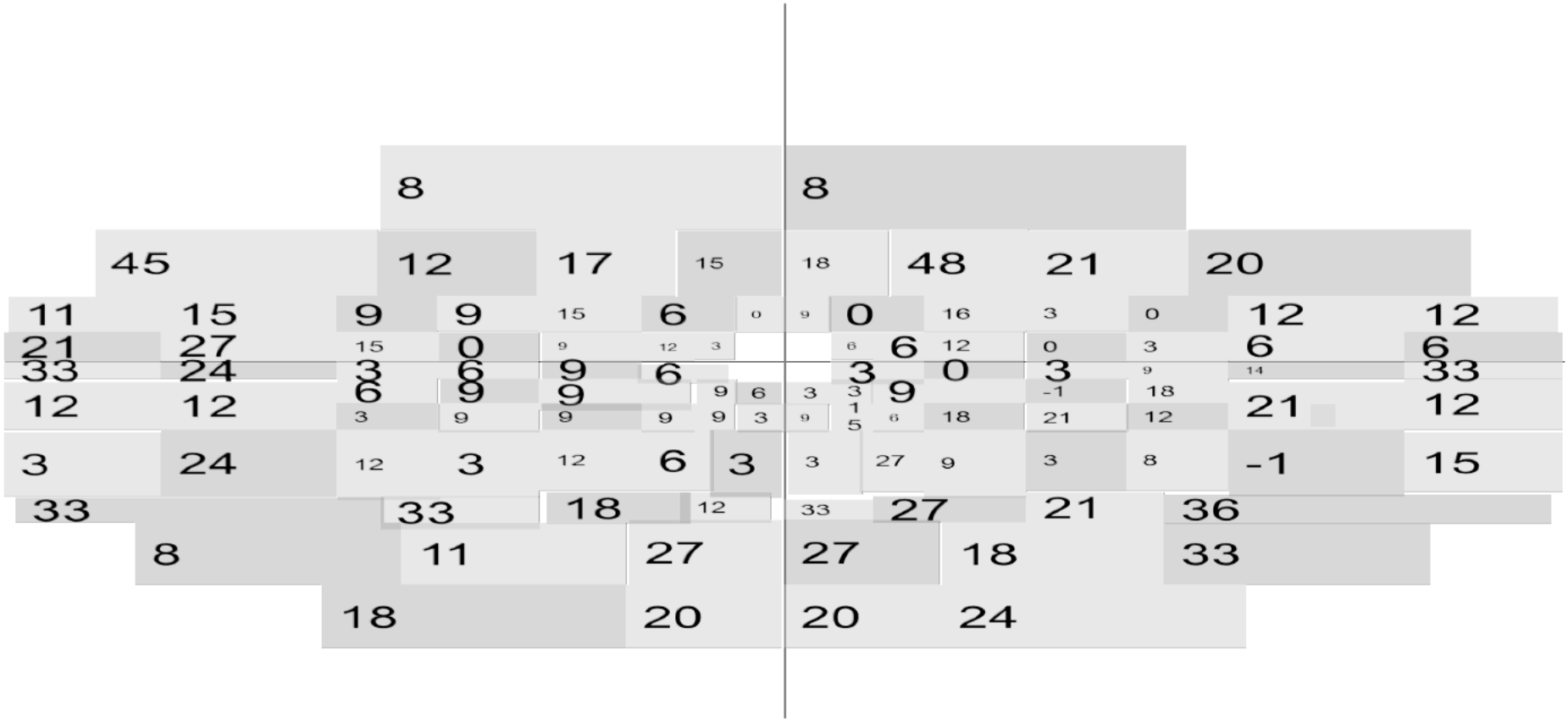


Figure 5-14. The change in defect status (%) per location between perimeters; between group. Change in status (%) whether a defect present or not present between the EVFT on the HFA and the EVFT on the Henson per location comparing those with VFL and the controls. The differences between the two groups are presented. Using the controls as the reference, positive numbers indicate those with VFL had more change within the specific location, negative numbers indicate the controls had more change within the specific location.

The change in defect status (%) data were shown to have non-normal distribution for both the study participants (SW(108)=0.902; p=<0.005) and control participants (SW(108)=0.723; p=<0.005).

A Mann-Whitney test confirmed that there was a significant difference (*U*=2558.000; z=-7.205; p=<0.005) in the change (% of participants) between defect status per location, between perimeters, between the controls (median=1.56; IQR=19.38) and the study participants (median=12.12; IQR=22.73) with a large effect size (r=-0.49).

Results demonstrate that the EVFT has poor reproducibility in the location of defect in those with VFL compared to controls.

Considering eccentricity, the zones for the change of defect status (% of participants) of up to 20º (zone 1) of eccentricity (median=9.00; IQR=9.00), >20º up to 40º (zone 2) eccentricity (median=9.00; IQR=19.00) and >40º (zone 3) eccentricity (median=33.00; IQR=23.00) were compared in those with VFL. A Friedman two-way analysis of variance determined that there was a significant difference ($\chi^2(2)=27.361$; p=<0.005) between the zones in those with VFL. Using a Bonferroni correction factor of 0.017, Wilcoxon tests found that there was significantly more change in defect status (% of participants) with increasing eccentricity. Zone 3 had significantly more change than zone 1 (z=-3.921; p=<0.002) with a large effect size (r=-0.50), and zone 2 (z=-4.371; p=<0.002) also with a large effect size (r=-0.53). There was no significant difference in changes of defect status when comparing zone 1 and zone 2 (z=-1.083; p=0.297) which provided a small effect size (r=-0.14). For the controls there was also found to be a significant difference ($\chi^2(2)=38.327$; p=<0.005) between zones and found to be driven by eccentricity. Zone 3 (median=15.50; IQR=19.00) had significantly more change than zone 1 (median=0.00; IQR=3.00) (z=-4.546; p=<0.002) with a large effect size (r=-0.59), and zone 2 (median=0.00; IQR=3.00) (z=-4.120; p=<0.002) which also presented with a large effect size (r=-0.50). There was no significant difference in changes per defect status when comparing zone 1 to zone 2 (z=-1.149; p=0.251) which presented with a small effect size (r=-0.15).

Results demonstrate that the poor reproducibility in defect location is also driven by eccentricity with increased variability with eccentricity.

5.4.8. Age and EES.

Age and EES was shown to have a very strong correlation (r_s=0.845; p=<0.005) when all participants and data from both perimeters were pooled with EES increasing with age. However, there was poor correlation between EES and age in all participants

when the HFA (r_s=0.142; p=0.288) and the Henson (r_s=0.050; p=0.696) were analysed separately.

There was a fair correlation between age for both HFA EES (r_s=0.353; p=0.048) and Henson EES (r_s=0.374; p=0.035) for the study participants.

For the controls there was poor correlation between both age and HFA EES (r_s=0.179; p=0.334) and a fair correlation between age and Henson EES (r_s=-0.370; p=0.041). These results therefore suggest that age is not a factor for EES.

A Kruskal-Wallis test found there was a significant difference between scores (HFA and Henson EES) for different age groups in those with VFL (X^2(5)=13.799, p=0.017). The significant difference was between the participants aged 51-60 (X^2(1)=5.639, p=0.018), who scored lower (median=22.00; IQR=16.00) than those aged 30-50 and 61-90 (median=71.50; IQR=29.50). No significant differences were found between other groups (p=0.066, p=0.782). Nor was any significant difference found in age when considering the HFA and Henson EES separately (HFA: X^2(5)=7.656, p=0.176; Henson: X^2(5)=7.013, p=0.220).

No significant difference was shown between scores for different age groups considering control participants separately (X^2(4)=0.540, p=0.994) with all scores from both perimeters, the HFA scores independently (X^2(4)=0.232, p=0.994) or Henson scores independently (X^2(4)=1.045, p=0.903).

5.4.9. Age and Variance of EES.

There was poor correlation between age and variance in EES between perimeters when data were pooled for all participants (r=0.172; p=0.177) or when the control participants (r=-0.255; p=0.166) were analysed separately. There was no correlation when the study participants (r=0.099; p=0.590) were analysed separately. The control participants demonstrated a decrease in variance with increasing age, but along with the pooled data and the study participant's it was not significant.

There is significant difference between variance of EES between study and control participants. A significant difference was also found between the variance in EES for those with NFD and the controls. These particular groups were separated into age groups and a one-way ANOVA found that there was a significant difference between groups (F=3.106; p=0.004) a post-hoc test could not be performed to establish where this difference lies due to one group having a very small sample.

5.5. Discussion.

To the author's knowledge, no one has researched or presented results on the reproducibility of the EVFT in any perimeter. The primary aim of this study was to establish if there are any differences in performance between the EVFT performed on the HFA II model 720 and the Henson Pro 5000 Perimeter and establish the reproducibility of the EVFT.

Within this study, certain factors that were, and were not controlled for, have previously been provided within section 3.3.

Differences between durations of the EVFT on the HFA and Henson were not of any significance (p=0.056) and therefore any differences arising from fatigue due to differences in duration were not expected to impact on the results.

As expected the HFA (p=<0.005) and Henson EES (p=<0.005) were both confirmed to have a trend of an overall significant difference between the study and control groups. The study group had an overall trend of scoring lower than the controls confirming the nature of the two groups.

The measured EES on the HFA for those with VFL ranged from 30-100 and from 14-98 on the Henson. For the controls, the EES ranged from 85-100 on the HFA and 79-100 on the Henson. The EES between the HFA and Henson show a very strong correlation (figure 5-7) for those with VFL and NFD. This determines a relationship between the two values, but neither set were along the 45º line of equality and hence agreement is not confirmed with the correlation. There was a fair and moderate relationship between the EES of both perimeters for the controls and CFD respectively, although the CFD correlation was not of any significance. Correlation however has the possibility of occurring by chance (Siegal & Castellan. 1988). Furthermore, Bland and Altman plots demonstrate the limits of agreement are substantially wider for those with VFL when compared to the limits of agreement of the controls and lacking in agreement between the two measured values. The NFD group possess the widest limits of agreement and the CFD the narrowest within the study sub-groups. The NFD limits of agreement were also wider than that of the study group pooled data. Indicating that the NFD participants were responsible for the lack of agreement as opposed to those with CFD. No groups with VFL were as close to the bias than that of the controls. There is a statistical lack of agreement between the measured EES values with the Henson EES being significantly lower than the EES of the HFA for all groups except the CFD participants (p=0.260). Previous literature informs us that those with VFL do have more

variance in results than those without VFL. However, this would not be the sole reason for the deviations of EES on the Henson from the EES on the HFA within this study, due to the trend in lower EES also arising within the control participants tested on the Henson. Fatigue effects have been shown to occur in prolonged examinations leading to a reduction in sensitivity and is shown to be exhibited more predominantly within the peripheral field that extends beyond 30° (Dengler-Harles. 1991). However, although fatigue may be of some influence, in this study the examination order was randomised. The fatigue effect would be expected to be evidenced on the second test and the lower EES would have also have been expected on the HFA if this was the second test. The consistency of the lower EES on the Henson means that fatigue does not explain the differences found in scores between the perimeters. Randomisation of the perimeters also acted as the control for factors of the learning effect, short-term fluctuation and attention. The differing amount of stimuli can mean that some defects are missed on the perimeter with the lowest amount of stimuli, this being the Henson with 112 test points. However, sensitivity is usually 100% when 80 test locations has been reached (Henson. 2001). The physical size of the stimuli presented vary in both perimeters, however, trigonometry informs that they both subtend the same angle at the eye (0.69° exact; approximately 0.50° as per manufacturers description) under examination and hence these factors will not have an impact on results. Contrast sensitivity is higher for wavelengths of 550 nm (Rovamo e*t al*. 1996), or around this value. At lower light levels the eye is more sensitive to shorter wavelengths (Uchida & Ohno. 2014) and LEDs are more visible to the eye increasing peripheral visual performance (Reyes *et al*. 2013, Reyes *et al*. 2014) and detection times (Sammarco e*t al*. 2010). LED stimuli have been found to increase sensitivity at eccentricities greater than 10° with an increase in pupil size in those with retinitis pigmentosa (Wood. 1987). CRI for the HFA is provided as 100, however, the CRI used in the Henson is currently not accessible knowledge. However, an LED's spectral output can be chosen depending upon the diode construction and the conducting element. The LED spectral range for the Henson is accessible and is broad at 530-600 nm. This pertains to the green/yellow (nearing to orange) rather than the blue end where the peak is found (below 500 nm) for white LEDs and therefore should not make an impact on EES. If the LEDs were considered to have made an impact this would have been expected to have been demonstrated by a rise of EES in the Henson, this however was not the case. Another factor that was not controlled for and is representative of high street practice is the lack of optical correction for near. The Henson bowl radius (r=25cm) and hence, the location of the target differs from the HFA (r=33cm) by 8 cm. This in essence means that an eye can be undercorrected by a further 1.00D when using the Henson. This fact may contribute

to the deviations of Henson EES from the HFA EES by adding extra difficulty for one perimeter in seeing the nearer stimuli without adequate accommodation or correction. However, an overly bright stimulus may not be overly sensitive to defocus blur. Blinking after presentation of a ST stimulus can lead to a missed stimulus on the next presentation. However, this fact would apply to both perimeters examining the EVFT, which is a ST test regardless of perimeter used. The results can therefore be explained by a rise in threshold as the luminance of the background rises (Lennie. 1979) and hence the perimeter with the highest background luminance has provided the highest EES. The results agree with the notion that contrast sensitivity is reduced when retinal illumination is reduced (Swanson *et al*. 2014) and more defects are found when background luminance of a perimeter is lowered (Klewin & Radius. 1986). The EVFT examines the visual field with a stimulus presented at 10 dB. However, the decibel is a relative scale dependent upon the maximum intensity of the stimulus. It is expressed as 0.1 log-unit of attenuation and hence can differ between perimeters. The HFA has a maximum light intensity of 10.000 asb (Heijl *et al*. 2012) which is the equivalent of 0 dB on the HFA. Ten decibels on the HFA is equivalent to 1000 asb. The Henson has a contrast value log0.5 compared to log1.5 for the HFA. The background luminance of the HFA falls within the range of photopic luminance and matches that of the Goldman perimeter which is recommended by the International Perimetric Society. This background requires less adaption time after the patient has been exposed to bright ambient lighting (Haley. 1993). The background of the Henson falls in the range of mesopic luminance according to International Commission of Illumination definitions. The results indicate the EVFT on the Henson is a harder and more sensitive test than the EVFT on the HFA. The Henson presents results with more defective points and therefore lowers the EES.

The false positive rate arising on the Henson had a significantly higher frequency than those arising from the HFA. Indicating that participants either found more difficulty determining if they had or had not seen a target when there was not one presented, or that the presenting audible noise of the Henson put patients into a routine more so than the HFA presenting audible noise. The rate of false negatives were unable to be ascertained as the Henson did record this parameter but provided 0/0 for every participant. False negatives are provided to determine attention and has been shown to be related to a participants VFL (Bengtsson & Heijl. 2000). This cannot therefore be compared to see if the contributed to the deviations in EES found between perimeters.

The correlation coefficient for the EES on both perimeters demonstrates a very strong correlation (r_s=0.845). The mathematical relationship of *1.194(HFA EES)-22.889* would

theoretically be able to determine the expected Henson EES to a reliable degree (p=<0.005). However, in practice the linear regression line may not provide an accurate prediction of EES for the other perimeter. Differences in the hill of vision profile and the variability presented in those with VFL means the use of the linear equation is flawed for real-life usage

It is established that dark adaption is compromised in certain pathological conditions (Gloriani *et al*. 2016, Freeman *et al*. 2009) and those with VFL present with fluctuations in visual field results. Variability increases in areas of reduced sensitivity (Wall *et al*. 2008, Haley. 1993, Turpin *et al*. 2007, Gardiner. 2003) and the increase in variance is related to the increasing size of the defect in those with glaucoma (Tattersall *et al*. 2007). Those with VFL were anticipated to provide more variance in EES results (figure 4-10) and hence the EES would not be the same between perimeters. A statistical significant difference between the EES on the HFA and the Henson was found in NFD participants. NFD participants demonstrated the greatest test-retest variability in the measured EES between perimeters but this was not found in those with CFD. The range of the variance was also anticipated to be greater in those with VFL than the controls. Those with VFL possessed significantly (p=<0.005) more variability (1-26%) between perimeters with an average of -8.41% from the HFA EES to the Henson ESS than the controls (0-13%) who had an average variance of -2.03%. Those with NFD significantly (p=0.001) contribute to this variance with an average of -11.36%. The CFD participants variance, which was an average of -1%, did not significantly (p=0.855) contribute to the variance exhibited. Possible explanations for this can be down to the sampling of the EVFT. There are no central testing points within the central 7.50º and therefore any variance within this zone would not contribute to the result. In the central 20° of the EVFT there are only 34 locations that are examined out of the total 120 locations. Therefore, a maximum change in EES is 28% if a participant went from seeing all to seeing none of the stimuli. It is well documented that those with glaucoma have increased test-retest variability (Bentley *et al*. 2012, Crabb *et al*. 1995, Haley. 1993, Gardiner *et al*. 2006, Miranda & Henson. 2008, Artes e*t al*. 2003) as well as those with diseases affecting nerve fibres, such as optic neuritis and ocular hypertension (Henson *et al*. 2000). The results of this study add to this notion with the deviation of the Henson EES from the HFA EES in those with NFD. Variance has previously been found to reach up to approximately 15 dB in patients with reduced sensitivity (Nouri-Mahdavi *et al*. 1997, Swanson *et al*. 2014) and even up to 20 dB (Gardiner. 2003) has been reported. As the EES is uniform in its presentation, it can not be established to the exact decibel the variance in these cases.

However, the large range provides every possibility of a bright stimulus being seen on one perimeter, but not on the other. Glaucoma has also shown variance in the UFOV examination, also possessing wider limits of agreement than controls (Bentley *et al*. 2012) and this variance is common to many testing methodologies (Wall *et al*. 2008, Artes e*t al*. 2002, Gardiner. 2003).

Variability in patients with VFL is well established. It was anticipated those with VFL would possess more variability on defect status per location between the perimeters than the controls. The change in defect status per participant was obtained and the average obtained for each location for the study and the controls. In addition, the differences in change between controls and VFL participants for each of these locations were obtained to compare these two groups. The HFA EVFT grid and the Henson EVFT grid have differing sampling. To obtain comparative data a mixed functional zones grid was mapped which averaged the locations. The hybrid locations were analysed and confirmed to be within the original HFA EVFT function zones. Those that did not were excluded. The percentage of defect status alterations between perimeters was mapped onto this combined points functional zones grid for both the study group and the controls (figures 5-12 & 5-13). No participants with VFL repeated the exact same results per location and 9.68% of the controls replicated their result on a pointwise basis for the HFA and Henson. This means that all participants with VFL would did not produce the same exact test when looking at missed or seen points and 90.32% of controls also did not produce the exact same test when considering missed and seen points between the two perimeters. Those with VFL present with significantly more variability in their difference in change of the defect status per location compared to the controls (p=<0.005). The percentage of change in status per location between study and control participants was obtained and also mapped (figure 5-14).

The EVFT's uniform stimulus does not lend itself to determine if a scotoma is relative or absolute (Ayala. 2012), neither does it lend itself to mapping a hill of vision profile (Haley. 1993). However, inspection of figures 5-12 & 5-13 permit a conclusion that the peripheral visual field is more likely to show variance in defect status between perimeters for both those with VFL and the controls. To assess variability the points on the EVFT grid were categorised into zones of up to 20º from fixation (zone 1), beyond 20 and up to 40º from fixation (zone 2) and >40º from fixation (zone 3). There was a significant difference found due to eccentricity for both those with VFL (p=<0.005) and the controls (p=<0.005). The percentage of study participants that had a change in defect status increased with eccentricity between zones 1 and 3 (p=<0.002) and between zones 2 and 3 (p=<0.002) which was not found between zones 1 and 2

(p=0.297). The same pattern was followed with the control participants with significant changes between zone 3 compared to zone 1 (p=<0.002) and zone 2 (p =<0.002). The median percentage of participants that had a change in defect status was 33% for those with VFL within zone 3 compared to a median of 9% for both zones 1 and 2. The detection of peripheral target stimuli decreases with eccentricity (Crundall *et al*. 1999) and uncertainty increases (Raj *et al*. 2005). The results are in agreement that variability increases with eccentricity (Chauhan & Johnson. 1999, Phu e*t al*. 2017).

The DVLA criteria assigns a method of location rather than EES to determine fitness-to-drive and hence the pass/fail frequencies (table 5-5) would allow determination of possible complications to a patient in practice on the possibility of failing if a particular perimeter is used for the examination. All controls passed the EVFT on both perimeters with only one of the study participants passing on the HFA and failing on the Henson. This is not a significant find (p=0.454) and therefore patients are likely to either be deemed as unfit-to-drive or fit-to-drive in line with current criteria regardless of which perimeter is used. The perimeters are therefore in good agreement utilising the current fitness-to-drive criteria. This reassures that the choice of perimeter itself will not have a bearing on a person's quality of life or be the reason to lead a person to depression if a licence is required to be revoked. Nor is the choice of perimeter a cause for a person to be on the road, who would be considered as unfit-to-drive on an alternative perimeter. Previously the Goldmann perimeter, considered to be 1.6x harder for the stimulus to be seen, also had similar pass/fail frequencies when compared to the EVFT performed at 10 dB intensity (Rijn. 2002). The particular participant who had an inconsistent result had a left superior quadrantanopia. The differences lay in the central coordinates of -12,+12;-6,+6;-12,0 missed on the Henson and the equivalent of -10,+10;-7,+3;-12,+3 seen on the HFA. A left quadrantanopia occurs when there is damage to the right side of the brain and therefore attention may be affected (Racette *et al*. 2005). Although any persons with neglect would have been excluded from the study, cognitive function was not examined objectively within this study and therefore it cannot be ruled out that the cause of the quadrantanopia itself was not the cause of the discrepancy. The lack of impact using either perimeter has on the population is further supported when those study participants who would be able to hold a driving licence when the visual field criteria is excluded were considered separately. Of those study participants who could hold a driving licence if the visual field criteria were excluded (n=13), eight passed on both perimeters and five failed on both perimeters. None of the participants had an inconsistent result been the two perimeters. The MD of the individual who had a pass/fail frequency was in between (MD=-10.13) those who failed both (MD=-15.77)

and passed both (MD=-8.67) but is deemed of little value in determining a pass/fail frequency based on the insignificant result and the one individual. Statistical significance however is the determination of chance. To the one individual who passed on one test and failed on another, a chance of this occurring can lead to detrimental outcomes which have been discussed in section 1.13.1. However, this had limited impact when the visual field criteria were ignored and those able to hold a driving licence with visual field criteria excluded were considered. This leads to total agreement in pass/fail frequencies between the perimeters.

The zone whereby a participant can fail on one test or pass on another extends from 75-86% with a sensitivity of 94.12% and a specificity of 100%. The range in the variance of the score to cause a pass/fail frequency is 11%. The variance range that can enable a pass or a fail on both perimeters extends over 26% (0-26%). This application of an overlap zone in reality has little meaning in determining likelihood of passing or failing dependent upon perimeter used. The pass/fail frequency itself proved to be insignificant. To have close scores that can still cause a difference in pass/fail results is not unknown in other tests. Crabb *et al* (2004) found that the mean UFOV score for participants who passed the EVFT but classed as unfit-to-drive with the UFOV as the arbiter did not differ significantly from the scores that failed the participants on both tests, nor did they differ significantly from the mean score provided that also passed participants on both tests (Crabb *et al*. 2004). This lack of definitive EES for a pass/fail is explained by the current criteria of location not score being the deciding factor on fitness-to-drive.

That sensitivity reduces with age is well established (Wood & Black. 2016, Wall *et al*. 2001, Esterman. 1985, Maynard *et al*. 2016, Gardiner e*t al*. 2006). The EVFT does not measure a threshold of sensitivity. It does however assign a point to a location. If the location reaches below 10 dB then this would result in a lower EES. A downward trend with age was anticipated, although difficult to hypothesise the exact impact of age when the stimulus starts at a very bright level, meaning small reductions in threshold values would be masked. Fatigue increases with age (Wall *et al*. 2001). This factor was again controlled for by randomising the perimeter test sequence. There was a relationship in increasing EES with age (r_s=0.845) when all data were pooled for both perimeters and all participants. Analysed separately, the lower the score had a relationship with increased age for the control group. The study group had an upward trend. Those age 51-60 scored significantly lower (p=0.018) than those 60+ indicating reduction in sensitivity with age is overshadowed by the nature of the visual impairment. The controls had no significant difference in any age group (p=0.994) on

either perimeter (HFA: p=0.994; Henson: p=0.903). There was poor correlation with age on both of the perimeters within the study and the control groups. When scores were analysed for each perimeter individually, there was no difference in age groups for EES scores on either the HFA (p=0.176) or Henson (p=0.220) for study participants. This is indicative of the difference in EES being due to the difference in performances on each perimeter with age having no impact.

A significant difference was found between the variance of the study group vs. the control group. A significant difference was found also between the variance in those with NFD vs. the control group. These particular groups were separated into age groups and there is significant difference in the range of variance between ages (p=0.004). However, a post-hoc test could not be performed to establish where this difference lies due to one group possesses a very small sample. There was a poor relationship between variance and increased age for participants overall. This is accounted for by the study participants. The controls had a poor relationship of less variance in score with increasing age. With the controls not providing a definitive relationship it cannot be established that the EES variance increases with increasing age. Although a relationship with the study participants has been shown, it cannot be ruled out that this would be down to the nature of the VFL itself.

Fankhauser & Switzerland (1986) have stated that unless pupil sizes and optical media clarity are perfectly identical between subjects then data gathered from perimetry cannot be truly comparable (Fankhauser & Switzerland. 1986). As obtaining identical pupil sizes is an impossibility and also identical optical clarity then this is a limitation of the study. However, using a range of these factors allows the study to represent the variation in the population that would visit an optical practice for perimetry or be sent for a DVLA perimetric test and the results are therefore representative of this general population.

The results of this study demonstrate that there is a significant lack of agreement in EES between perimeters (p=0.011), with the EES on the Henson being significantly lower than the EES on the HFA. The difference in EES is driven mostly by those with NFD (p=0.001).

The results also demonstrate that those with VFL have significantly (p=<0.005) more range of variability in EES.

The EVFT performed on the Henson records more points that the test considers defective than the EVFT performed on the HFA, and the change in location of defect is

found to be significantly more (p=<0.005) in those with VFL, with no participants with VFL having an exact replication of defects between perimeters. A notable lack of replication was also found in 90.32% of the controls.

Variability in defect location was driven by eccentricity, found in both those with VFL and the controls (p=0.002).

These results demonstrate that the EVFT has poor reproducibility in EES and defect location.

However, the variance in both, EES and location of defect, does not significantly impact on a persons fitness-to-drive status (p=0.454). With the current fitness-to-drive criteria, the EVFT is classed as a highly reproducible test.

Although fitness-to-drive classification is reproducible, it is however recommended that the EVFT is performed on the HFA to account for variance in EES and defect location between perimeters to avoid unnecessary difficulty to an already stressful examination.

6. The Reproducibility of the Ring of Sight Visual Field Screener.

Summary.

The ROS is a novel perimetry methodology delivered via a computer monitor which has yet to be validated against established perimetry methods. The primary aim of this study was to investigate the reproducibility of the ROS 24-2 FT in those with known disease against the HFA SITA Standard 24-2 (established method). Eighteen right eyes with known VFL (mean age 70.56; SD 10.13) and eighteen right eyes (mean age 68.75; SD 6.43) of age and gender matched controls were examined with both methods. There is no agreement between the sensitivity values of the ROS 24-2 FT and the HFA SITA Standard 24-2 examinations. The sensitivity values of the ROS FT program were consistently and significantly lower than the HFA (mean 7.07 dB) in those with VFL ($t(51)=13.998$; $p=<0.005$) and in the controls ($z=-6.275$; $p=<0.005$) (mean 10.74 dB). Differences increased at higher sensitivity values. There was increased variability in those with VFL compared to the controls which was driven by those with NFD. Bland and Altman plots found the bias for the controls to be furthest from zero than those with VFL establishing that the test has no validity. Peak (HFA: 29 dB; ROS: 21 dB) and range of sensitivity values (HFA: 0-39 dB; ROS: 0-30 dB) indicate that the HFA 24-2 SITA Standard has a greater dynamic range than the ROS FT. There is no agreement in defect depth and pointwise analysis demonstrated a significant difference ($z=-3.419$; $p=0.001$) between the ROS Error Greyscale and the HFA Probability Plot in those with VFL. There is lack of agreement in the MD between perimeters. ROC generated by plotting MD of the ROS against known defect established by the HFA generated an AUC of 0.681 providing poor sensitivity (0.647) and acceptable specificity (0.737) compared to that of the HFA (sensitivity: 0.824; specificity: 0.789). One third of the participants with VFL were unable to conduct the test due to being unable to distinguish the green moveable target that is used to indicate if the ROS stimulus has been seen. When employing the Hodapp-Parrish-Anderson (HPA) criteria (adapted) the ROS misses 66.67% of defective fields providing 33.33% sensitivity. Fixation is significantly ($z=-2.552$; $p=0.011$) better on the ROS in those with VFL, but there is no gain in the reduced time (6.67% faster) of the ROS examination in this cohort. Participant preferences did not establish a preference for either perimetry method overall. These results suggest that the ROS is not suitable for use for patients with reduced visual function. Furthermore, results indicate that the ROS is unable to identify individuals with and without defective fields and thus does not support the use of this perimeter in optometric practice.

6.1. Introduction.

An opportunity arose to evaluate a novel program for visual field testing, the Ring of Sight (ROS) which to date has not been investigated on patients.

VFL is an area where there is reduced sensitivity within the visual field. There are many conditions that can give rise to VFL which have been previously discussed in section 1.2. The importance of perimetry to assess visual function (Houston *et al*. 2010), locate the consequence (Miranda & Henson. 2008) and detection of disease (Swanson e*t al*. 2005), particularly in the case of glaucoma whereby the disease is symptomless until its later stages (Lowry *et al*. 2016) has been previously discussed in section 1.3. Perimetry is valuable in the detection of early glaucomatous loss to allow management and prevent further loss of sight (Heijl *et al*. 2012, Haley. 1993, Bergin. 2011, Brusini e*t al*. 2005, Bengtsson e*t al*. 1997) which is irreversible (Hatt e*t al*. 2007). Perimetry also enables clinicians to monitor those diagnosed with the condition and determine progression (Wroblewski *et al*. 2014, Swanson *et al*. 2014, Vesti *et al*. 2003). SAP is currently considered the gold standard for the testing of the visual field (Brusini e*t al*. 2005, Gedik e*t al*. 2007, Nouri-Mahdavi e*t al*. 2011). Although there is currently no official gold standard perimetry tool (McKendrick. 2005) the HFA is commonly considered the gold-standard investigative tool (Gedik e*t al*. 2007, Brouzas e*t al*. 2014, Tattersall et *al*. 2007) and has been previously discussed in section 1.4.1.

The HFA offers various test strategies including the SITA algorithm, The ROS test menu currently offers FT or ST strategies. These examination strategies have been previously discussed in section 1.6. Perimetry should not only be reliable but quick and easy to use (Artes *et al*. 2003). FT on SAP is a long and tiring test with durations of 15 minutes plus (Bengtsson *et al*. 1997) which makes it a source of visual fatigue (Wall *et al*. 2001) and in many cases has been replaced by the SITA algorithms (Artes *et al*. 2002) which were designed to have retest characteristics similar to, and as accurate as, FT testing (Turpin e*t al*. 2007, Bengtsson *et al*. 1997) with the added advantage of being faster (Betz-Stablein *et al*. 2013, Conway *et al*. 2014, Artes e*t al*. 2002, Wall e*t al*. 2001, McKendrick. 2005, Murray *et al*. 2009, Tattersall *et al*. 2007).

Other novel ways to examine visual fields effectively and with ease has been the focus of many researchers. Giving rise to alternative perimetry methods which have been previously discussed in section 1.6.4. Performing perimetry on a computer monitor can be desirable for reasons of reducing costs (Brunn-Jenson. 2011, Ong e*t al*. 2014), portability allows use in domicillary and hospital settings (Houston *et al*. 2010) and it can potentially allow more frequent testing due to accessibility (Lowry e*t al*. 2016).

6.1.1. Ring of Sight (ROS).

The ROS (Ibis Vision, Lanarkshire, U.K.) is a novel program for visual field testing. The ROS has yet to be established in clinical practice and has no known literature evaluating or validating its performance. To date the ROS has yet to be compared to gold standard visual field testing. The designer's rationale for the ROS was to produce a visual field screener that could be utilised for domicillary visits and be considered more pleasant for the patient to undertake. This therefore has the potential to allow more frequent examination for patients who find monitoring of their condition difficult due to scheduling conflicts and lack of transportation to the optometrist (Lowry *et al*. 2016). It is also anticipated that this will be a quicker test than other FT methodologies. The shorter duration should reduce fatigue which can negatively impact on test reliability. However, rapid thresholding strategies can impact on the precision of the result (Spry *et al*. 2003). The ROS includes a FT strategy within its test menu, providing a potentially more accurate method than ST. The combination would theoretically provide an accurate and reliable examination. The rationale behind the target chosen, the depth of stimulus used, and the presentation time is currently unobtainable and hence unknown. It was desired that the greyscale would be comparable to results produced by the HFA (Donaldson. 2016b, personal communication, 07 October). Current lack of validation is a limiting factor as to the marketing capability of the ROS. The grid design matches the HFA 24-2 grid and the ROS examines the same 52 locations as the HFA ignoring the blind spot. Figure 6-1 Illustrates the grid used for examination on the ROS.

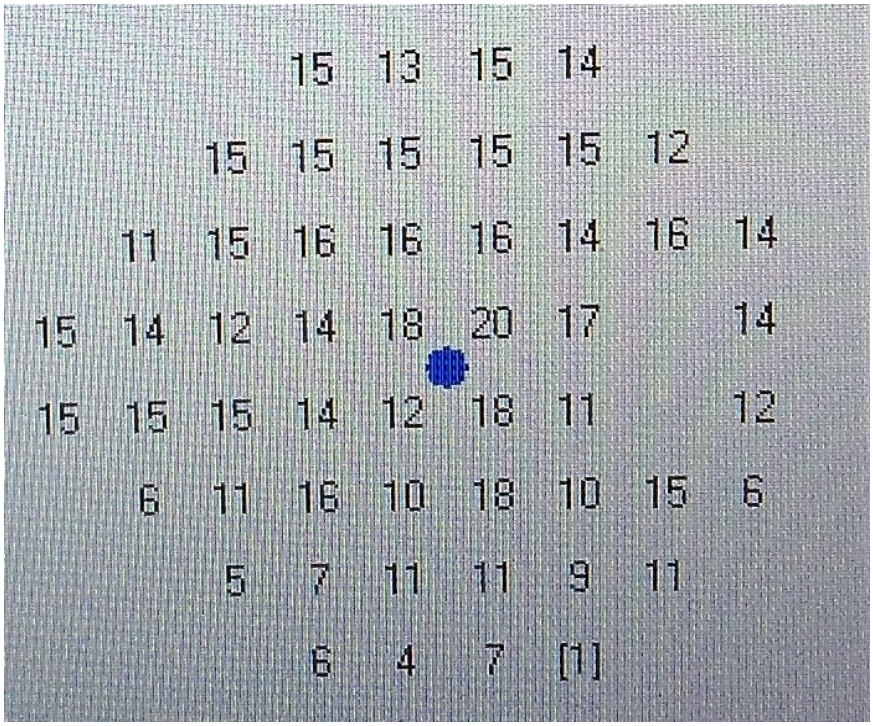


Figure 6-1. Image of the 24-2 grid utilised on the ROS FT visual field program.

The format of the ROS examination is significantly different to conventional bowl perimetry and differs in terms of ergonomics. It is a computer software program and the patient views the stimuli, based on the Digital Imaging Communications in Medicine (DICOM) greyscale on a monitor. Similar to the 3D computer-automated visual field test evaluated by Nazemi *et al* (2007) this examination varies the contrast by the alteration of greyscale target depth rather than altering the luminance of a bright target. The various depths of presenting contrast range from near white through to black. The stimulus presented is a circular target. When a new stimulus is detected the patient moves fixation to the new stimulus and then this becomes the new fixation point. Once indicated by the patient the target now acting as the fixation target acquires the addition of rotational 'wind-mill' arms that surround the circular target. Similar to the UFOV test, it requires the patient to identify this central target and to also identify the location of a peripheral target (Bentley *et al*. 2012). To inform the program the stimulus has been detected, the patient indicates this by having the task of moving a green circular target to the new stimulus via a Wacom electronic pen and pad. The threshold is measured at the moment the circular target has made contact with the stimulus on the display screen. Each greyscale level is shown for 0.1 seconds and the maximum timed average the ROS will present a stimulus is 9.94 seconds. It therefore has a range of approximately 100 different greyscale levels to present. The program determines the presenting level of greyscale to start the test with by presenting five

stimuli in various locations within the visual field. It uses the average greyscale level from this initial calibration as the level to present the stimuli to the patient. The program takes the patients reaction time, from the presentation of the stimulus to the moment they make the circular target contact the stimulus, into account when calculating the resultant threshold. The program records the patients reaction times to five stimuli presented at the maximum level of contrast the stimulus can obtain at the beginning of the program. It uses the mean average of these reaction times to correct the final threshold results. The examination only re-examines a visual field if the patient does not identify a stimulus at the pre-determined greyscale level obtained from the initial calibration during the test. If the patient does indicate they have seen all the stimuli at the pre-determined greyscale it was expecting, the program will only examine all the locations once. This calls into question whether the FT program is actually measuring the patients FT, or if the ROS is a screening test employing a retest.

Fixation is monitored subjectively by the clinician who informs the program if fixation is lost by pressing a space bar on a laptop. The ROS records the physical number of fixation losses, which is equal to the number of times the space bar is pressed, that have occurred during the test. Figure 6-2 illustrates the output of the ROS with a recorded fixation loss. Other examinations performed on computer monitors may be more advantageous by having eye tracking systems in place utilising an infrared camera to track the pupil (Lo *et al*. 2010).

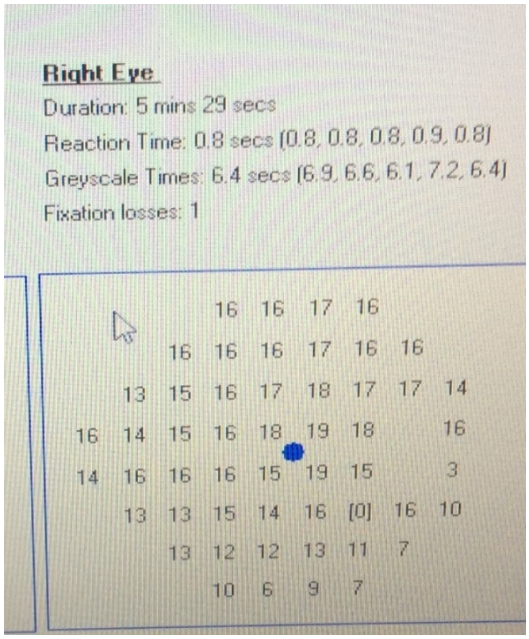


Figure 6-2. Output of the ROS showing the recording of the number of fixation losses.

The patient sits in a chair at 40 cm, which is measured from the monitor. Ergonomically the ROS may be advantageous to the patient in terms of comfort as there is no chin-rest or forehead rest. However, this may provide limitations in terms of no provision for accurate patient location throughout the examination which would be provided by a chin and forehead rest such as that used in the development of a laptop based perimetry program developed by the University Hospital, Rigshospitalet in Denmark (Brunn-Jensen. 2011). This may hinder the accuracy due to the test location of the participant only being measured at the beginning of the test. It is impossible to measure throughout the test with the current set-up. Varying distance equals varying angular subtense of the target at the eye. Movement of the participants head may alter position of the targets in the visual field and be a factor for variability. There is currently no guidance on the ambient room lighting for this visual field examination.

The test is conducted with habitual correction and the machine allows for distance or near to be used. The patient details section allows for this to be indicated but the examination does not appear to take this difference in correction into account. Those wearing distance correction may show a generalised reduction in visual field sensitivity unless adequate accommodation is possessed by the patient undergoing the examination.

The results of the visual field test can be stored on the computer and printed off as desired in-line with other conventional perimeters.

6.1.2. Digital Imaging Communications in Medicine (DICOM).

The ROS uses the DICOM greyscale for the presentation of the stimulus. DICOM is a greyscale standard commonly used in radiography. The standard commonly used is the DICOM part 14: Greyscale Standard Display Function. The purpose of this standard is to ensure images are harmonised with equal contrast sensitivity (NEMA. 2009) regardless of differing monitor luminance and settings. Most colour monitors have 3 colour channels, red, blue and green. When all these sub-pixels have the same input value grey is perceived. Different greyscales can be obtained by allowing a colour tint. This permits approx. 1,700-1,800 greyscale values (Sund *et al*. 2010). The presentation of the stimuli are of a constant size for the ROS but at differing contrast levels (Donaldson. 2016a, personal communication, 15 February).

6.1.3. Comparative Aspects of the HFA and ROS Perimeters.

The HFA print out assists the clinician interpreting the visual field result with the use of global indices Table 6-1 outlines these aspects with the ROS alternative and comparisons of other operative aspects.

6.1.4. Presentation Time.

The HFA and Henson perimeters both have a presentation time of 200 ms. The ROS has a variable presentation time with the target presented and contrast altered until the target is detected to determine the result of sensitivity. Contrast sensitivity increases with increased presentation time and becomes constant at higher luminance within a test field (Seim & Valberg. 2015). Presentation time therefore impacts upon the hill of vision profile (Haley. 1993). It is not known if an increase in participants contrast sensitivity, that is possible due to the variable presentation time, is taken into account within the final result on the ROS.

6.1.5. ROS and MD.

The ROS does not provide an MD statistic. The MD on the HFA is a weighted value and therefore the MD on the printout of the HFA cannot be compared to a calculated mean of deviation across the points for the ROS. However, it is possible to calculate the MD for both perimeters as the actual (true) mean of the deviations from the individual plots of both tests to enable comparative data.

	HFA Parameter	ROS Alternative	Meaning/comments
Operational characteristics	Lens holder and correction- calculated for working distance.	Habitual correction- whether distance vision or near vision noted.	
	Fixation monitor- stimulus presented within blind spot (Heijl-Krakau method). No response if fixation correct. Response if fixation incorrect. Allows a fraction of fixation losses out of the stimulus presented to be generated.	Fixation monitor- manual via camera. Noted with space bar. Fixation loss amount recorded.	
	Light stimulus projected onto bowl.	DICOM greyscale	The DICOM is commonly used in radiography. It ensures that images are harmonised under different monitor luminance settings.
	Dimmed ambient light.	Normal room lighting. No specific standard specified.	
	Presentation time 200 ms	Presentation time is variable depending upon when participant notices the target and indicates if seen by	

		movement of a Wacom pen to move the target to the stimulus. Average of the maximum possible presentation time is measured at 9.94 seconds.	
	Duration of test measured in minutes and seconds.	Measured in minutes and seconds.	
	Stimulus size is size III.	Measured as 6 mm.	
	Background luminance=31.5 asb.	Normal monitor background setting 300 cd/m^2 (942 asb).	
Reliability	False positive score.	No equivalent	A score generated by the amount of times a patient responds when no stimulus is presented.
	False negative score.	No equivalent	No response to a stimulus presented brighter than threshold already determined.
Analysis	Mean Deviation (MD).	Error scale plot (not calculated)	Indicates a generalised depression of the visual field/diffuse loss compared to a normal reference field.
	Pattern Standard Deviation (PSD).	No equivalent	Loss of sensitivity in localised areas/focal loss. A measure of the degree the shape of the patients measured field departs from the normal reference field.
	Total Deviation. (TD)	No equivalent	For each point of the visual field examined: The differences in dB between the age-matched population and the measured field.
	Pattern Deviation (PD) numeric and Probability Plot.	No equivalent	After adjustment for overall differences in height of the hill of vision; The differences in sensitivity from the normal population.
	Probability Plot.	Error greyscale	The chance of the loss in sensitivity occurring in <5, <2, <1 and <0.5% of the age-matched population. Presented as a scaled indicative plot with a key. For total deviation this probability is taken from the age matched norms. For pattern deviation this is taken from the age matched norms after adjustment for any overall shift in sensitivity (height of the hill of vision).
	Glaucoma Hemifield Test	No equivalent	Devised from STATPAC2 statistical package on the probability of glaucoma comparing results of aged matched normal and glaucomatous visual fields.

Table 6-1. Comparative aspects of the HFA and the ROS Perimeters.

6.1.6. Validating New Perimeters.

If a new instrument is proposed for the purposes of determining disease, confirming the absence of disease and determining progression to enable correct management of disease it will require high sensitivity and specificity. The consequence of incorrect diagnosis and management is loss of sight. If new stimuli are proposed it is difficult to ascertain if they will perform better than another test. Therefore, it is usually typical to compare new testing methodologies with those already existing (McKendrick *et al*. 2005) such as the HFA. It has been considered that to investigate glaucoma patients other machines can be used, but they should be validated against the HFA (Foster *et al*. 2002). No literature on the ROS being compared with other perimeters has been located. The HFA has been used to validate various perimeters and methodologies collated in table 1-2.

6.1.7. Incidental Factors Influencing the Differential Light Threshold.

There are many factors influencing the variability in perimetry which have been previously discussed in section 1.7. Visual field results are affected by noise. Defects in the visual field can only be established if they exceed the noise variability that is present in perimetry (Artes *et al*. 2003). It can be argued that to make a true assessment between different testing methodologies that noise should be eliminated by the use of a filter. This has not been considered for this study for the following reasons. It can be difficult to establish which filter to use, particularly with two different testing methodologies. Filters have been researched in glaucomatous patients (Bertz-Stablin *et al*. 2013, Schell *et al*. 2013, Deng *et al*. 2014) and a filter established to be clinically useful for glaucoma can result in the blurring out of neurological defects (Gardiner *et al*. 2004). The HFA uses double determination of the sensitivity at certain points in the visual field and this acts as a basic form of filtering, which is done in order to reduce variability. The SITA algorithm uses a semi-Baysian approach whereby the sensitivity is predicted at a point prior to the actual measurement (Gardiner. 2003). The ROS is not known to possess a strategy to correct for noise. Therefore, the two are likely to start from a different baseline of noise correction for comparison. It is also considered unlikely that a clinician will filter for noise other than the strategies already employed by the perimeter in ordinary optometric practice.

Variability is also increased in areas of lower sensitivity previously discussed in section 1.8.

Lapses in attention can increase variability and reduce sensitivity. It has been found that using a different methodology can decrease variability and increase sensitivity.

Using a multiple stimulus method has been found to achieve this whereby the reporting of the stimulus seen was verbal in terms of number of stimuli and it's location. It is considered that the fact the test may increase and maintain attention by this reporting of the stimuli may be the reason why the variability reduces. It must be noted that this study comparing single-stimulus automated perimetry with multiple stimuli automated perimetry in participants with glaucoma, did avoid presentation within areas that would have been considered damaged or close to the damaged areas, except for one area chosen within a known area of damage (Miranda & Henson. 2008). Areas of damage are areas that have been found to increase variability in visual field testing (Wall *et al*. 2008, Haley. 1993, Crabb *et al*. 1996, Henson *et al*. 2000, Wall *et al*. 1998, Turpin *et al*. 2007, Gardiner. 2003, Gardiner *et al*. 2006, Artes *et al*. 2003, Mouri-Mahdavi *et al*. 1997, Viswanathan *et al*. 1997, Birch *et al*. 1998, Heijl *et al*.2012, Heijl *et al*. 1989).

Although the ROS does not utilise self-reporting and neither is a statement required due to only one stimulus being presented, it does offer an alternative method for reporting stimuli seen other than pressing a response button. The participant does need to physically move the target over the seen stimuli. This may therefore enable attention to be held and hence reduce variability in results.

The background luminance of the HFA and the ROS differ. The impact of retinal illuminance and retinal adaption has been discussed previously in section 1.15.1. Contrast sensitivity is increased when retinal illumination is increased (Swanson *et al*. 2014). The monitor of the ROS provides a measured higher background luminance compared to the background of the HFA perimeter bowl. This may give rise to a higher sensitivity produced on the ROS.

Stimulus size impacts on perimetry and is previously discussed in 1.15.3. The ROS also has a larger measured stimulus which has the potential of providing a larger dynamic range and less variability (Wall *et al*. 2010, Gardiner e*t al*. 2006). In addition the effects of blur are also reduced, which can be up to 3D for targets larger than 0.43º (Fankhauser. 1979). In contrast, smaller stimuli have the ability to determine smaller defects (Kalloniatius & Khuu. 2016) and more severe loss (Phu *et al*. 2017).

6.2. Primary Aim.

This novel perimeter methodology has not been validated with existing methodologies in those with VFL. The primary aim of this study was to establish if this perimeter is comparable to established perimeters by determining the reproducibility of the ROS FT

examination to the HFA SITA Standard examination in those with VFL. Secondary aims have been previously outlined in section 2.2.4.

6.3. Methods.

6.3.1. Participants.

Participant recruitment and initial exclusion of data has been previously discussed in section 3.1. Of the 70 examination results attempted, a further 34 results were excluded for reasons outlined in table 6-2.

Reason for excluded test.

	Participant unable to see green target of ROS.	Test did not save.	Equipment failure/error on program.	Default to suprathreshold.	Unreliable test.
Number excluded.	10	2	1	1	20

Table 6-2. Excluded tests from data analysis.

6.3.2. Instrumentation.

The HFA was chosen for comparison. There is no gold standard for perimetry, but if new methodologies are being tested then they are required to be compared to those methodologies that are already in use. The program used was SITA Standard 24-2. This was chosen as it is a commonly used test in high street practice (Wall *et al*. 2010) and in many cases has replaced the FT test within clinical practice proving to be a faster test with similar accuracy to FT testing.

The 24-2 FT test on the ROS (Ibis Vision) was used. The 24-2 is currently the only visual field test grid available on the program. Details of the ROS has previously been provided in section 3.2.

6.3.3. Procedure.

The procedure has been previously outlined in section 3.3 and 6.1.1. Each visual field test varied upon duration between participants. The mean duration of the SITA

Standard 24-2 was 6.39 minutes for the study participants and 5.04 minutes for the control participants. The mean duration of the ROS examination was 5.59 minutes for the study participants and 3.96 minutes for the control participants.

6.3.4. Data analysis.

The primary analysis was to establish the agreement between the SITA 24-2 on the HFA and the FT on the ROS by establishing agreement in sensitivity in those with VFL and whether the HFA SITA 24-2 and ROS agreed on whether a defect was present or found not to be present. The ability for the ROS to discriminate between those who had known defects and those who were known to possess no defect was to be established. Secondary analysis was to evaluate participant experience on each perimeter. Data analysis has been previously outlined in section 3.4.

Pattern standard deviation was not compared due to there being no comparative data to compare on the ROS program or print out. Unweighted MD between perimeters was compared. However, it is considered that global measures are not a true indication of the depth of the visual field defect and therefore it becomes necessary to analyse the pointwise differences in sensitivity between the perimeters (Conway *et al*. 2014) which was also undertaken.

6.3.4.1. Defining defect.

Defect was defined with the use of the Hodapp-Parrish-Anderson (HPA) grading (appendix 8) which was adapted to consider one visit only. In addition, a cluster was not considered to only be defective if it arose in an area typical for glaucoma when considering participants with other conditions. A defect was considered to be present if there:

> 'Was a cluster of 3 or more non-edge points all of which were depressed on the pattern standard deviation plot at p=<5% level with one of which was depressed at a p=<1% level.
> Or a pattern standard deviation that occurs in <5% of normal fields.
> Glaucoma hemifield test was outside normal limits' (Hodapp-Parrish-Anderson criteria)

6.4. Results.

The study group presented with no unreliable test results for the right eye. Controls presented with 52.5% of unreliable test results for the right eye.

6.4.1. *Agreement. Sensitivity (dB).*

Figure 6-3 plots the mean sensitivity threshold values per location for the HFA and the ROS and illustrates the differences in mean sensitivity between the HFA and ROS for all study participants right eye (ranked in ascending HFA sensitivity (dB)).

Figure 6-4 plots the mean sensitivity threshold values per location for the HFA and the ROS and illustrates the differences in sensitivity between the HFA and ROS for all control participants right eye (ordered in increasing HFA sensitivity (dB)).

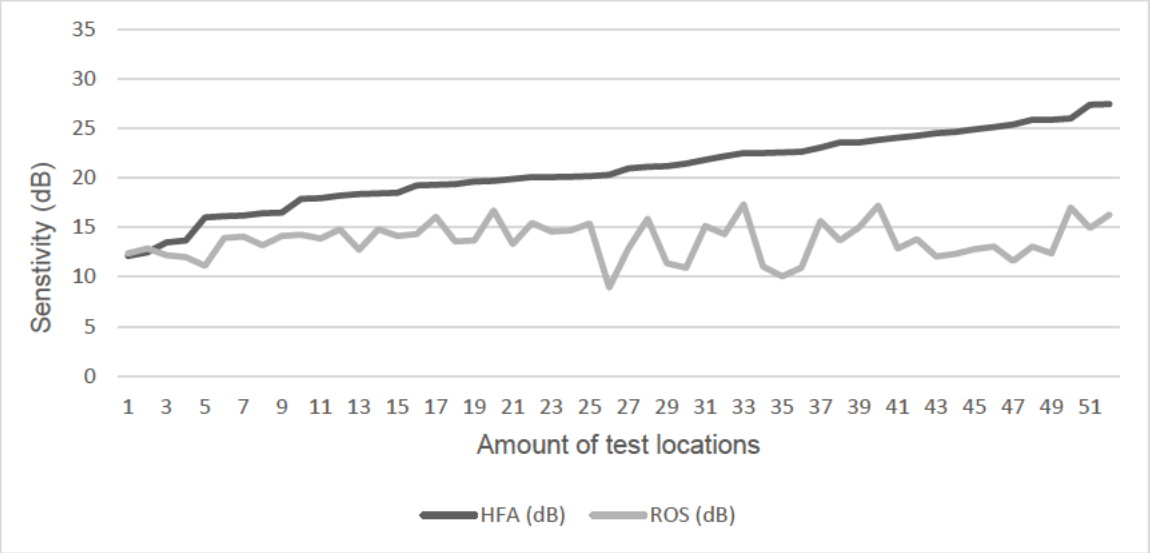


Figure 6-3. Mean differences in sensitivity (dB) per location for those with VFL. Plots of the average scores per location for the HFA and the ROS and illustrates the differences in sensitivity between the HFA and ROS for all study participants (ranked in ascending HFA sensitivity (dB)).

Inspections of figures 6-3 and 6-4 demonstrate that the ability of the ROS to show a range in sensitivity is poorer than the ability of the HFA. This may be due to the instrument being technically insensitive and/or the dynamic range of the ROS is poor.

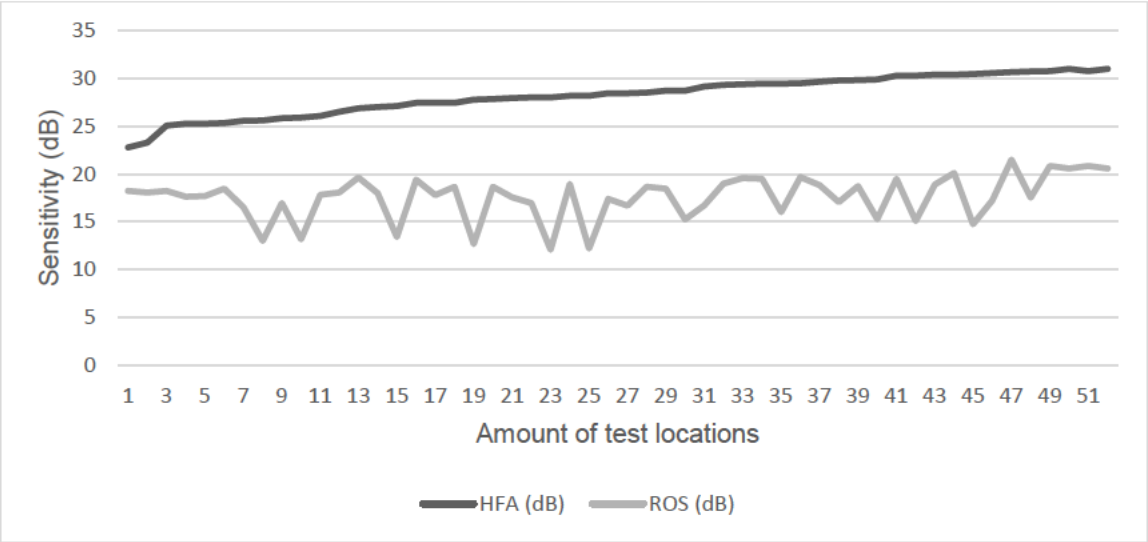


Figure 6-4. Mean differences in sensitivity (dB) per location for the controls. Plots of the average scores per location for the HFA and the ROS illustrates the differences in sensitivity between the HFA and ROS for all control participants (ranked in ascending HFA sensitivity (dB)).

Taking the HFA as the gold standard, on average the ROS sensitivity was lower than that recorded by the HFA by 7.07 dB for those with VFL. The difference in sensitivity ranged from -0.37 to 13.48 dB with the mean differences increasing for the higher HFA sensitivity values. For the controls the ROS sensitivity values also differed from the HFA, being lower by an average of 10.74 dB. With a range of 4.56 to 16.00 dB. The mean differences also increased for the higher HFA sensitivity values. The trend of ROS variance of sensitivity was more positive in the lower HFA sensitivity values with an increasing negative trend (decrease in sensitivity) as the HFA sensitivity value increased.

Figures 6-5 and 6-6 present the variance in sensitivity between perimeters. The thick vertical bars indicate the interquartile ranges. The thin vertical lines indicates minimum and maximum values (excluding outliers (dots)).

Figures 6-7 and 6-8 present the variance in sensitivity between perimeters with the division of the sensitivity values within centile subsets for participants with and without VFL respectively. Centile subsets are grouped into 0-9 dB, 10-19 dB, 20-29 dB and ≥30 dB.

Figure 6-9 presents the correlation in sensitivity values for each location between each perimeter for all participants Pearson's correlation coefficient between the two measurements (R^2=0.056) showed no correlation between measurements.

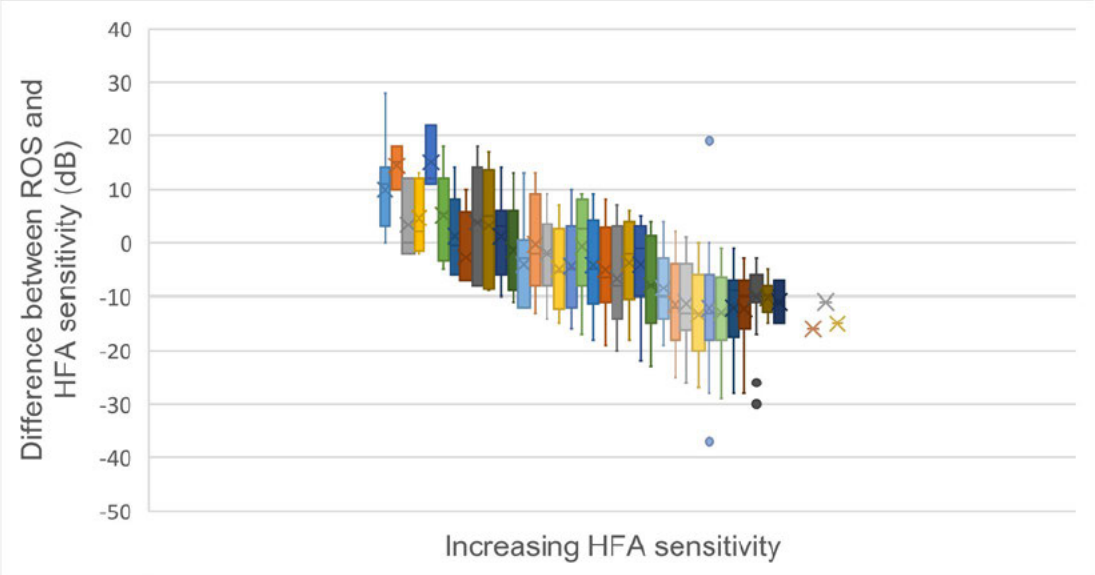


Figure 6-5. Variance in sensitivity between perimeters for participants with VFL. Comparing the HFA SITA standard and the ROS 24-2 FT. Values are the difference from the HFA threshold value. The thick vertical bars indicate the interquartile ranges. The thin vertical lines indicates maximum and minimum values. Outliers are represented as dots. Median indicated by thin horizontal line. Mean indicated by x.

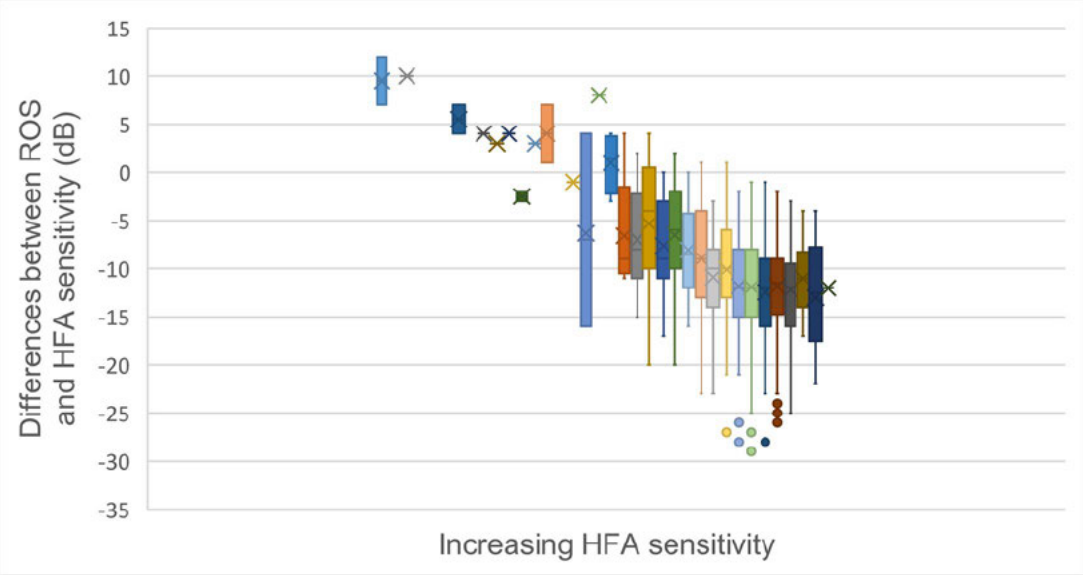


Figure 6-6. Variance in sensitivity between perimeters for control participants. Comparing the HFA SITA standard and the ROS 24-2 FT. Values are the difference from the HFA threshold value. The thick vertical bars indicate the interquartile ranges. The thin vertical lines indicates maximum and minimum values. Outliers are represented as dots. Median indicated by thin horizontal line. Mean indicated by x.

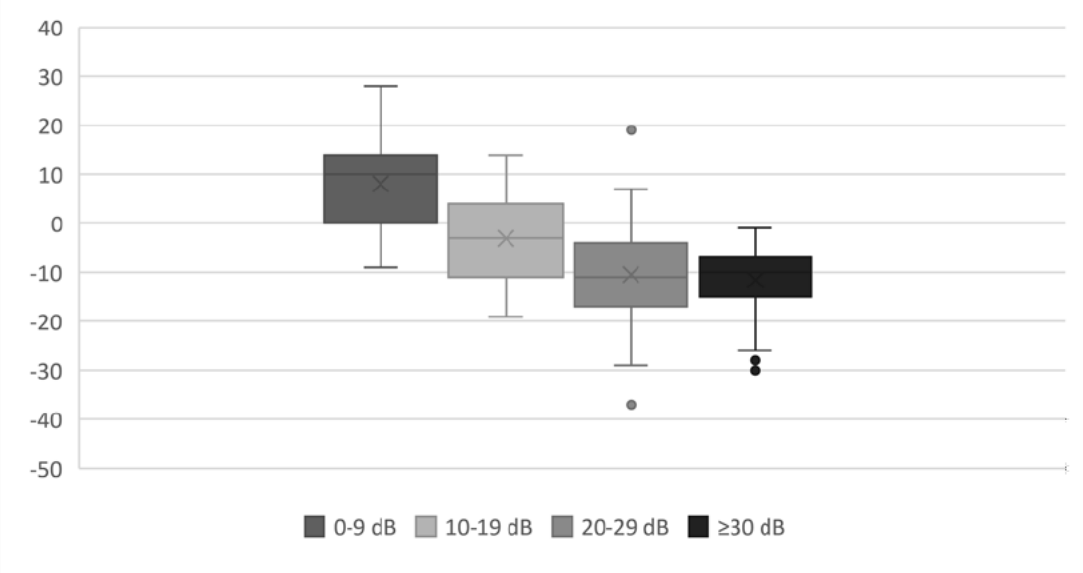


Figure 6-7. Variance in sensitivity between perimeters for participants with VFL presented in centile subsets. Sensitivity differences from HFA grouped into centile subsets of 0-9 dB, 10-19 dB, 20-29 dB and ≥30 dB. The thick vertical bars indicate the interquartile ranges. The thin vertical lines indicates maximum and minimum values. Outliers are represented as dots. Median indicated by thin horizontal line. Mean indicated by x.

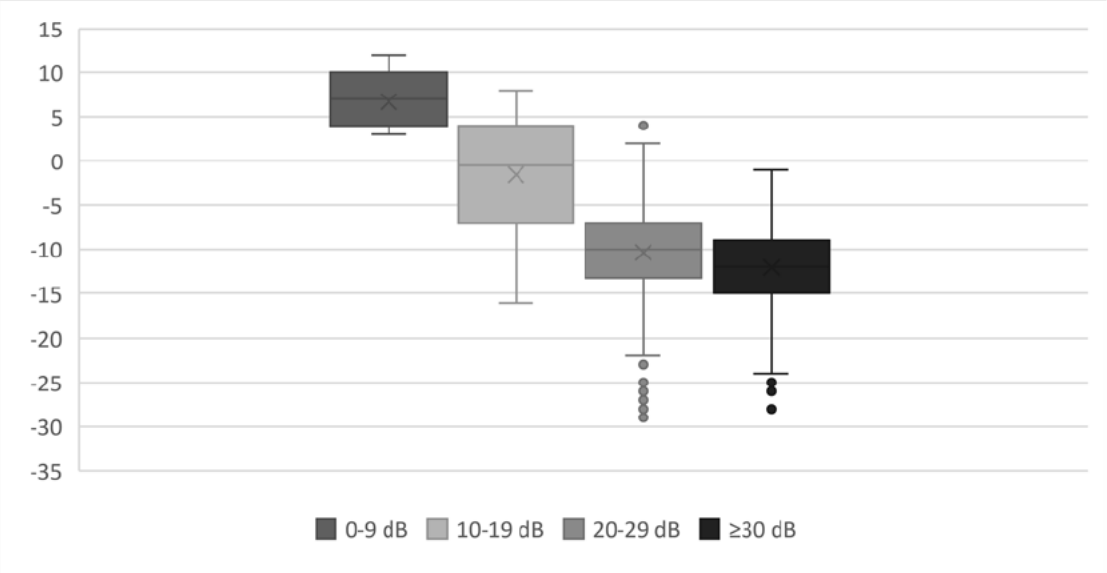


Figure 6-8. Variance in sensitivity between perimeters for control participants presented in centile subsets. Sensitivity differences from HFA grouped into centile subsets of 0-9 dB, 10-19 dB, 20-29 dB and ≥30 dB. The thick vertical bars indicate the interquartile ranges. The thin vertical lines indicates maximum and minimum values. Outliers are represented as dots. Median indicated by thin horizontal line. Mean indicated by x.

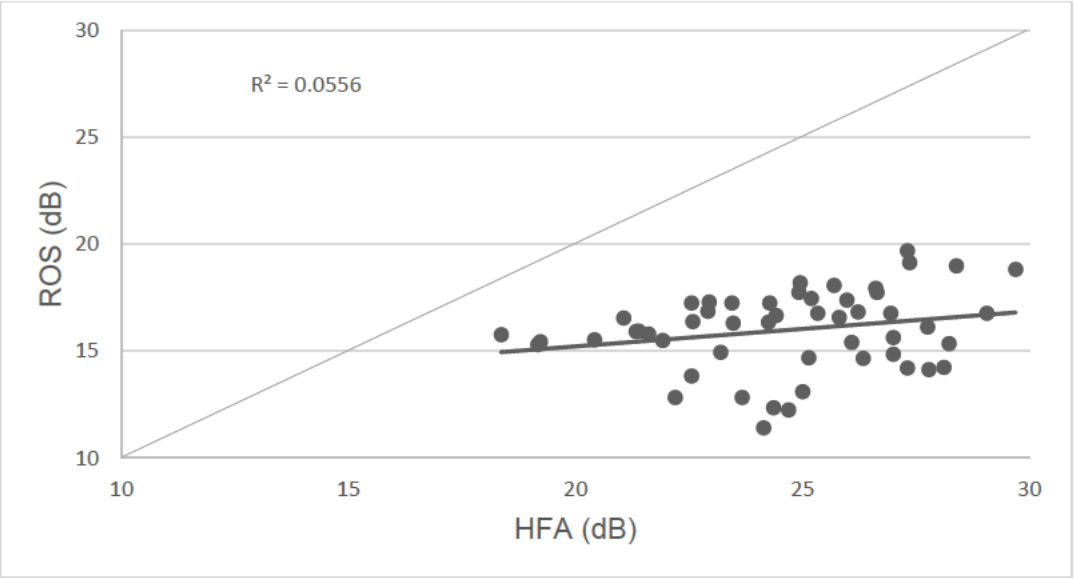


Figure 6-9. Correlation in mean sensitivity threshold values for each location between each perimeter. Data for all participants. Grey diagonal line indicates line of equality. Pearson's correlation coefficient (R^2) provided.

Figure 6-10 and figure 6-11 illustrates via Bland and Altman plots the agreement between sensitivity (dB) between the HFA and the ROS for each location for those with VFL and the controls respectively. Figure 6-12 and figure 6-13 illustrates via Bland and Altman plots the agreement between sensitivity (dB) between the HFA and the ROS for those with NFD and CFD respectively.

Taking the HFA as the gold standard, figure 6-14 and figure 6-15 presents the differences in sensitivity threshold (dB) for each test location for the ROS for those with VFL and for those without VFL respectively. Figure 6-16 and figure 6-17 presents the difference in sensitivity threshold (dB) for each test location possessed by the ROS for those with NFD and those with CFD.

Sensitivity values for study participants demonstrated normal distribution with the data from the HFA (SW(52)=0.984 p=0.712) and the ROS (SW(52)=0.990; p=0.939). Data from both perimeters had non-normal distribution for control participants (HFA: SW(52)=0.947; p=0.022. ROS: SW(52)=0.926; p=0.030). A paired samples t-test, one-tailed, confirmed a significant difference between the HFA and the ROS mean sensitivity values for each location (t(51)=13.998; p=<0.005; Upper CI=7.327; Lower CI=5.489) with the ROS sensitivity values (mean=14.78; SD=1.63; CV=11.00) being significantly lower than the HFA (mean=21.19: SD=3.52; CV=16.59) in those with VFL with a large effect size (d=1.94). A Wilcoxon signed rank test found a significant difference in sensitivity values between the HFA and ROS for control participants (z=-

6.275; p=<0.005) with ROS sensitivity values (median=28.44; IQR=26.61) being lower than HFA sensitivity values (median=18.00; IQR=0.89) with a large effect size (r=-0.87).

A Mann-Whitney U test confirmed that the study participants HFA sensitivity values were significantly lower (*U*=103.000; z=-8.120; p=<0.005) than that of the controls with a large effect size (n^2=-0.64). A Mann-Whitney U test confirmed that the ROS sensitivity values were also significantly lower in those with VFL (*U*=103.000; z=-5.718; p=<0.005) than that of the controls with a large effect size determined (n^2=-0.32).

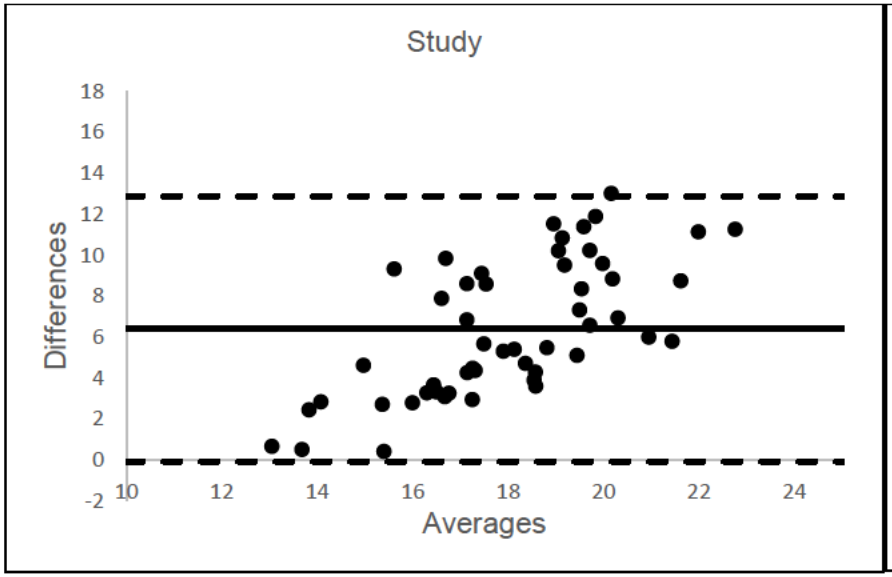


Figure 6-10. Bland and Altman plot.

The agreement of sensitivity (dB) between the HFA and the ROS for those with VFL. Solid line indicates mean test-retest difference and dashed lines indicates 95% limits of agreement.

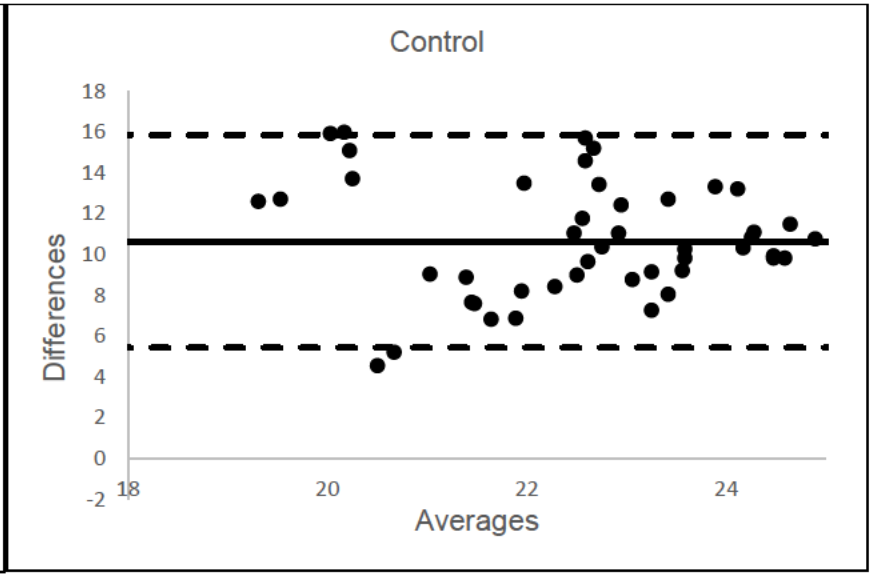


Figure 6-11. Bland and Altman plot.

The agreement of sensitivity (dB) between the HFA and the ROS for the controls. Solid line indicates mean test-retest difference and dashed lines indicates 95% limits of agreement.

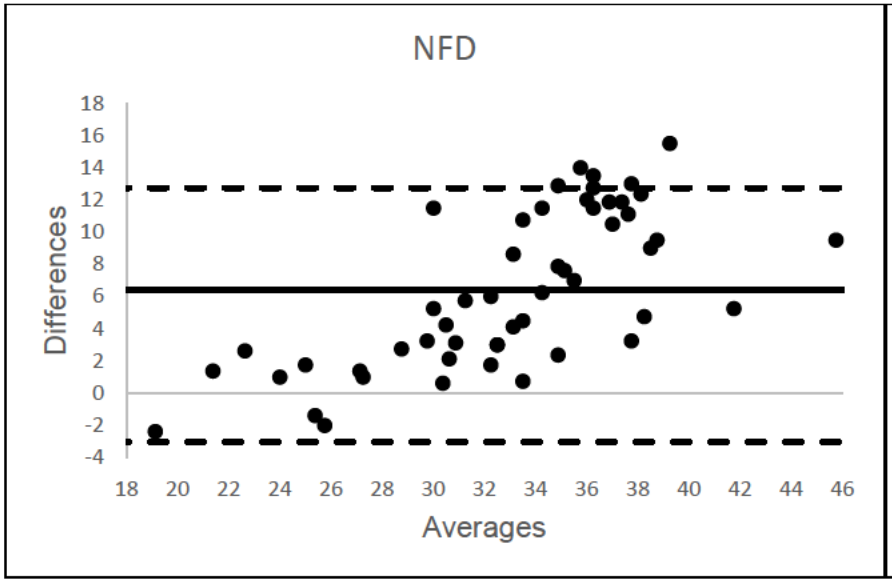


Figure 6-12. Bland and Altman plot.

The agreement of sensitivity (dB) between the HFA and the ROS for those with NFD. Solid line indicates mean test-retest difference and dashed lines indicate 95% limits of agreement.

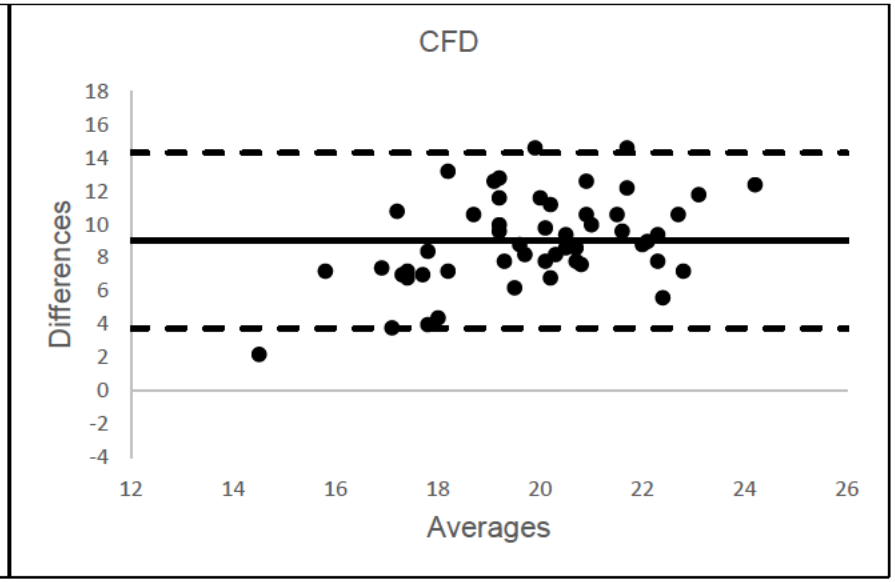


Figure 6-13. Bland and Altman plot.

The agreement of sensitivity (dB) between the HFA and the ROS for those with CFD. Solid line indicates mean test-retest difference and dashed lines indicate 95% limits of agreement.

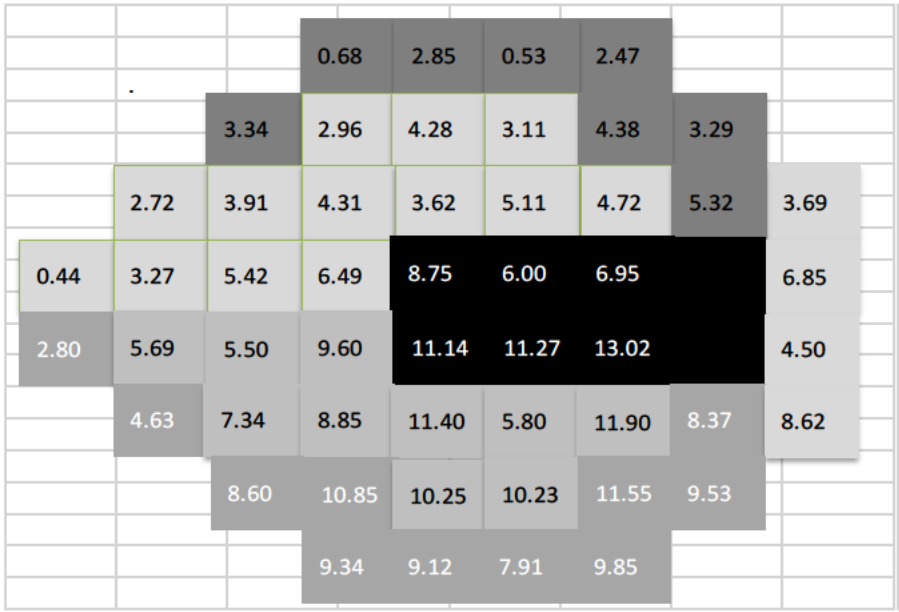


Figure 6-14. The mean sensitivity difference (dB) for each location possessed by the ROS when the HFA is taken as the gold standard in those with VFL. Positive value indicates recorded sensitivity threshold value lower than that of HFA recorded threshold. Areas of the same colour shade indicate areas that have the same retinal ganglion cell axon course within the retinal nerve fibre layer.

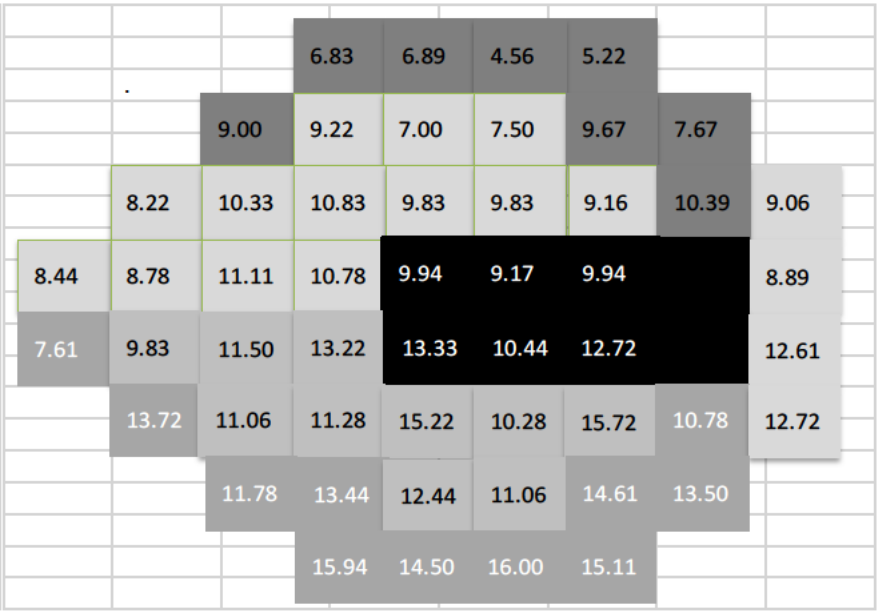


Figure 6-15. The mean sensitivity differences (dB) for each location possessed by the ROS when the HFA is taken as the gold standard in the controls. Positive value indicates recorded sensitivity threshold value lower than that of HFA recorded threshold. Areas of the same colour shade indicate areas that have the same retinal ganglion cell axon course within the retinal nerve fibre layer.

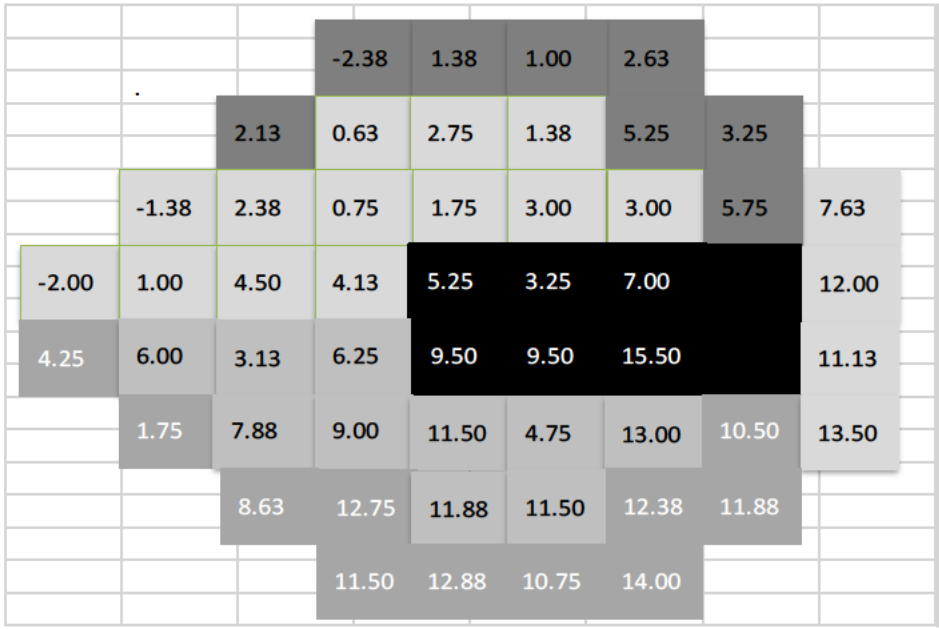


Figure 6-16. The mean sensitivity differences (dB) per location possessed by the ROS when the sensitivity of the HFA is taken as the gold standard in those with NFD. Positive value indicates recorded sensitivity threshold value lower than that of HFA recorded threshold. Areas of the same colour shade indicate areas that have the same retinal ganglion cell axon course within the retinal nerve fibre layer.

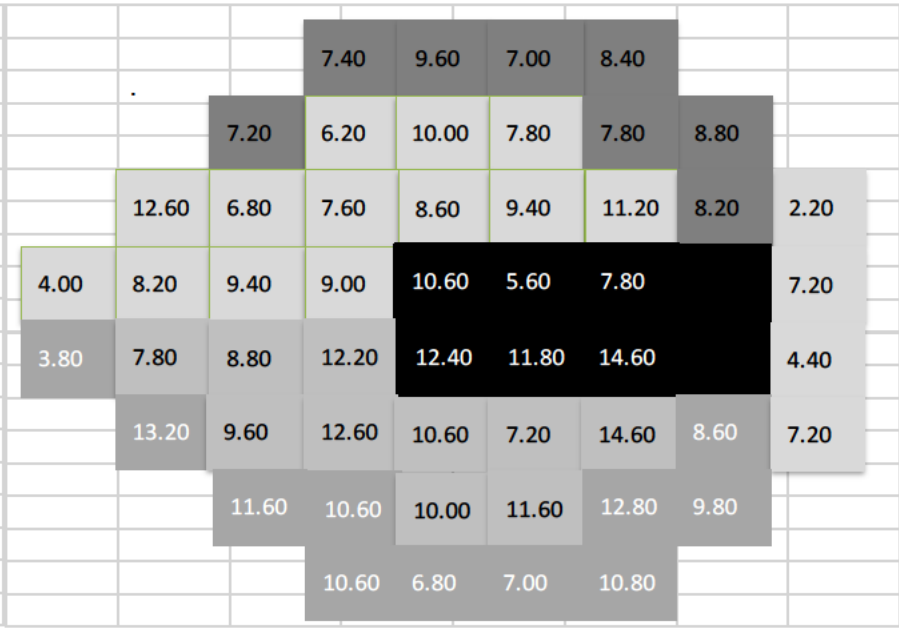


Figure 6-17. The mean sensitivity difference (dB) per location possessed by the ROS when the sensitivity of the HFA is taken as the gold standard in those with CFD. Positive value indicates recorded sensitivity threshold value lower than that of HFA recorded threshold. Areas of the same colour shade indicate areas that have the same retinal ganglion cell axon course within the retinal nerve fibre layer.

6.4.2. Zone Comparison. Sensitivity.

In a similar method employed by Conway *et al* (2014), The differences in sensitivity (dB) between each perimeter were separated into zones. Outer, middle and inner as shown in figure 6-18. This resulted in 18 stimulus locations within the inner zone, 14 within the middle zone (excluding the blind spot) and 20 within the outer zone.

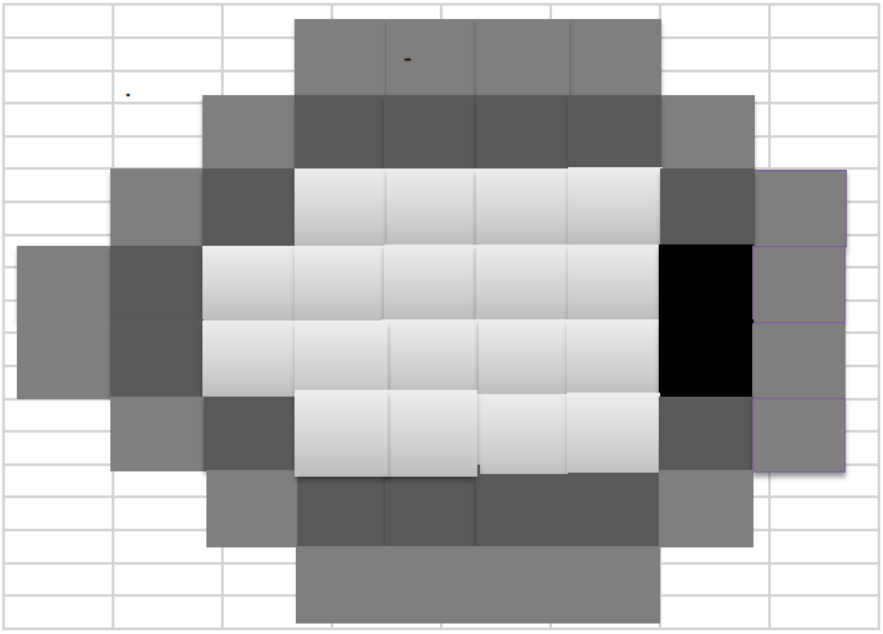


Figure 6-18. The visual field zones separated for comparison. Outer zone (grey), middle zone (dark grey) and inner zone (light grey). Black area indicates blind spot.

The outer zone difference values were found to have a non-normal distribution for the study pooled data (SW(20)=0.882; p=0.029). A normal distribution was shown for the control participants (SW(20)=0.932; p=0.166). The middle zone presented with a normal distribution for both those with VFL (SW(14)=0.880; p=0.059) and the controls (SW(14)=0.972; p=0.901). The inner zone also presented with normal distribution for those with VFL (SW(18)=0.915; p=0.107) and non-normal distribution was found for the controls (SW(18)=0.877; p=0.023).

A Kruskall-Wallis test determined a significant difference between zones for the difference between perimeters for those with VFL ($X^2(2)=7.350$; p=0.004; $w^2=0.14$). Post-hoc testing determined the difference (p=0.010) that gave rise to the significance to be between the outer (median=4.10; IQR=5.85) and inner zones (median=7.72; IQR=5.72). There was not a significant find between these zones and the middle zone (median=5.32; IQR=3.91). Bonferroni correction for multiple comparisons was considered to be p=0.017. In those with VFL the differences between the perimeters decreases with increasing eccentricity.

A Kruskall-Wallis test determined there was no significant difference between zones for the difference between perimeters for the controls ($X^2(2)=1.933$; $p=0.381$; $w^2=0.04$).

6.4.3. Dynamic Range.

The range of sensitivity values is presented in figure 6-19. Both perimeters provided recordings of their maximum stimulus brightness of 0 dB. The HFA maximum sensitivity and hence the dimmest stimulus recorded was 39 dB and the ROS recorded to 30 dB. The average peak sensitivity recorded for the HFA was 29 dB, whereas the ROS peaked at 21 dB.

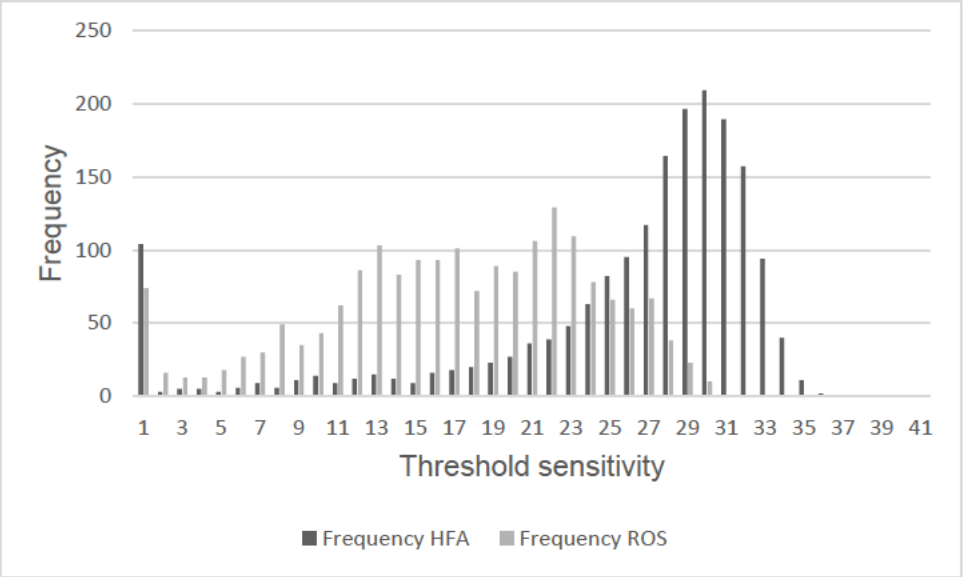


Figure 6-19. Frequency of sensitivity values (dB). Data for all participants.

For those with NFD (figure 6-20). The HFA gave a range of sensitivity values of 0-39 dB with a mean of 21.73 dB compared to the ROS range of 0-30 dB with a mean of 12.40 dB.

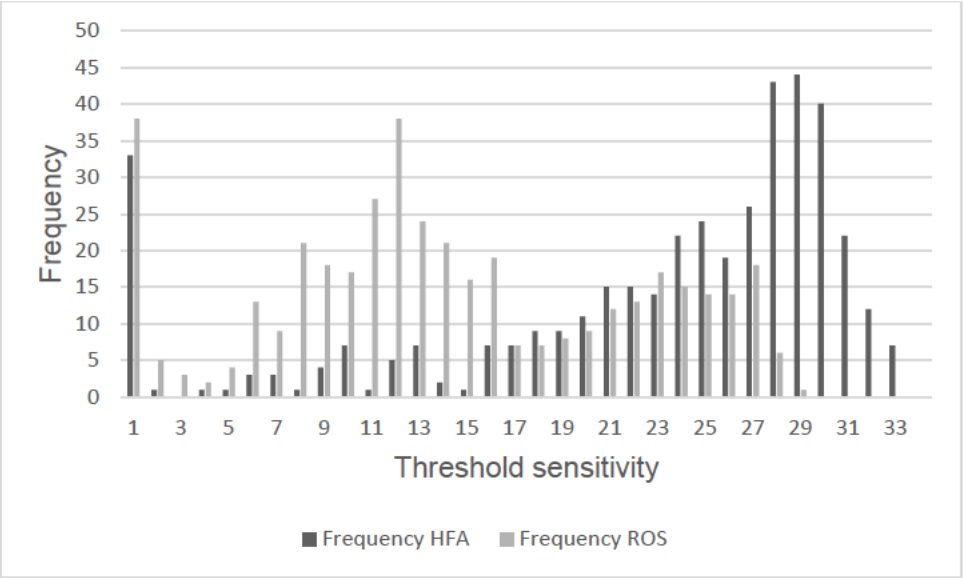


Figure 6-20. Frequency of sensitivity values (dB). Data for NFD participants. Data presented from both the ROS and the HFA.

Inspection of the figures 6-19 and 6-20 shows an apparent shift in mean sensitivity values between the two perimeters and indicates the ROS has less dynamic range than the HFA.

6.4.4. Greyscale. Defect Present/not present and Depth of Defect.

The numerical scoring to determine defect depth is outlined within section 3.4.1. The sum of the defect status was calculated for each participant, for each perimeter, in order to enable analysis of the assignment of defect and defect depth for each algorithm. Data calculated from the HFA for the study participants had normal distribution (SW(18)=0.901; p=0.061) and the data calculated from the ROS had non-normal distribution (SW(18)=0.805; p=0.002). Non-normal distributions were also found for the control participants for data calculated from both the HFA (SW(18)=0.802; p=0.002) and the ROS (SW(18)=0.864; p=0.014).

Figure 6-21 presents the calculated mean greyscale values per participant for the HFA and the corresponding ROS values for each participant for the study participants (left) and the normal control participants (right).

A Wilcoxon test found a statistically significant difference (z=-3.419; p=0.001) between the mean calculated greyscale values of the HFA (median=1.07; IQR=1.78) and the ROS (median=0.26; IQR=0.32) for the study participants with a large effect size (r=-0.81).

No statistical difference (z=-0.937; p=0.349) was found between the calculated greyscale mean values of the HFA (median=0.19; IQR=0.22) and the ROS (median=0.11; IQR=0.09) for control participants with a medium effect size (r=-0.22). Post hoc testing established power of 1-β=0.14 when α=0.05. Differences between the HFA and ROS greyscale mean per participant was also calculated for both study and control participants.

Figure 6-22 presents the variance of the greyscale values between study and control participants.

The differences between the HFA and ROS greyscale values were found to be of non-normal distribution for the control participants (SW(18)=0.859; p=0.012) and of normal distribution for the study participants (SW(18)=0.907; p=0.077).

A Mann-Whitney test established that there was a significant difference in the range of variance between the study and control participants (*U*=64.000; z=-3.103; p=0.002). With the range of variance being more extensive in the study participants (median=-1.62; IQR=-1.17) than that of the control (median=-0.05; IQR=0.24) participants with a large effect size (n^2=-0.52).

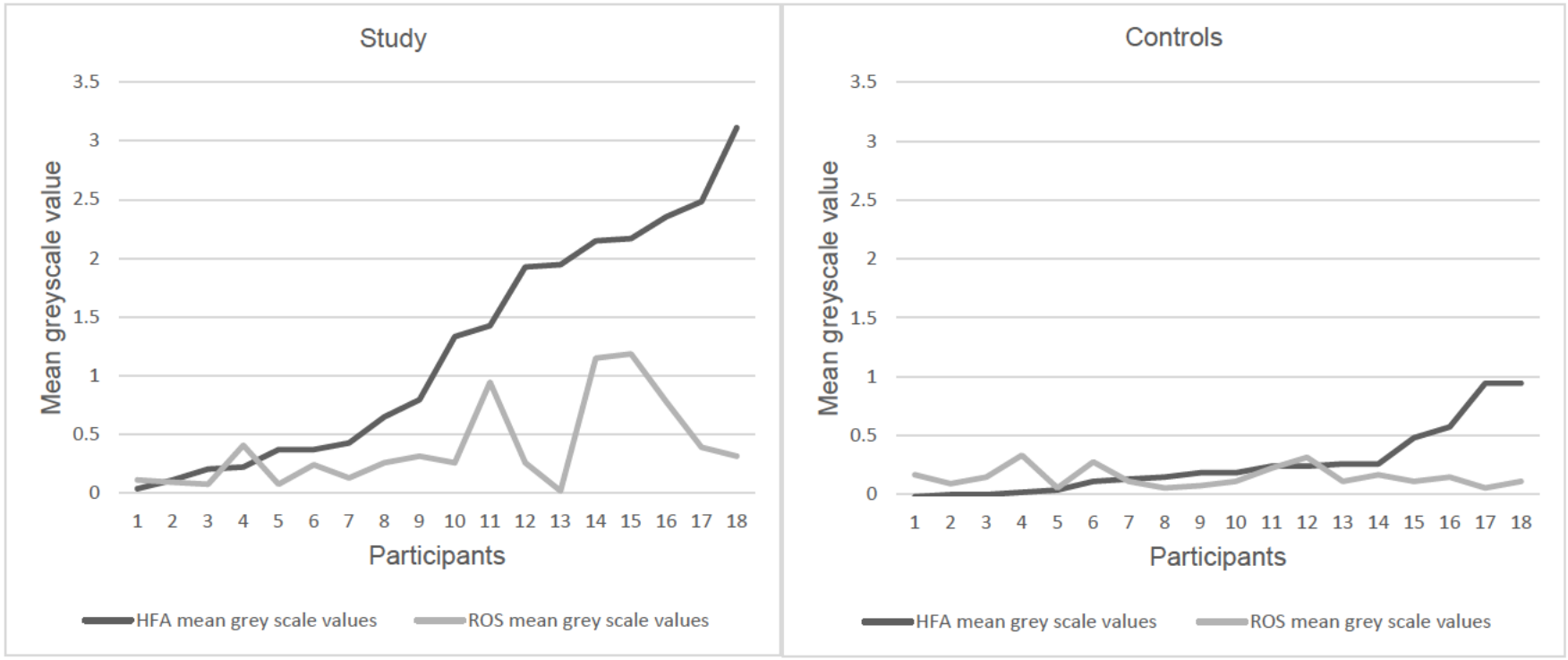


Figure 6-21. Calculated greyscale values between perimeters; within group. Mean calculated value per participant for the HFA and the corresponding ROS presented. Data for the VFL participants (left) and the control participants (right). Data ranked in ascending greyscale mean calculated values for the HFA.

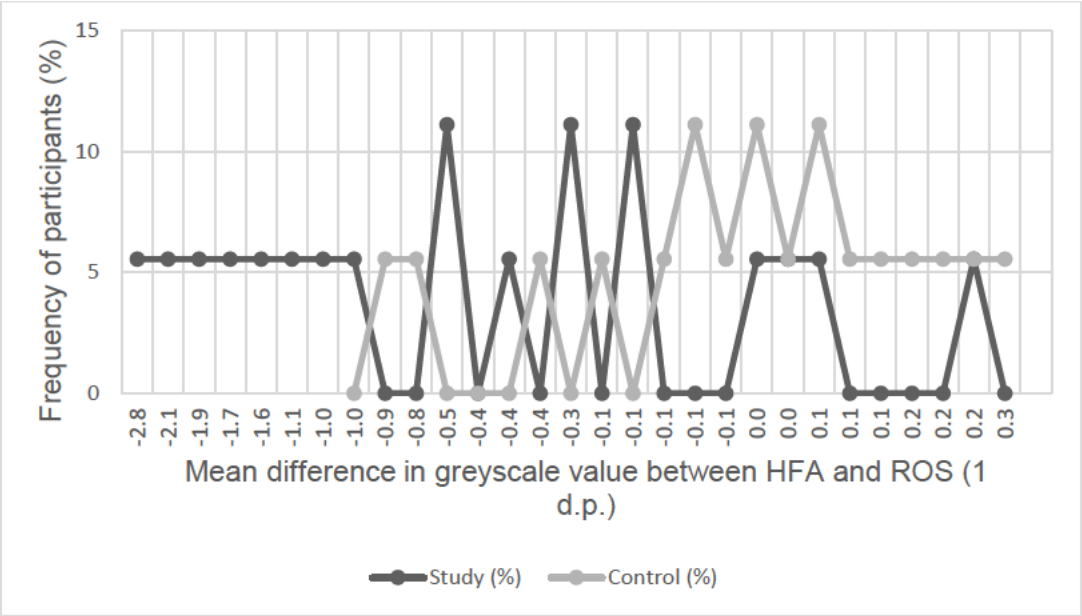


Figure 6-22. Variance of the greyscale mean values between the HFA and ROS. The difference in greyscale value (to 1 d.p). Data presented uses the greyscale value of the HFA as the reference. Data provides the values the ROS varied from the HFA plotted against the percentage of participants comparing the variance between VFL and control participants.

6.4.5. Pointwise. Greyscale.

Using the same scoring system previously explained within methods, the sum of the defect status was also calculated per location. The difference in each perimeters sum for the same participant was then calculated. The mean of the differences were then calculated and plotted.

Figure 6-23 presents the difference between the greyscale sums for the study participants per location. The HFA sum is used as the standard. Difference orientation (negative, positive) is that of the ROS difference. A positive change indicates the defect recorded by the ROS was less severe and a negative value would indicate the ROS recorded a more severe defect than the HFA.

A score of 4 indicates the maximum degree of change for each location between the HFA and ROS. A zero score means there was no change between tests.

A Shapiro-Wilks test established non-normal distribution of the data for the mean greyscale values for each location found on the HFA for study (SW(52)=0.942; p=0.014) and control (SW(52)=0.926; p=0.003) participants and non-normal

distribution for the mean greyscale values for each location found on the ROS for both study (SW(52)=0.839; p=<0.005) and control (SW(52)=0.744; p=<0.005) participants.

A Wilcoxon test found that there was a significant difference (z=-6.011; p=<0.005) between the greyscale values per location for the HFA (median=1.25; IQR=0.92) and the ROS (median=0.36; IQR=0.39) with a large effect size (r=-0.59) in those with VFL. There was also a significant difference (z=-2.599; p=0.009) found between the greyscale values per location between these two perimeters for the controls (HFA median=0.17; IQR=0.42: ROS median=0.03; IQR=0.22) with medium effect size (r=-0.25). Post hoc testing established power of 1-β=0.42 (α=0.05).

Results determine that the ROS records a less significant depth of the defect or misses defect for those participants with VFL.

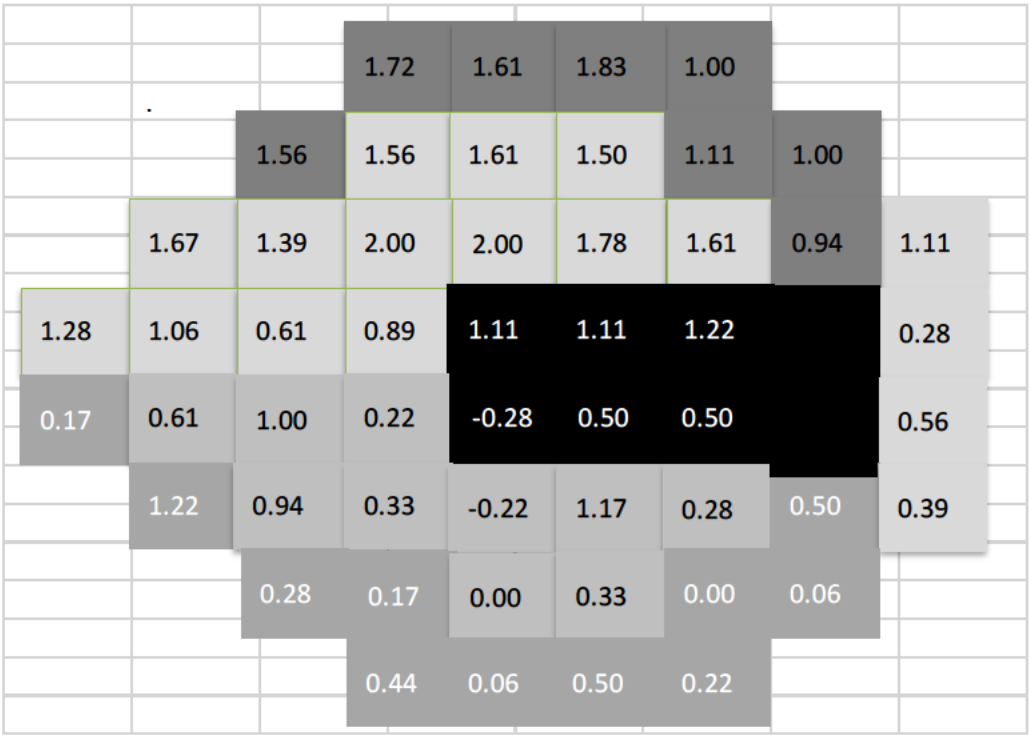


Figure 6-23. Difference between sums for the VFL participants per location. The HFA sum has been used as the standard. The difference orientation (negative, positive) is that of the ROS difference. A positive change indicates the defect recorded by the ROS was less severe and a negative value indicates the ROS recorded a more severe defect than the HFA.

A Sharpario-Wilks test found the data of the differences between perimeters of the greyscale scores, for each location, were normally distributed for both participants with VFL (SW(52)=0.958; p=0.066) and controls (SW(52)=0.965; p=0.134)

A Levene's test for homogeneity established there was a significant difference between the variance of data (F=33.376; p=<0.005) of the differences of the HFA and ROS values between study and control groups.

A one-tailed independent samples t-test with equal variances not assumed found there was a significant difference (t(77.531)=7.539; p=<0.005; Lower CI=0.542; upper CI=0.931) between the greyscale differences between the study (mean=0.86; SD=0.62; CV=72.66%) and control groups (mean=0.12; SD=0.33; CV=28%) with a large effect size (d=1.91).

The difference found between the greyscale scores for each location per perimeter is greater for the study participants than the control participants indicating that those with VFL have more variance.

6.4.6. Agreement. Defect/no Defect with HPA Grading.

Table 6-3 presents the agreement between tests when determining if the participant has a defect (2) or no defect (1) with the HFA 24-2 (test 1) and the ROS 24-2 (test 2) in those with VFL utilising the HPA grading (adapted).

Defect was defined with the use of the HPA grading. This was adapted to consider one visit only. A cluster was not limited to an area typical for glaucoma to allow consideration of participants with various conditions. A defect was considered to be present if there:

Was a cluster of 3 or more non-edge points all of which were depressed on the pattern deviation plot at a p=<5% level with one of which was depressed at a p=<1% level. Or; A PSD that occurs in <5% of normal fields (Hodapp-Parish-Anderson. 2014).

A kappa test showed no agreement (Kappa=0.182) between the tests for those with VFL (n=18) but this was not statistically significant (p=0.180).

Of the included participants with VFL, 8 were categorised as having NFD. Table 6-4 presents the agreement between tests when determining if the participant has a defect (2) or no defect (1) with the HFA 24-2 (test 1) and the ROS 24-2 (test 2) in those with NFD utilising the HPA grading (adapted).

A kappa test showed poor to fair agreement (Kappa=0.250) between the tests for those participants with NFD (n=8) but this was not of statistical significance (p=0.285)

ROS * HFA Crosstabulation					
			HFA		Total
			1.00	2.00	
ROS	1.00	Count	2.00	8.00	10.00
		Expected Count	1.10	8.90	10.00
	2.00	Count	0.00	8.00	8.00
		Expected Count	0.90	7.10	8.00
Total		Count	2.00	16.00	18.00
		Expected Count	2.00	16.00	18.00

Table 6-3. Agreement between tests when determining if the participant has a defect or no defect. Frequencies provided of visual fields presenting with defect (2) or no defect (1) with the HFA SITA 24-2 and the ROS FT 24-2 in those with VFL utilising the HPA grading (adapted).

ROS * HFA Crosstabulation					
			HFA		Total
			1.00	2.00	
ROS	1.00	Count	1.00	3.00	4.00
		Expected Count	0.50	3.50	4.00
	2.00	Count	0.00	4.00	4.00
		Expected Count	0.50	3.50	4.00
Total		Count	1.00	7.00	8.00
		Expected Count	1.00	7.00	8.00

Table 6-4. Agreement between tests when determining if the participant has a defect or no defect. **NFD.** Frequencies provided of visual fields presenting with defect (2) or no defect (1) with the HFA SITA 24-2 and the ROS FT 24-2 in those with NFD utilising the HPA grading (adapted).

Five of the participants with VFL were categorised as having CFD. Table 6-5 illustrates the agreement between tests when determining if the participant has a defect (2) or no

defect (1) with the HFA 24-2 (test 1) and the ROS 24-2 (test 2) in those with CFD utilising the HPA grading (adapted)

ROS * HFA Crosstabulation					
			HFA		Total
			1.00	2.00	
ROS	1.00	Count	1.00	2.00	3.00
		Expected Count	0.60	2.40	3.00
	2.00	Count	0.00	2.00	2.00
		Expected Count	0.40	1.60	2.00
Total		Count	1.00	4.00	5.00
		Expected Count	1.00	4.00	5.00

Table 6-5. Agreement between tests when determining if the participant has a defect or no defect. **CFD.** Frequencies provided of visual fields presenting with defect (2) or no defect (1) with the HFA SITA 24-2 and the ROS FT 24-2 in those with CFD utilising the HPA grading (adapted).

ROS * HFA Crosstabulation					
			HFA		Total
			1.00	2.00	
ROS	1.00	Count	10.00	8.00	18.00
		Expected Count	10.00	8.00	18.00
Total		Count	10.00	8.00	18.00
		Expected Count	10.00	8.00	18.00

Table 6-6. Agreement between tests when determining if the participant has a defect or no defect. Controls. Frequencies provided of visual fields presenting with defect (2) or no defect (1) with the HFA SITA 24-2 and the ROS FT 24-2 for the controls utilising the HPA grading (adapted).

A kappa test showed fair agreement (Kappa=0.286), but no significance (p=0.361) between the tests for those participants with CFD (n=5).

Table 6-6 illustrates the agreement between tests when determining if the participant has a defect (2) or no defect (1) with the HFA 24-2 (test 1) and the ROS 24-2 (test 2) for the controls utilising the HPA grading (adapted).

A kappa test showed no agreement could be computed (Kappa=0.000) as the ROS had a constant of 1 (no defect) and hence, led to no significance (p=1.000) between the tests for the controls (n=18).

6.4.6.1. Sensitivity and specificity.

The reference standard used was whether an eye was diagnosed with a defect or without a defect with the HPA grading using the SITA Standard 24-2 examined on the HFA.

Reference standard: SITA standard 24-2 + HPA scale		Defect	No defect
ROS	**Positive result (defect)**	8	0
ROS	**Negative result (no defect)**	16	12

Table 6-7. Sensitivity and specificity of the ROS. Showing true positive, false positive, true negative and false negative of the ROS. Reference standard for decision of defect or no defect is the HPA glaucoma scale used to assess the visual fields on the SITA Standard 24-2 performed on the HFA.

ROS Sensitivity=8/(8+16)=33.33%. Eqn. 9.

ROS Specificity=12/(12+0)=100% Eqn. 10.

These results indicate that the ROS is not a sensitive examination and would miss 66.67% of visual field defects.

Results inform that the ROS possesses poor agreement with the HFA when determining when a field is defective.

6.4.7. Mean Deviation.

Figure 6-24 presents the correlation of the unweighted MD for each perimeter.

The unweighted MD was calculated for all participants (procedure outlined within chapter 3). The unweighted MD HFA values for all participants had non-normal

distribution (SW(36)=0.726; p=<0.005) as was the unweighted MD ROS values for all participants (SW(36)=0.837; p=<0.005).

Spearman's correlation coefficient found a fair (r_s= 0.526; p=0.001) correlation between the unweighted MD between perimeters (data from all participants).

A Wilcoxon test found that there was a significant difference between the unweighted MD (z=-3.095; p=0.002) between perimeters with the ROS unweighted MD being significantly higher (closer to zero) than the HFA unweighted MD with a large effect size (r=-0.51).

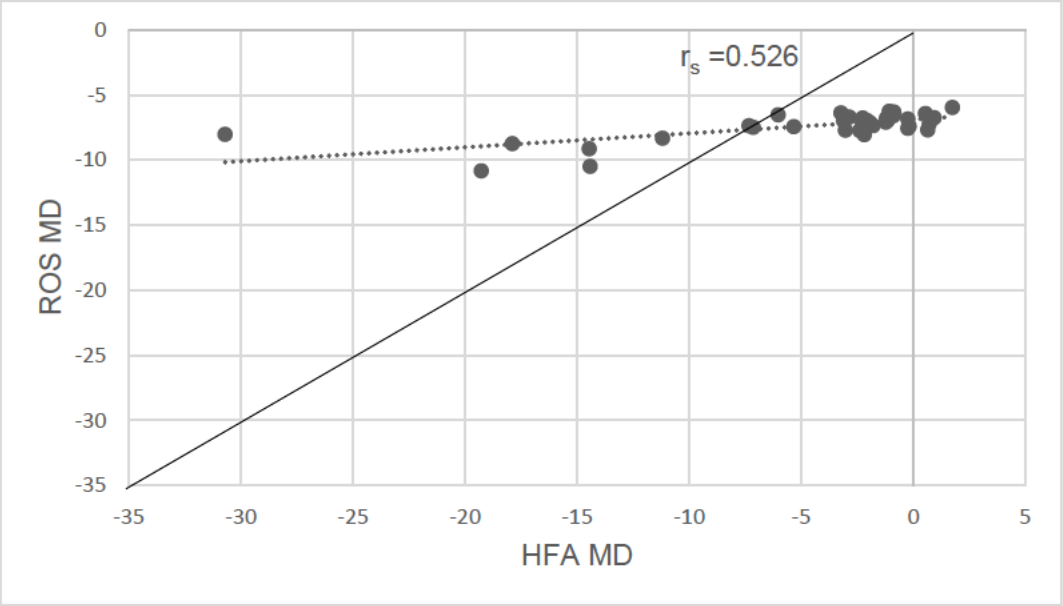


Figure 6-24. Correlation of the unweighted MD for each perimeter. Data for all participants. HFA MD= unweighted mean deviation calculated from the SITA Standard 24-2 visual field plots. ROS MD= unweighted mean deviation calculated on the ROS FT 24-2 visual field plots. Spearman's correlation coefficient shown ((rho) r_s). Diagonal grey line represents line of equality.

Out of the 36 participant's 91.67% had a change in unweighted MD of -2 dB or more between perimeters. Of these 18.89% had a higher (closer to zero) score on the ROS and a lower (further from zero) on the HFA. The other 81.11% had a lower (closer to zero) score on the HFA and a higher (further from zero) on the ROS.

For the scores on the HFA more negative than approximately -8 dB, the ROS provides a lower (closer to zero) unweighted MD. HFA unweighted MD between approximately -8 to -6 dB had a corresponding ROS unweighted MD of less than -2 dB variation.

Unweighted HFA MD scores of approximately -5 dB and more positive than this had a corresponding unweighted MD that is more negative in value.

Plotting the unweighted MD as the test variable against the true positive rate and the false positive rate for the ROS, Receiver operator characteristics (ROC) (figure 6-25) provided an area under the curve (AUC) of 0.202 (SE=0.118; CI lower band=0.000, upper band=0.434) and found to be statistically significant (p=0.008). The more negative the value of the unweighted MD the more positive (defect present) the test result is likely to be. The AUC value informs that this test is considered to have no value.

Plotting the unweighted MD as the test variable against the true positive rate and the false positive rate for the HFA, ROC (figure 6-26) provided an AUC of 0.873 (SE=0.057; CI lower band=0.761, upper band=0.985) and is statistically significant (p=<0.005). The more negative the value of the unweighted MD the more positive (defect present) the test result is likely to be. Using a cut-off of -2.13 for the unweighted MD provides sensitivity of 0.824 and specificity of 1-0.211=0.789. Meaning that if an unweighted MD value is less (more negative) than -2.13 the patient is more likely to have disease and less likely above this value.

Taking the HFA as the gold standard. Plotting the unweighted MD as the ROS test variable against the defect and no defect results for the participants ascertained by the HFA, ROC (figure 6-27) provided an AUC of 0.681 (SE=0.097; CI lower band=0.492, upper band=0.871) and was not statistically significant (p=0.064). The unweighted MD of the ROS does not relate well to any positive results of possessing a defect as found by the HFA for the same participant. If requiring good sensitivity of 0.824 the cut-off of the unweighted MD provides a value of -6.62 and allows a specificity of 1-0.789=0.211. If requiring good specificity of 1-0.211=0.789 the cut-off of the unweighted MD is -7.40 providing a sensitivity of 0.588. Looking at the values along the plateau of the curve commencing at the upper right hand corner the cut-off that provides the best balance between sensitivity and specificity is -7.28 providing a sensitivity of 0.647 and specificity of 1-0.263=0.737. However, these findings were found not to be statistically significant.

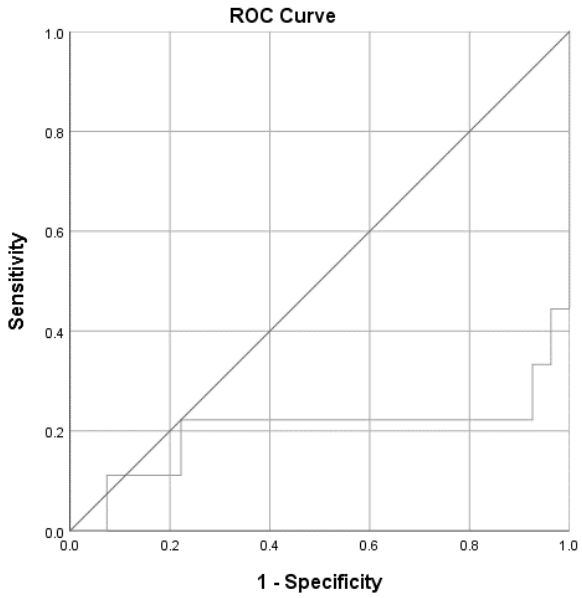


Figure 6-25. ROS unweighted MD plotted as the test variable against the true positive rate and the false positive rate provided by the ROS. AUC = 0.202. Standard error=0.118; confidence interval lower band=0.000, upper band=0.434.

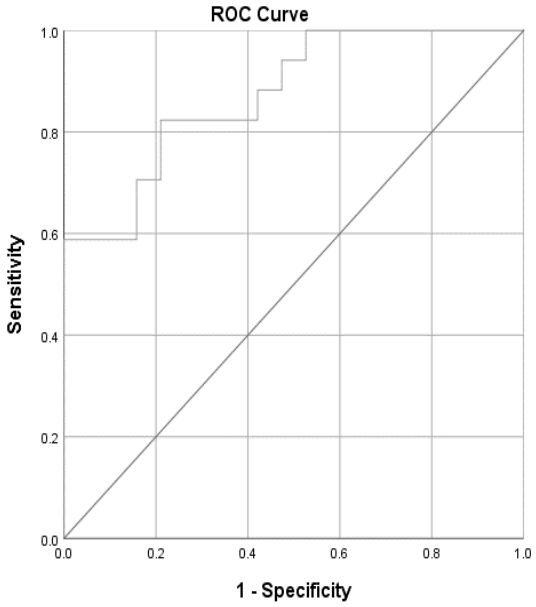


Figure 6-26. HFA SITA Standard 24-2 unweighted MD plotted as the test variable against the true positive rate and the false positive rate provided by the HFA. AUC=0.873. Standard error=0.057; confidence interval lower band=0.761, upper band=0.985.

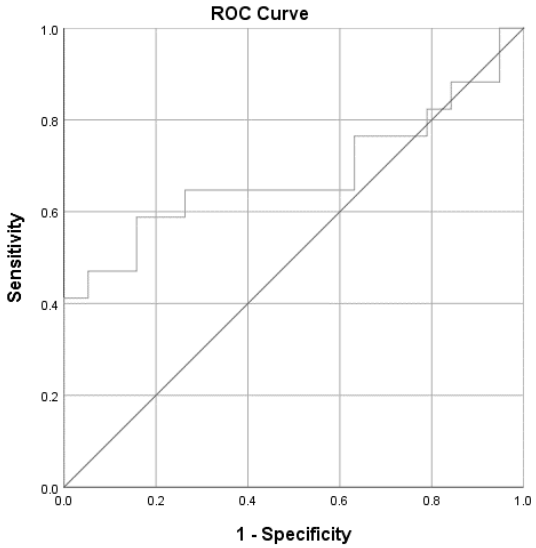


Figure 6-27. ROS unweighted MD plotted as the test variable against the true positive rate and the false positive rate provided by the HFA. AUC=0.681. Standard error=0.097; confidence interval lower band=0.492, upper band=0.871. Sensitivity=0.647 and specificity=0.737 when cut-off=-7.275.

The unweighted MD for the ROS is plotted to show the values for those participants who are known to be defective and those who are known to be normal (figure 6-28). The vertical line establishes the cut-off whereby a score below this would indicate a defective field. The area of uncertainty is established. No cut-off to establish a score that would indicate normal can be located.

There is a wide area of uncertainty whereby a field could be determined as either normal or defective. The only area of certainty that can be established is for a cut-off of an unweighted MD lower than -8.00 dB, whereby it would determine that a visual field is defective. There is no unweighted MD score that would allow a confident establishment of normal.

Results of the low AUC and sensitivity produced by the ROS demonstrates this examination would be unable to determine defective fields with the same accuracy as the HFA.

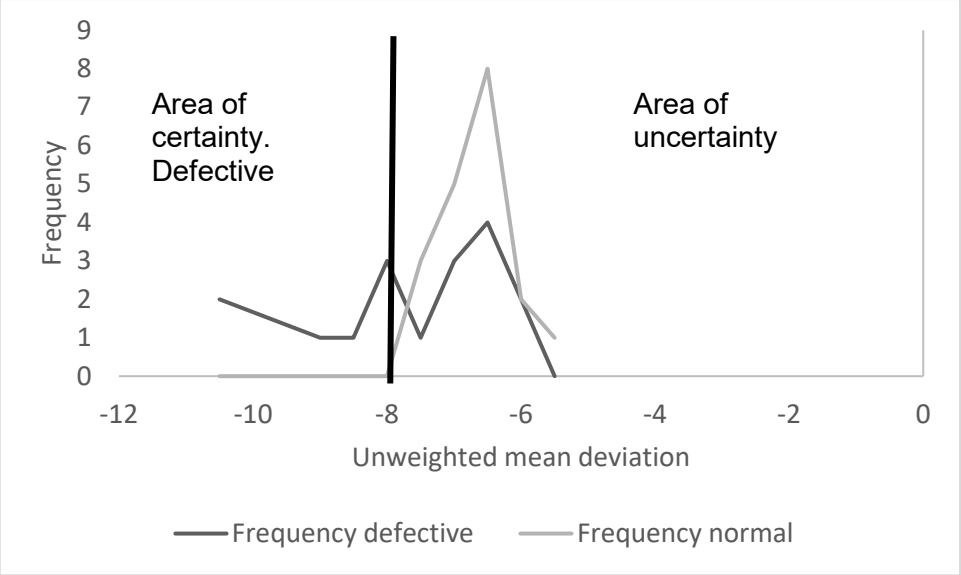


Figure 6-28. Frequency of unweighted ROS MD value for both known defective and known normal visual fields. Vertical line shows the demarcation between certainty of defect and area of uncertainty. No area of certainty of not defective can be established.

6.4.8. Fixation Losses.

The ROS does not provide a number of catch trials but provides a count of fixation losses and hence, does not enable a percentage to be ascertained in the same way the HFA provides. The HFA provides a fraction determined by how many checks on fixation occurred that fixation was actually lost, this can then be transcribed into a percentage. To enable the data to be comparative the ROS counts were divided by the mean of the HFA checks in order to provide a percentage for ROS fixation loses.
The data for the percentage of fixation losses were not normally distributed for either the study group HFA data (SW(18)=0.838; p=0.006) and the ROS data (SW(18)=0.543; p=<0.005). The data for the control group were also of non-normal distribution for both the HFA (SW(28)=0.497; p=<0.005) and ROS (SW(28)=0.497; p=<0.005).

Figure 6-29 presents the fixation losses on both perimeters for the study participants and the controls.

Figure 6-30 presents the percentage of study and control participants and their fixation losses (%) encountered on the HFA and the ROS comparing the two cohorts.

Participants considered to have good fixation for the HFA amounted to 39.29% and for the ROS this figure was established as 82.14%.

A Wilcoxon signed rank test found there was a significant difference in fixation losses between each perimeter (Z=-2.552; p=0.011) in those with VFL. With the ROS (median=0.000; IQR: 0.000) having significantly less fixation losses than the HFA (median=10.000; IQR=38.889). A medium effect size was established (r=-0.43). There was also a significant difference in fixation losses between each perimeter (Z=-3.529; p=<0.005) in the controls. With the ROS (median=0.000; IQR=14.286) also having significantly less fixation losses than the HFA (median=11.665; IQR=75.00) with a large effect size (r=-0.47).

A Mann-Whitney test found that there was no significant difference in the percentage of fixation losses on the HFA (*U*=222.000; Z=-0.680; p=0.496) or on the ROS (*U*=204.000; Z=-1.274; p=0.203) between the study and control participants with small (HFA: n^2=-0.10; ROS: n^2=-0.19) effect sizes. Post hoc testing established power of 1-β=0.09 and 1-β=0.15 respectively when α=0.05.

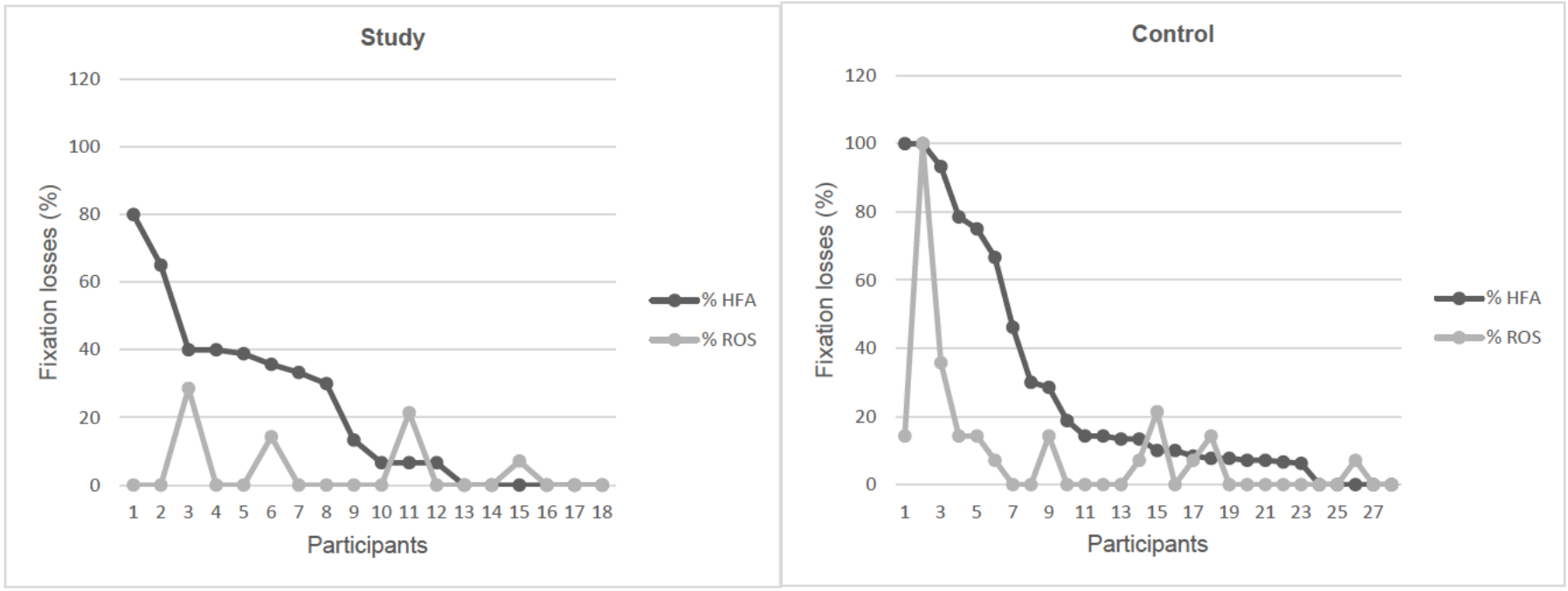


Figure 6-29. Fixation losses on each perimeter. Frequency of fixation losses shown in percentages for each participant. Comparing fixation losses calculated on the ROS and those recorded on the HFA. Fixation losses shown for the VFL participants (n=18) (left) and the controls (n=28) (right). Data ranked in descending order of fixation losses recorded on the HFA.

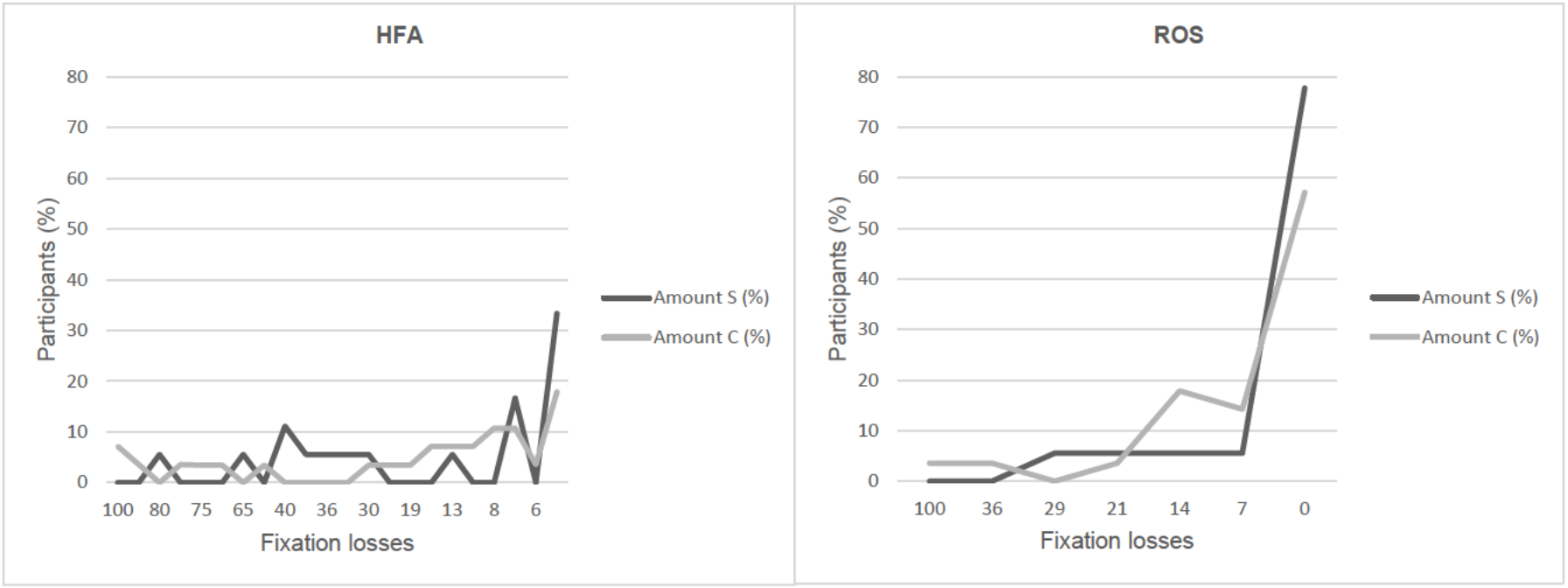


Figure 6-30. Fixation losses on the HFA (left) and ROS (right). Comparing the amount of fixation losses (%) for the VFL participants and for the control participants on each perimeter. S= study VFL participants. C= control participants.

6.4.9. Duration.

The distribution of the duration of the visual field tests were of non-normal distribution for the HFA (SW(18)=0.881; p=0.027) and for the ROS (SW(18)=0.878; p=0.024) for those with VFL and for the controls on the ROS perimeter (SW(18)=0.812; p=0.002), and found to be normally distributed on the HFA (SW(18)=0.927; p=0.171) for the controls. Data were normally distributed for NFD (HFA: SW(8)=0.935 p=0.563; ROS:SW(8)=0.841; p=0.077) and CFD participants for the HFA (SW(5)=0.848; p=0.189) and ROS (SW(5)=0.885; p=0.331)

Figure 6-31 presents the duration of each test for each of the study participants (top left), for each of the control participants (top right), for each of the participants with NFD (bottom left) and for each of the participants with CFD (bottom right).

Levene's test for homogeneity of variance concluded a statistically significant variance between each test duration for NFD (F=12.453; p=0.003) and CFD (F=6.247; p=0.037) participants.

The median duration for the HFA was 6.15 (IQR=2.16) minutes, and 6.21 (IQR=4.88) minutes for the ROS for those with VFL. For control participants the median duration for the HFA was 5.29 (IQR=0.93) minutes, and 4.24 (IQR=3.11) minutes for the ROS. Overall, when based on the average (mean) durations, the ROS was 12% faster for the control participants and 6.67% faster for those with VFL.

A Wilcoxon signed rank test found there was not a significant difference in the durations between perimeters for those with VFL (z=-1.699; p=0.089) with a medium effect size (r=-0.40). The ROS was performed in significantly less time than the HFA for the controls (z=-2.199; p=0.028) with a large effect size (r=-0.52).

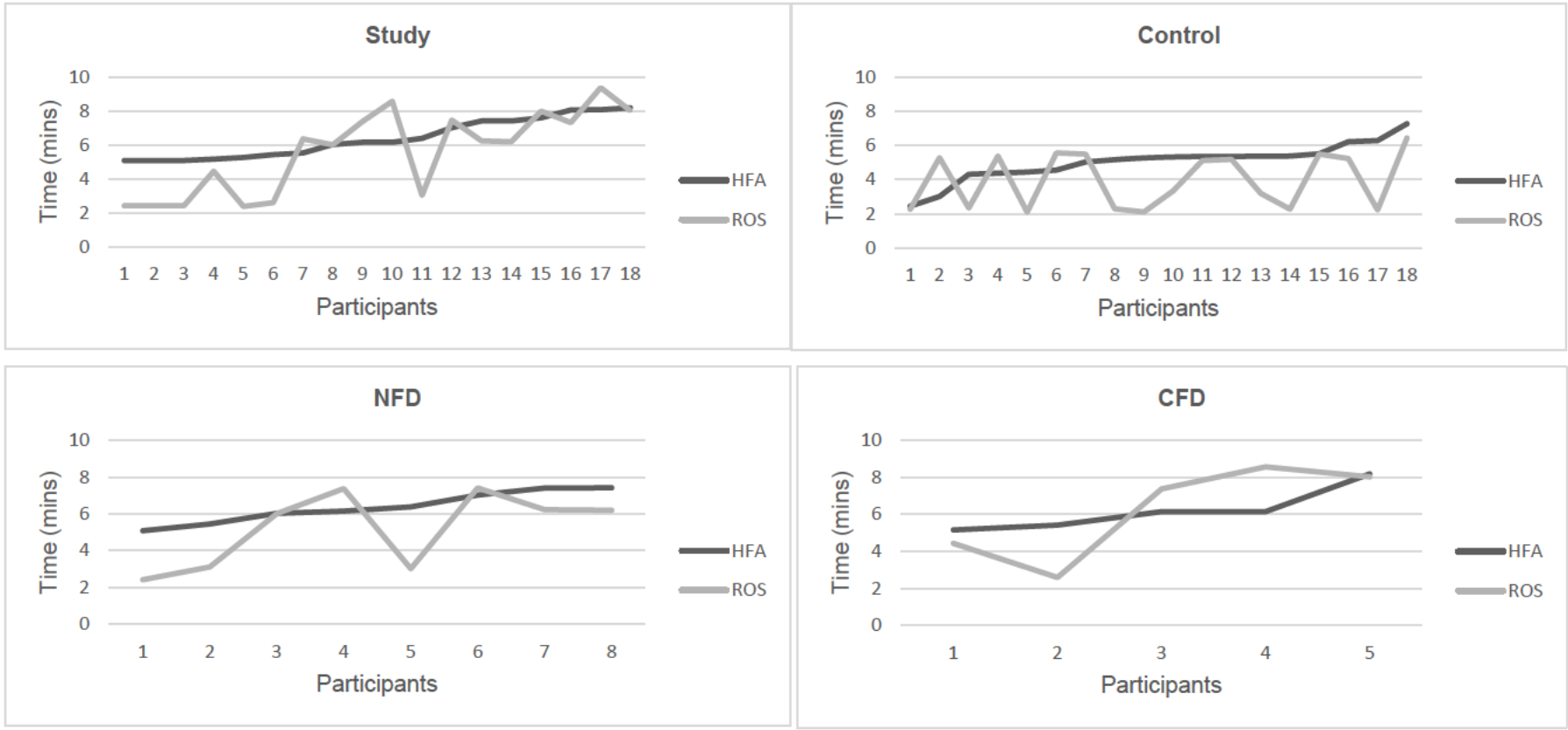


Figure 6-31. Duration of the HFA SITA Standard 24-2 and the ROS 24-2 FT examination. Top left= Data for VFL participants. Top right= Data for controls. Bottom left= Data for those with NFD. Bottom right= Data for those with CFD. Data ranked in ascending HFA duration and presented for each participant.

A paired samples t-test found no statistical significant difference between the duration of each test for those participants with CFD (t(4)=0.013; p=0.990; CI upper=2.489; CI lower=-2.465) with a small effect size (d=0.01). Post hoc testing established power of 1-β=0.05 when α=0.05. No statistical significant difference was found using a paired samples t-test, in durations for those with NFD (t(7)=2.029; p=0.082; CI upper=2.488; CI lower=-0.190) with a medium effect size (d=0.71). Post hoc testing established power of 1-β=0.81 when α=0.05.

Figure 6-32 presents the duration of the 24-2 test performed on the HFA (y axis) for study, including sub-categories and control participants. The trendline is based on the control data and Spearman's correlation coefficient demonstrates (r_s=0.192; p=0.444) there is poor agreement for the duration of this test for each of the study participants and their sub-categories.

Figure 6-33 presents the duration of the 24-2 test performed on the ROS (y axis) for study, including sub-categories and control participants. The trendline is based on the control data and Spearman's correlation coefficient demonstrates (r_s=0.400; p=0.100) there is fair agreement for the duration of this test for each of the study participants and their sub-categories.

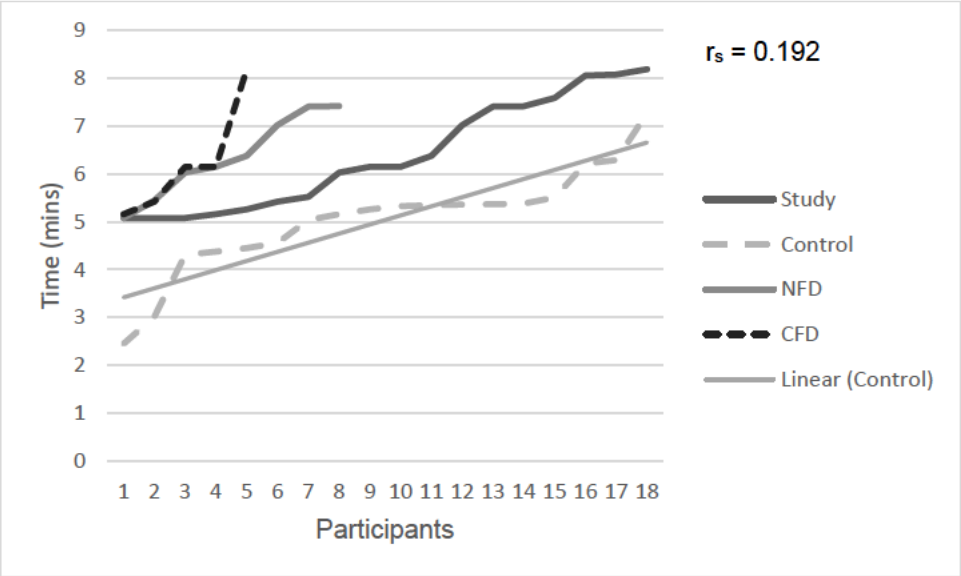


Figure 6-32. Duration of the SITA Standard 24-2 test performed on the HFA. Between groups. Data for VFL study participants, including sub-categories, and control participants for each participant. Trend-line based on the control data. Spearman's correlation ((rho) r_s) provided.

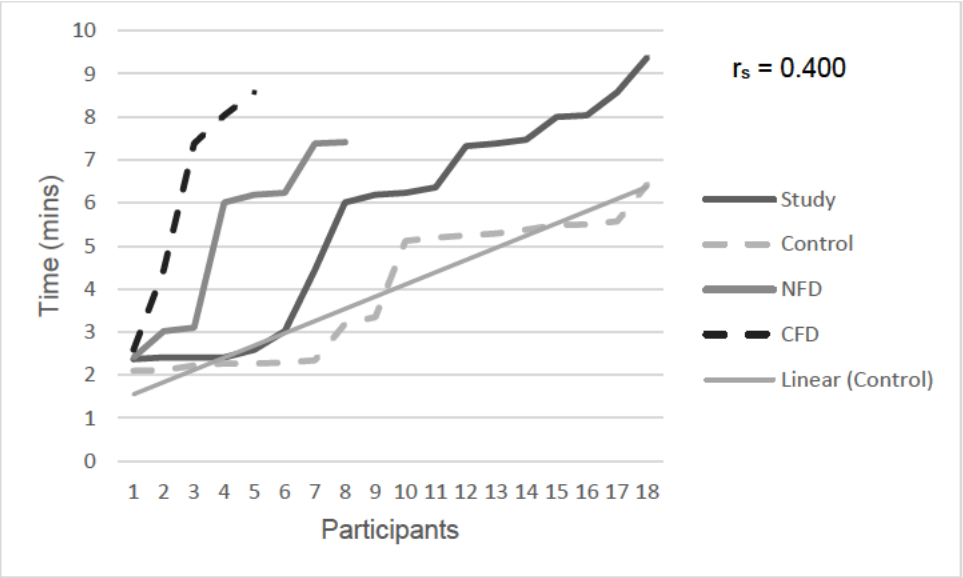


Figure 6.33. Duration of the 24-2 FT test performed on the ROS. Between groups. Data for VFL study participants, including sub-categories, and control participants. Trend-line based on the control data. Spearman's correlation ((rho) r_s) provided.

6.4.10. Age.

The age ranges of the controls were normally distributed (SW(18)=0.907; p=0.076) as was the MD (unweighted) values for controls, for both the HFA (SW(18)=0.947; p=0.385) and ROS (SW(18)=0.960; p=0.611). The age ranges for the study participants had normal distribution (SW(18)=0.937; p=0.255), but non-normal distribution was found for the MD (unweighted) values for study participants, for both the HFA (SW(18)=0.836; p=0.006) and ROS (SW(18)=0.884; p=0.031).

For those participants with VFL Spearman's correlation coefficient shows there is a poor linear relationship (r_s=0.109; p=0.668) with age and HFA MD. There is also no relationship with age and ROS MD (r_s=0.068; p=0.789).

There was a small association (R^2=0.154) with age and HFA MD in the controls. Pearson's r=0.393 and shows limited association between age and MD scores. Less than 1% of change in MD score being associated with age. There is a decrease of 0.12 in MD per increase in age per year which has no statistical significance (p=0.107). There is no association (R^2=0.023) between age and ROS MD scores. Pearson's r=-0.147 and shows limited association between age and MD with only 7.72% of MD change being associated with age. There is an increase of 1.47 in MD per increase in age per year which also has no statistical significance (p=0.561).

6.4.11. Questionnaire results.

Figures 6-34 to 6-38 present the results of the questionnaire questions for the study, study sub-groups and control participants.

A randomness check, using the runs test for randomness on SSPS for the participant responses to the questionnaire, confirmed that the series of answers choosing the HFA or the ROS as their preference occurred in random order. (Q1: p=1.000; Q2: p= 0.688; Q3: p= 0.211; Q4: p= 0.567; Q5: p= 0.683).

Data were coded for preference, with 2 being the preferred test and 1 being the least preferred test. The differences were tested with Kendall's coefficient of concordance W and the preferred perimeter was determined (table 6-8).

Post hoc testing of non-significant results of the questionnaire determined power of 1-β=0.97 when α=0.05.

Results indicate that there is no perceived ergonomical advantages between the perimeters.

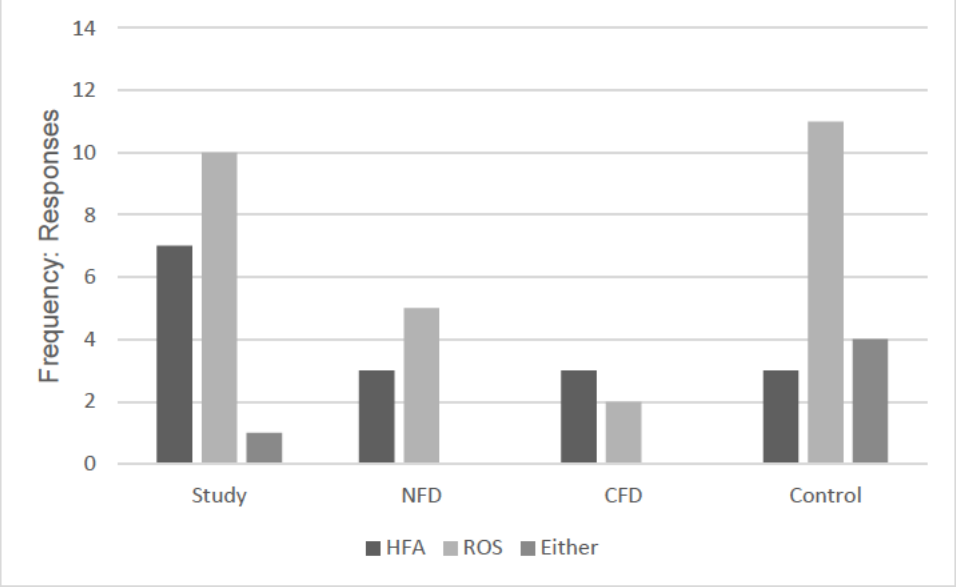


Figure 6-34. Machine participants perceived the test as easier.

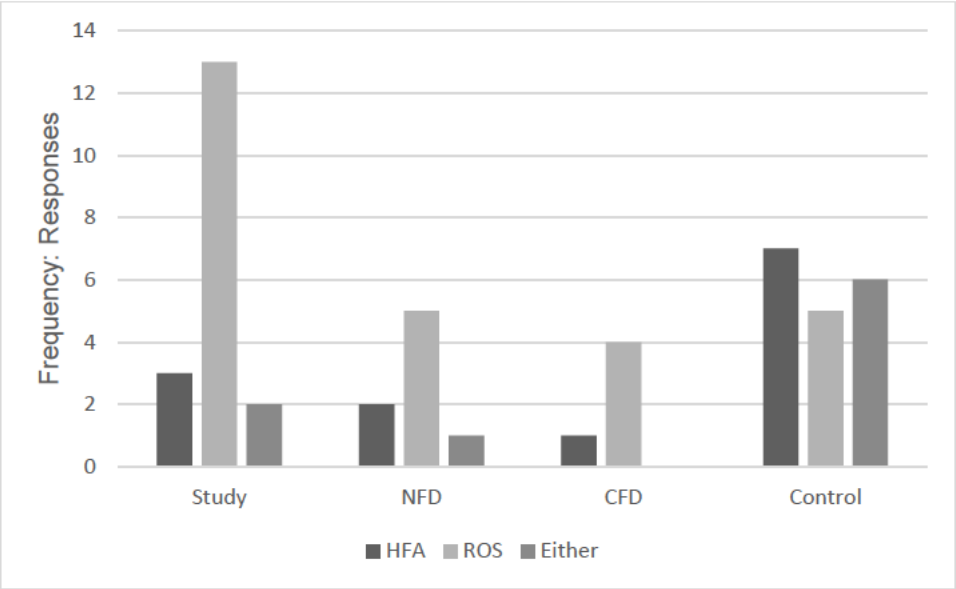


Figure 6-35. Machine participants felt was easier in terms of posture, head position and chin rest comfort.

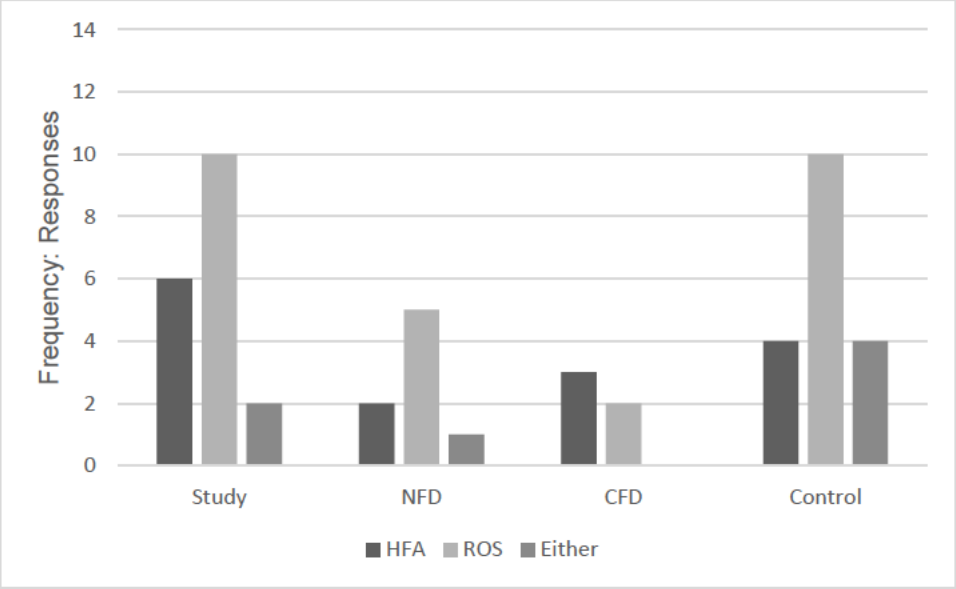


Figure 6-36. Machine participants felt was visually more comfortable.

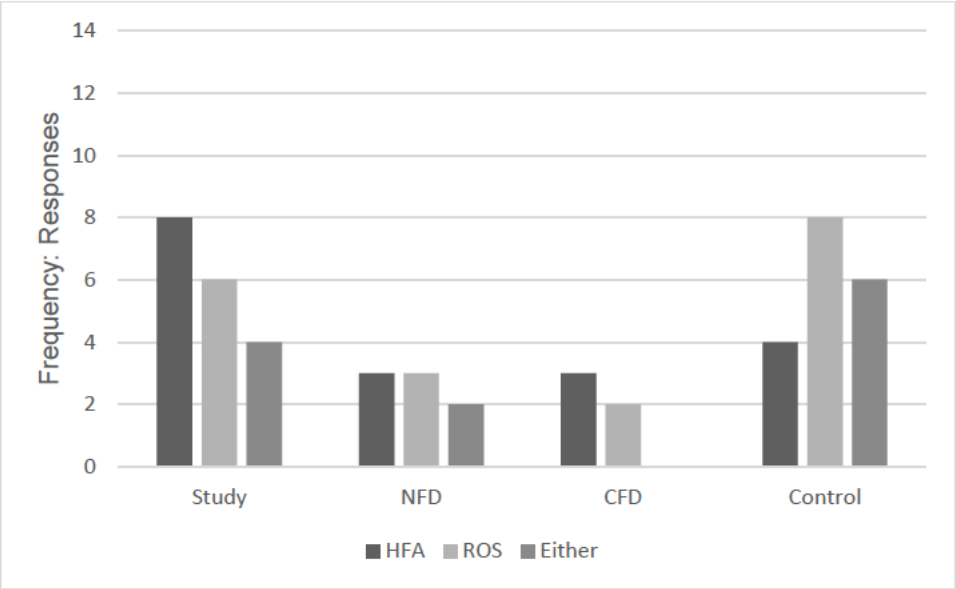


Figure 6-37. Machine participants perceived the test duration was quickest.

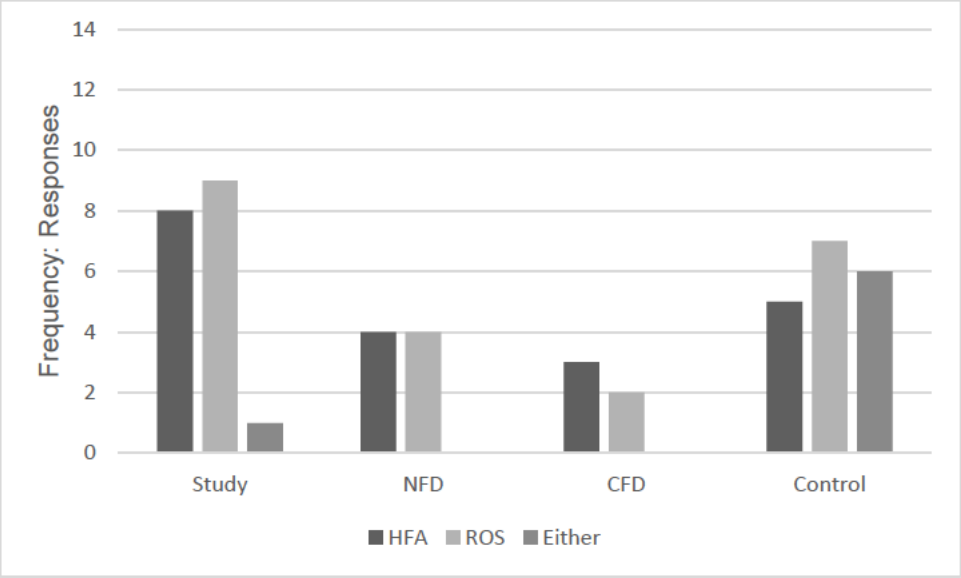


Figure 6-38. Machine participants preferred overall.

Participant cohort	Kendall's coefficient of concordance W	HFA mean rank.	ROS mean rank.	'no difference' mean rank.	Preferred machine.
Q1. "On which machine do you feel the test was easier on?"					
VFL	W(2)=0.223; א^2=12.069; p=0.030.	2.08	2.33	1.58	No difference.
NFD	W(2)=0.297; א =4.750; p=0.093.	Not significant	Not significant	Not significant	No difference.
CFD	W(2)=0.250; א^2=2.800; p=0.247.	Not significant	Not significant	Not significant	No difference.
Controls	W(2)=0.176; א^2=6.333; p=0.042.	1.75	2.42	1.83	ROS
Q2. 'Which machine did you feel was easier to carry out on in terms of your posture, head position and chin rest comfort?'					
VFL	W(2)=0.343; א^2=12.333; p=0.002.	1.75	2.58	1.67	ROS
NFD	W(2)=0.203;א^2=3.250; p=0.197.	Not significant	Not significant	Not significant	No difference.
CFD	W(2)=0.520; א^2=5.200; p=0.074.	Not significant	Not significant	Not significant	No difference
Controls	W(2)=0.009; א^2=0.333; p=0.846.	Not significant	Not significant	Not significant	No difference.
Q3. 'On which machine did you feel the test was visually more comfortable?					
VFL	W(2)=0.148; א^2=5.333; p=0.069.	Not significant	Not significant	Not significant	No difference
NFD	W(2)=0.203; א^2=3.250; p=0.197.	Not significant	Not significant	Not significant	No difference.
CFD	W(2)=0.280; א^2=2.800; p=0.247.	Not significant.	Not significant.	Not significant.	No difference.
Controls	W(2)=0.111; א^2=4.000; p=0.135.	Not significant	Not significant	Not significant	No difference.

Q4. 'On which machine did you feel the test was quicker to complete?'					
VFL	W(2)=0.037; א^2=1.333; p=0.513.	Not significant.	Not significant.	Not significant.	No difference.
NFD	W(2)=0.016; א^2=0.250; p=0.882.	Not significant.	Not significant.	Not significant.	No difference.
CFD	W(2)=0.280; א^2=2.800; p=0.247.	Not significant.	Not significant.	Not significant.	No difference.
Controls	W(2)=0.037; א^2=1.333; p=0.513.	Not significant.	Not significant.	Not significant.	No difference.
Q5. 'Overall, which machine did you prefer to be tested on?'					
VFL	W(2)=0.176; א^2=6.333; p=0.042.	2.17	2.25	1.58	No difference.
NFD	W(2)=0.250; א^2=4.000; p=0.135.	Not significant.	Not significant.	Not significant.	No difference.
CFD	W(2)=0.280; א^2=2.800; p=0.247.	Not significant.	Not significant.	Not significant.	No difference.
Controls	W(2)=0.009; א^2=3.333; p=0.846.	Not significant.	Not significant.	Not significant.	No difference.

Table 6-8. Questionnaire results. No difference was established if the significant difference was found between the mean rank for the option for 'no difference' and the choice of perimeters with no significant difference between the mean ranks of the perimeters. No difference was also established if the results were not significant. The preferred perimeter was established when the significant difference was between the mean ranks for the HFA and the ROS and the highest ranking perimeter provided a significant difference from the option of 'no difference'. The preferred perimeter was established with the highest mean rank score.

6.5. Discussion.

To the authors knowledge the ROS has not previously been validated against another perimeter. The ROS is a computerised perimeter delivered by a personal laptop computer and monitor. Perimetry delivered via a lap-top presenting stimuli on a computer monitor can reduce the cost of perimetry, reducing both outlay and maintenance related costs (Brunn-Jensen. 2011) which limit the costs being passed onto the patient within their eye examination fee. The added portability of delivering the examination via a lap-top and on a computer monitor makes this method of perimetry a desirable notion.

Average sensitivities (dB) were calculated for each location for both HFA and ROS perimetry examinations and compared. All values used were from the right eye of the participants. As would be expected, HFA values for study participants was significantly lower ($p=<0.005$) than values for control participants. This expected lower sensitivity values for the study participants also occurred with the ROS sensitivity values. The sensitivity values for the study participants were significantly ($p=<0.005$) lower than those of the controls. This confirms the nature of the participant groups.

One of the functions of perimetry is the monitoring of diseases and to determine progression (Wroblewski *et al*. 2014). Perimeters measure sensitivity at each location on a dB scale. SITA has been previously found to overestimate the threshold value, when compared to FT perimetry, between 0.9 dB (Artes e*t al*. 2002) to 1.3 dB (Wall e*t al*. 2001) and rising to 3 dB with sensitivities of 15 dB-20 dB (Artes *et al*. 2002). Therefore, it would be expected that the sensitivity values of the SITA Standard examination performed on the HFA would be slightly higher within this range of threshold differences compared to a FT examination. However, the HFA stimulus has a presentation time of 200 ms. The ROS has a variable presentation time as the contrast of the target heightens and is dependent upon when the participant sees the target. It is assumed the reaction time therefore influences the recorded sensitivity value on the FT ROS. The measured average for the longest duration the ROS will present a target was 9.94 seconds. The retinal system adapts to achromatic stimuli and this can strongly depend on the duration of presentation (Seim & Valberg. 2015). Contrast sensitivity of a participant increases with increased presentation time (Haley. 1993). This fact may give rise to higher threshold sensitivities recorded with the ROS. A further confounding factor is the subjective fixation monitoring by the clinician on the ROS. Taking the HFA as the gold standard the ROS sensitivities were significantly ($p=<0.005$) lower by a mean value of 7.07 dB which increased to 13.48 dB with higher

HFA sensitivity values for those with VFL. This difference was also present and significant within the controls (p=<0.005) with a mean reduction of 10.74 dB. These values were lower than the expected difference of 3 dB between SITA Standard and FT examination. The difference in sensitivities also showed a trend of increasing difference when higher sensitivity values were reached with the HFA SITA Standard. The difference from HFA to ROS sensitivity was also on average a positive move with the lower sensitivity values, with the difference becoming increasing more negative with increasing HFA sensitivity (figures 6-4 & 6-6). However, an artefactual element creating values closer to zero and a more positive movement in differences at lower sensitivities is the low value of the lower sensitivities. At 0 dB you can not vary any lower and at a value of 2 dB you can only reduce by a maximum of 2 dB. As these effects were experienced with all participants it cannot be attributed to differences in individual perception. Noise can impact upon sensitivity values, however, the examinations were presented in random order and the lower sensitivities found were not affected by the order of the tests. The ROS was significantly lower and hence it can be ascertained this is a feature of differences in sensitivity between perimeters. Inspection of figures 6-3 and 6-4 show the range of sensitivity with the ROS is much poorer than that of the HFA which may be due to the ROS being insensitive technically and/or the dynamic range of the ROS is poor. PROGRESSOR software analyses significant progression point-by-point of 1 dB annually (Fellman. 1995). Spry *et al* (2000) looked at linear regression of -1 dB/year to ascertain progression. Although their model would take into account normal values for short-term and long-term fluctuation in those with glaucoma, and recommend a minimum of eight examinations to determine progression (Spry *et al*. 2000). The immediate lower values of the ROS could lead the clinician to suspect a progressive field and hence, can potentially lead to unnecessary referrals if this examination was used as a subsequent examination for the majority of individuals it examines. Shirato e*t al* (1999) found that there was a 1 dB overestimation with SITA compared to FT. Although they stated this was clinically small, they considered this would be significant in longitudinal comparisons of an individuals field (Shirato *et al*. 1999). The ROS difference in recorded sensitivity is much larger than 1 dB and hence it would have more of an impact if using the ROS and comparing with other methodologies to determine progression.

Other alternative perimetry methods that do not utilise a conventional bowl perimeter, have shown to have high correlation to established perimeters. Brouzas e*t al* (2014) found that their video projection of FT 30-2 examination was highly correlated considering pointwise sensitivities to that of the HFA of between 0.75-0.90

(p=<0.0001) (Brouzas e*t al*. 2014). In this study the sensitivities between each perimeter for all participants were poorly correlated (R^2=0.056) and hence, a linear regression to determine a mathematical relationship was not considered useful. Bland and Altman plots demonstrate the lack of agreement between the sensitivity values of the perimeters for both study and control participants. Individuals suffer fatigue whilst undertaking perimetry (Tattersall *et al*. 2002). Fatigue can cause a difference in sensitivity values previously found to be 0.75 dB on successive SITA examinations (Wall *et al*. 2001). In this study the examinations were presented to the participants in random order with a rest period in-between. The order of tests had no impact upon the results and hence fatigue does not provide an explanation for these differences. Randomisation of the tests also controlled other influencing factors upon results, such as patient's response, their psychological status and attention. Both sessions (HFA 24-2 and ROS 24-2) were performed on the same day. Miranda and Henson (2008) consider this technique to potentially mask differences in attention. Therefore, the variables that can impact results due to performing the test on different days and at different times of day (Haley. 1993) were also controlled for. Again, any variances caused by these factors would be assumed to show up on both examinations and the effects of noise would also be expected to occur in the results of both perimeters and hence is not considered a causative factor for the large differences in results. The difference in presentation time of the ROS has not provided higher sensitivity values. A difference that may cause impact between the perimeters would be the use of habitual spectacles for the examination. It is therefore variable on whether the participant is corrected for the 40 cm distance used by the ROS. Those wearing an inappropriate correction could present with reduced sensitivity across the entire field caused by approximately 2.50D of defocus blur if the participant had no accommodation. However, it is considered that high contrast targets larger than 0.43º can mask defocus blur up to 3D. However, to make the perimeters truly comparable and to rule out this factor, then it is recommended that the creators of the ROS match the methodology utilised by the HFA, whereby correction is calculated dependent upon ametropia and presbyopia in the form of age. Additionally spectacle frames can give rise to a peripheral scotoma (Cubbidge. 2005). If the rim impacts upon the individuals visual field this may cause a variance in results between the perimeters, however, analysing the visual field results there were two cases where this factor may have been a possibility, one of which was excluded for other reasons leaving one potential case. This is therefore unlikely to have had a significant impact upon the variance in the results. Fatigue can be more apparent in older patients and this can have a bearing on results (Haley. 1993) being found in patients aged over 60 when performing

successive SITA examinations, with the second test yielding a small decrease in sensitivities than the first test (Wall *et al*. 2001). There is a reasonable correlation with ageing and SAP (Gardiner *et al*. 2006). However, in this study there was no relationship between the MD and age for any of the participants and is not considered to be a contributing factor within the variance of the results.

The ROS monitor background setting is 942 asb, and the examination is conducted in normal ambient room lighting of no specific standard. The HFA is performed in a dimly lit room. Using optokinetic perimetry dark stimuli on a light background has shown to be less impacted by ambient lighting and background luminance (Mutlukan & Damato. 1992). There is a rise in threshold as the luminance of the background rises (Lennie. 1979) and contrast sensitivity is reduced when retinal illumination is reduced (Swanson *et al*. 2014) with more defects being found when background luminances of a perimeter are lowered (Klewin & Radius. 1986) and hence, the perimeter with the highest background luminance would usually be expected to provide the highest sensitivity value. The decibel is a relative scale dependent upon the maximum intensity of the stimulus. It is expressed as 0.1 log-unit of attenuation and hence can differ between perimeters. The HFA has a maximum light intensity of 10.000 asb (Heijl *et al*. 2012) which is the equivalent of 0 dB. The background luminance of the HFA falls within the range of photopic luminance and matches that of the Goldman perimeter which is recommended by the International Perimetric Society. This background requires less adaption time after the patient has been exposed to bright ambient lighting (Haley. 1993). The background of the ROS also falls within the photopic range, but at a higher level. The retina will adjust to the mean sensitivity within the visual field (Freeman e*t al*. 2009). Variations in ambient lighting, spectral distributions and angular subtense (Cengiz e*t al*. 2015) are adapted to by the visual system with adjustment to its sensitivity (Sharpe e*t al*. 1992, Virsu & Lee. 1993) and the average light level that the human eye is exposed to influences the eyes sensitivity (Rasengane e*t al*. 2001, Freeman e*t al*. 2010) and between-subject variability is affected by retinal illumination. If the background varies between perimeters, the state of retinal adaption is different and therefore the normal hill of vision profile will differ. However, the highest contrast for the ROS would be calculated from the darkest target presented on the background luminance of the monitor whereas the HFA would have the contrast calculated from the maximum brightness of the stimulus against the background of the perimeter bowl. The ROS is also assumed to base its sensitivity values on the duration of the presentation time prior to being recognised whilst the contrast is being heightened. Therefore, the different methodologies make establishing the difference in

backgrounds as a possible factor to cause variance difficult. However, it can be ascertained that the higher luminance has not presented with higher sensitivities. Pupil size is likely to vary due to the differences in room lighting and a smaller pupil is likely to give rise to reduced sensitivities (Cubbidge. 2005). This may explain the lower sensitivity values found in the ROS but not the lack of defective fields found with this perimeter. A further explanation for the differences in sensitivity values may be the ergonomics of how the test is conducted. The participant also had to move the target to identify that they had seen the target. Out of 70 right eyes examined, 10 were excluded due to the participant failing to make out the green target, which they then proceed to move over the ROS stimulus, this limits the perimeters use for those who have reduced visual function. It essentially means that the task also requires a threshold that requires identification of this moveable target, and hence identifying where one was may cause a delay in movement of the target. The attended field of view (AFOV) test records the threshold presentation time of the targets identified correctly via a staircase procedure (Coeckelbergh e*t al*. 2004). It is recommended that the ROS manufacturers look at this method to see if they can produce a more accurate test. A likely explanation for the lower sensitivities recorded is that the assigned dB value for the starting point starts at two low a value, and hence it is not possible to record higher sensitivities. The ROS presents the stimuli at a pre-determined greyscale level obtained from the initial five recordings made when the participant first identifies the stimuli. The stimulus will darken, but it does not lighten. This strategy will provide a pre-determined limit on the sensitivity range that can possibly be recorded. This limit is further confounded by the lack of retesting of the test locations. The ROS will only examine the location once if all the stimuli are considered detected at the pre-determined level, and will only retest if a stimulus was not identified at the pre-determined level. This strategy will only record lower sensitivity values and provides no opportunity to achieve higher sensitivity values. There is a further possibility that the detection of a grey contrast target may prove harder to identify than a light stimulus. A further possible explanation is the difference provided by static and kinetic perimetry. The ROS requires a participant to move fixation after each identification of a target. Kinetic perimetry (moving fixation) has previously been found to present significantly more errors in controls. The Dicon perimeter presented an error rate of 25.5% compared to an error rate of 12.6% for static perimetry. A difference of 10 dB was found in those with glaucoma and like the results for the ROS, was found to be larger in the controls at 16 dB (Asman *et al*. 1999). Differences generally widened at the higher dB level on the HFA. VirtualEye has also shown lower sensitivities in participants with glaucoma of -4 to -6 dB and greater difference occurs for higher dB

values (Wroblewski *et al*. 2014). However, the range is a smaller difference than the ROS. All participants were not naive to perimetry, they were however naive to the ROS. The program starts with a practice run before recording sensitivities. This should lessen the impact of perimetry on a novel machine. However, it is possible that lack of experience on the ROS had a bearing upon the results and it would require retesting to determine if sensitivities improved with learning.

The ROS target calculated via trigonometry subtends 0.86º at the eye compared to the 0.69º subtended by the HFA stimulus. Larger stimuli (size V) have provided greater dynamic ranges in perimetry than smaller stimuli (size III) (Wall e*t al*. 2010). It was anticipated that the ROS stimulus may provide a greater dynamic range. SAP's estimated dynamic range is 33 dB (Gardiner *et al*. 2006). The larger size stimulus of the ROS did not provide greater dynamic range although the range falls within usual scores of 0 dB and 30 dB stated by Betz-Stablein e*t al* (2016). The ROS threshold values ranged from 0-30 dB. The scores for the HFA ranged from 0-39 dB when considering all the sensitivity values for all participants. The HFA average sensitivity peaked at 29 dB and the ROS peaked at 21 dB (figure 6-19). The HFA has a greater dynamic range than the ROS being able to either present dimmer stimuli or by potentially starting at a higher level of luminance for the equivalent 0 dB. Due to the lower sensitivity values recorded by the ROS in general and the evident shift in the peak sensitivity across the recordings it seems prudent to assume that the assigned dB values for the depth of the stimulus is not in-line with that of the HFA and the pre-determined presenting value of the stimulus, which only darkens and does not lighten, limits the dynamic range. Previously in those with glaucoma the FT examination has shown a lower sensitivity value by a mean of 0.9 dB in sensitivity compared to the HFA SITA Standard examination (Artes *et al*. 2002). Within NFD participants the mean sensitivity was 19.68 dB for the HFA and 13.21 dB for the ROS providing a larger difference with a mean of 6.37 dB.

The differences in the sensitivities between perimeters were calculated and these differences plotted across the 24-2 grid (figures 6-14-6-17). The stated differences on the plots are the value the ROS differs from the HFA. The differences in sensitivity would result in unnecessary referrals to the hospital eye services should an ROS 24-2 examination be preceded by a HFA 24-2 examination and considered to be comparative in dB values.

It is well established that areas of damage are found to increase variability in visual field testing (Wall *et al*. 2008, Haley. 1993. Crabb *et al*. 1996, Henson *et al*. 2000,

Miranda & Henson. 2008, Artes *et al*. 2003, Mouri-Mahdevi *et al*. 1997, Susana *et al*. 2014, Viswanathan *et al*. 2010, Birch *et al*. 1998, Heijl *et al*. 2012, Wall *et al*. 1998, Turpin e*t al*. 2007, Gardiner. 2003, Gardiner e*t al*. 2006) which can reach up to 15 dB making early defect detection difficult (Nouri-Mahdevi *et al*. 1997, Swanson e*t al*. 2014). Fluctuation increase is related to the severity of the defect (Tattersall e*t al*. 2007). Retest variability is common to more than one testing strategy which includes both FT (Turpin e*t al*. 2007, Spry *et al*. 2003) and SITA Standard (Wall *et al*. 2008, Gardiner. 2003). Those with VFL were anticipated to exhibit more variability in results between perimeters compared to controls. Those with VFL had wider limits of agreement than the controls. Those with NFD had limits of agreement that were wider still. However, the CFD participants also had wide limits of agreement but these were somewhat narrower than those with NFD and appear to contribute less to the lack of agreement. The NFD participants therefore demonstrate the majority of the contribution to the lack of agreement for the study participants. Those with glaucoma have previously been found to have wider limits of agreement when establishing test-retest variability on the UFOV (Bentley *et al*. 2012). However, the bias for the controls within this study is the furthest from zero compared to the study participants and the study subgroups, meaning the two methods are generating different results for the controls and the test has no validity if sensitivities were to be comparable to the HFA. What is also surprising is the greater difference in sensitivities between the two perimeters occurs when the HFA recorded higher sensitivities when it is established that the greater variability occurs when there is greater loss of sensitivity.

To compare the differences in sensitivities between the two perimeters across areas of the visual field for each perimeter, the zones were separated into outer, middle and inner (figure 6-18), and the differences within groups were compared. A significant difference was located between the inner and outer zone, with more variability being present in the inner visual field for those with VFL. For the controls, no significant difference could be firmly established between zones. The variability presented by those with VFL is surprising due to the small cohort of those who possessed CFD within the study pooled data. However, the central zone was a large area and may have encapsulated other visual defects that contributed to this variability.

In perimetry one of the important aspects is to detect the presence of disease (Swanson *et al*. 2005, Swanson *et al*. 2014, Wroblewski *et al*. 2014, Haley. 1993), monitor progression (Alencar & Mederios. 2011) and also confirm absence of a disease (Wyatt *et al*. 2007). To preserve vision in glaucoma it requires early detection and management (Hejil *et al*. 2012, Viswanathan *et al*. 1997, Nazemi *et al*. 2007,

Haley. 1993, Bergin. 2011, Brusini *et al*. 2005). SITA has been found to be similar to FT when determining defect status (Wall *et al*. 2001) although SITA Standard has previously shown to produce a more severe defect compared to FT when examining epileptic patients exposed to vigabatrin. However, this difference in defect severity was not found to be statistically significant (Conway e*t al*. 2014). The head-mounted Kasha visual field system has provided similar results to the HFA examination (Hollander *et al*. 2000) and Rarebit perimetry has been found to correspond to 72% of SITA Fast visual fields in those with neurological or neurosurgical diseases (Houston *et al*. 2010). The higher the luminance presented there is less likelihood of false-positive results, but a higher likelihood of shallow defects being undetected (Johnson e*t al*. 1983). Therefore, there was a possibility that the monitor luminance of the ROS may mask shallow defects. A variance in stimulus size can produce a result of absolute (smaller stimulus) to relative scotoma (larger stimulus) (Haley. 1993). A smaller stimulus size has greater resolution in detecting small scotomas compared to a large stimulus and using varying sized targets (I,II & III) are able to find greater field loss than using size III alone (Kalloniatis & Khuu. 2016). However, a large (1.72º) size V stimulus has been found to locate similar abnormal test locations when compared to a size III (0.43º) stimulus with no significant difference between the abnormal test locations identified by either stimuli (Wall *et al*. 2008). In this study the ROS was unable to pick up the same defect depth as the HFA. There was a significant difference (p=0.001) in defect depth utilising the Probability Plot (HFA) and Error Greyscale (ROS) and using the assigned scale outlined within section 3.4.1. The assigned scale ranged from 0-4 with 0 being no defect and 4 being normal for less than 0.5% of the population. There was no significant difference found within the calculated mean greyscale errors for the control group participants. The ROS underestimated the defect depth by an average of 0.81 on the scale. The scale itself is limited. The greyscale differences were calculated using a numerical scale assigned to percentages of a normal population. If 4=<0.5% of the population, 3=<1% of the population, 2=<2% of the population, 1=<5% of the population then 0=95% of the population. A change of 4 could indicate a change within a range from anything from 5-95% of the population, a change of 3 could indicate a change from 4.5-95% of the population, 2 could indicate a change from 1.5-95% of the population and 1 could mean a change from 0.5-95% of the population. However, even with this limitation, it can be ascertained that the ROS is likely to miss defects or unable to determine the depth of the defect if the HFA is taken as the standard. This could be explained by the use of the smaller target on the HFA. However, this is still surprising considering the lower sensitivities found by the ROS compared to the HFA. It would be expected that more defects would be determined with lower sensitivities.

Therefore, the algorithm utilised for the Error greyscale does not appear to relate well to the sensitivity values recorded. SITA incorporates population information (Hitchings. 1994). One possible explanation for the lack of expected outcome is that there may be a lack of data from normal and glaucomatous patients incorporated in the ROS when the manufacturers determined when a sensitivity value determines a defect and when it does not. Another explanation is that the generalised scale may not be based on other perimeters and hence may not be comparable. It was desired that the greyscale would be comparable to results produced by the HFA (Donaldson. 2016b, personal communication, 07 October). In this instance the ROS does not compare well to the HFA. This would limit using various perimeters in practice per member of the population. However, even with differing incomparable sensitivity results this would only require a practitioner to become familiar with the expected results when operating a chosen perimeter. This however does not explain the lack of defects found when the participants were considered defective by the HFA. There would still need to be an appropriate outcome of results that can be interpreted to detect or confirm absence of disease. When using the Error Greyscale and Probability Plots, none of the participants in this study had an exact replication of the defective location or depth of the scotoma.

It is established there is more variance where there is reduced sensitivity. As anticipated, there was significant difference in the mean range of variance ($p=0.002$) in detected defect depth per participant between perimeters for those with VFL compared to the controls.

Pointwise analysis using the same scoring system previously discussed established that there was also a significant difference ($p=<0.005$) between the greyscale values per location between the two perimeters for those with VFL. The plotted values (figure 6-23) use the HFA as the standard. Using a scale of positive and negative values indicated the direction with a positive meaning that the defect found on the ROS was less severe, and a negative meaning the defect found was more severe on the ROS than that found on the HFA. Here the ROS either underestimated the defect depth or missed the defect for that point entirely. There was also a significant difference ($p=0.009$) found in defect status per location between perimeters for the controls. There was a significant difference ($p=<0.005$) in the differences in defect status per location between perimeters comparing the study and control group. The study group had a mean of 0.89 change in defect status whilst the control group had a mean of 0.14. The range of presenting range of variance in defect status per location between

perimeters was also greater (p=<0.005) for those with VFL than the controls. These results confirm that those with VFL lack in reproducibility compared to the controls.

Other perimetry test alternatives to bowl perimetry have performed well when being compared to the HFA. A laptop based program evaluated at the University Hospital, Rigshospitalet in Denmark demonstrated 100% sensitivity and 78% specificity when screening for glaucoma within a glaucoma clinic (Brunn-Jensen. 2011). Missed stimulus locations on the Peristat perimeter were highly correlated to the missed stimulus locations on the HFA but Peristat did miss 46% of early and 14% of moderate to severe glaucoma cases (Lowry e*t al*. 2016). A computer game method investigated by Aslam (2011) presented defects in-line with the conditions of the cohort of glaucomatous children examined (Aslam. 2011). The method of varying contrast by altering greyscale depth has previously been found to show repeatable glaucomatous defects in those who were a glaucoma suspect and provided no defects for controls. These defects were shown to be present even when SITA 24-2 or 30-2 test results had provided no defect (Nazemi *et al*. 2007). The ROS test used in this study was the FT examination from the ROS menu, and hence expected to be sensitive to areas of loss and should be able to detect early change (Artes e*t al*. 2003, Heijl e*t al*. 2012). This has not been found to be the case with the ROS which also alters contrast by varying greyscale depth like the method investigated by Nazeemi. However, the lack of retesting of locations to determine accurate threshold calls into question the accuracy of this being considered a FT examination. It seems prudent to assume this examination is a screening test. To determine a defective field the HPA grading was utilised. This scale is used to determine change across subsequent visits. Here, it was adapted for the consideration of one visit and for conditions other than glaucoma. Therefore, it would be possible for certain defective fields to be missed and the use of a scale designed for glaucoma is a limitation when using it to assess defect in other conditions. This was considered acceptable due to both examinations being analysed with the same scale and hence would be comparable. Using the HPA grading in this adapted form there was no agreement in determining defect or no defect between perimeters in those with VFL overall (Kappa=0.182) and controls (Kappa=0.000), and poor to fair agreement in those with NFD (Kappa=0.250) and fair agreement in those with CFD (Kappa=0.286), but this was of no significance. Analysing all visual field results with the HPA grading to determine defect established that the HFA found 24 participants with a defect whilst the ROS found defects in 8 participants within these 24. The HFA found 12 to be without defect which the ROS confirmed. Therefore, the sensitivity of the ROS is 33.33% and specificity 100% when using the HPA grading to

determine defect/no defect. Therefore, it is unlikely this perimeter would diagnose someone incorrectly with a defect when the HPA grading is applied to the greyscale results. This implies that the lack of agreement only occurs when there is a defect present. Therefore, those without a defect would not be referred unnecessarily but those with a defect would not be detected. The ROS missed 66.67% of visual field defects entirely and hence provides a false positive error rate of 66.67%. The HFA also determines defect with the use of global indices. There are no global indices on the ROS, this would pose a disadvantage when determining defect as the global indices are utilised in the HPA grading.

High correlation has been found with rarebit perimetry when comparing the MHR with the MD of the HFA (30-2 SITA Standard) by values of R^2=0.1531 (Brusini e*t al*. 2005) when looking at those with glaucoma and additionally with ranges of R^2=0.746-0.882 when analysing the visual field quadrants in those with homonymous hemianopia (Gedik e*t al*. 2007). A laptop based perimeter studied for development in Denmark has provided 100% sensitivity and 78% specificity when compared to the Octopus 1-2-3 threshold perimetry in participants with glaucoma (Bruun-Jensen. 2011). The MMDT has also shown to perform well diagnostically in those with glaucoma (Ong e*t al*. 2014) The MMDT, a computerised portable visual field examination, has generated an AUC of 0.930 with a suitable cut-off allowing sensitivity of 85% and specificity of approximately 95% (Ong *et al*. 2014) in those with glaucoma. AUCs measured on Peristat on-line perimetry have ranged from 0.77-0.81 for mild glaucoma and 0.85-0.87 for those with moderate to severe glaucoma but missed 46% of early glaucoma and 14% of moderate to severe glaucoma cases when used as a single screener (Lowry *et al*. 2016). Rarebit has also shown it is useful in locating macular deficits (Winther & Frisen. 2015) and its MHR has shown significant correlation with the MD of the HFA in those with hemianopia and in those with POAG providing specificity of 92.7% and sensitivity of 97.4% with an AUC of 0.95 (Brusini e*t al*. 2005) and is significantly quicker than the HFA. In addition, participants reported it to be easier and more comfortable than the SITA Standard on the HFA (Gedik *et al*. 2007). To enable comparable MD, then calculations of the unweighted MD values were used. There was fair correlation (r_s=0.526) between perimeters and the difference in their unweighted MD was significant (p=0.002) with 91.67% of participants having a change of -2 dB or more between perimeters. Eighteen-point-eight-nine percent had a higher (closer to zero) score on the ROS than the HFA and 81.11% had a lower score (further from zero) on the ROS than the HFA. There appears to be a distinct cross-over for what the unweighted MD HFA value needed to be to determine if the ROS was to be within -2

dB of the HFA, further from zero than the HFA or closer to zero than the HFA. When the HFA unweighted MD score was -8 dB then the ROS provided a closer to zero MD. When the HFA presented an MD score between -8 to -6 dB the corresponding ROS MD had less than -2 dB of variance. For HFA MD scores of -5 dB or less then the ROS MD was more negative. An ROC curve (figure 6-25) did provide agreement that the more negative the ROS MD then the more likely a positive test result will occur. The AUC was 0.202 (p=0.008) for the ROS compared to 0.873 for the HFA and indicates the ROS test is of no value. The HFA has a sensitivity of 0.824 and specificity of 0.789 when -2.13 dB cut-off is used. Any value more negative than -2.13 indicates the patient is more likely to have disease. The HFA is commonly considered the gold-standard investigative tool (Gedik *et al*. 2007) in the U.K. (Tattersall *et al*. 2014) used to aid diagnosis and monitor glaucoma. Therefore, it seemed a better approach to take the ROS MD against the defect and no defect results of the HFA (figure 6-27). In this situation, the ROC provided an AUC of 0.681. The ROS MD does not relate well to the positive results found by the HFA. To provide good sensitivity of 0.824 the cut-off provides an MD of -6.62 dB which is in the order of nearly 4 dB lower than the HFA MD cut-off. This also provides a specificity of 0.211. Trying to obtain a high specificity of 0.789 then the cut-off provides an MD of -7.40 dB, which is even further from the HFA MD cut-off and only provides a sensitivity of 0.588. There was also found to be a large area of uncertainty with the ROS MD (figure 6-28) whereby a participant could be either normal or defective spanning over 2 dB. Only at the point of -8.00 dB would a participant be considered as certainly defective. No area for those who would certainly be normal could be established. Other alternatives to bowl perimetry have out-performed the ROS in this aspect. Therefore, it is recommended that the ROS looks at the algorithms utilised by other perimetry methods, that have also utilised a computer or portable lap-top along with a monitor, that have provided better sensitivity and specificity than the ROS.

Using either the criteria, whereby on pointwise analysis, change is deemed to have occurred if there is a slope worse than -1 dB per annum at inner locations, or -2 dB per annum at outer locations, at one or more test points (Henson. 2001) or the criteria used by Gardiner (2003) in their thesis looking at the statistical methods to analyse data in glaucoma, of a regression of -2 dB at each location per year is taken (ignoring the blind spot) then it can be calculated that the study group had progression in 100% of locations for the right eye. Progression would be considered to have occurred in 100% of locations in the control groups right eye if using the HFA as the first test followed by a test performed on the ROS at the following annual examination. In

addition, out of the 36 participants 91.67% had a change in unweighted MD of -2 dB or more. A progression of -2 dB is considered as rapid progression in those with glaucoma (Heijl. 2010). Therefore, if the sensitivities were considered comparable, the consequence would be that approximately 100% of patients would be presumed to have progressed based on their perimetry results alone. Although various methods can be employed by a clinician to determine progression. Progression however is unlikely as each participant was examined on both tests on the same day and progression should not be apparent in the control group.

MD determines generalised loss of sensitivity rather than focal loss (Henson. 2001). It was not possible to obtain comparisons of PSD data due to no comparative calculation for PSD exists on the ROS.

Fixation losses can present with local fluctuations in the mean light intensity received by the retina. Both head and eye movements impact on the mean light intensity received (Freeman *et al*. 2010). The ROS perimeter did provide significantly less fixation losses (p=0.011) than the HFA. Those considered to have good fixation was 39.29% for the HFA compared to 82.14% for the ROS for participants with VFL. There was also significantly less fixation losses in the controls on the ROS perimeter. There was no significant differences between fixation losses on either perimeter between the study and control group. This is indicative that the ROS can provide reliable test results even in those with VFL if basing this on fixation loss indices. It has previously been reported that moving the fixation target helped maintain attention (Houston e*t al*. 2010). However, one limitation is the manual nature of monitoring the fixation losses on the ROS. The HFA measures fixation losses objectively. This difference in measurements does mean that they are not entirely comparative and it is unknown the impact the monitoring of a clinician may have on these results. A distinct disadvantage of the ROS perimeter is the lack of reliability indices. The lack of determination of false positives and false negatives means that an unreliable test may be used for diagnosis or progression.

The possibility of whether it is the false negative responses for each test that contributed to the differences between the sensitivities can not be ascertained as there are no catch trials presented by the ROS. Therefore there is no comparative data or method to compare with the HFA. The program may find it advantageous to present some of the targets at a higher contrast level than is expected to be seen to determine attention to allow determination of a reliable test.

Ideally, perimetry should not only be reliable, but should also be quick and easy for patients to use. Fatique increases with increases in test duration. FT perimetry can be 15 minutes plus (Artes *et al*. 2002), taking 50% longer than SITA Standard which makes this test a source of visual fatigue (Wall *et al*. 2001). The SITA algorithms were developed in order to reduce examination time (Conway e*t al*. 2014) and is therefore one of the advantages of the SITA 24-2 test strategy on the HFA along with its ability to perform accurate testing compared to FT strategies (Tattersall *et al*. 2007). SITA is one of the shortest duration perimetry examinations (Hitchings. 1994) and it would be expected that the FT examination on the ROS test menu would potentially take longer to complete. The ROS was significantly quicker ($p=0.028$) for the controls when compared to the HFA. However, this was not found within the participants with VFL, or those participants with NFD and CFD. Fatigue can occur 3 minutes into a visual field examination (Cubbidge. 2005) and the usually longer FT examination produces lower sensitivity in participants aged from 20 onwards (Wall *et al*. 2001) with the fatigue effect increasing with age. The average test duration for the ROS was 5.59 minutes for the study participants and 3.96 minutes for the control participants making it less likely to suffer the effects of fatigue arising in FT examinations. The ROS has a comparatively quick test with the average duration being 4.78 minutes when data for study and control participants are pooled. Other alternatives to bowl perimetry have presented similar results; the laptop based perimetry examination developed by the University Hospital Rigshospitalet provided an average duration of 3 minutes; Peristat is conducted approximately under 5 minutes and the head-mounted Kasha visual field system has an average examination time 4.8 minutes (Hollander e*t al*. 2000). Rarebit has been found to be significantly quicker than SITA Standard 30-2 on the HFA, being concluded on average within 4.19 minutes in those with homonymous hemianopia whilst the HFA was concluded on average within 7.26 minutes (Gedik *et al*. 2007), and for those with neurological or neurosurgical diseases Rarebit has provided an average test time of 4.8 minutes (Houston *et al*. 2010). The reduced examination time the ROS yields would be beneficial to patients in terms of fatigue and examining those with neurological illnesses whose attention may be affected. However, the quicker duration of the ROS was not perceived by the controls, those with VFL or those with NFD when analysing the results of the questionnaires.

For those with CFD the perception of the duration of the test agreed with the timed results of the test with neither showing a significant difference. This is a positive for the ROS, which was concluded within 5.59 minutes on average ($SD=1.16$) for those with VFL.

The study participants perceived no statistical difference (p=0.030) when deciding on which machine was the easiest to perform the test on. The control participants however found the ROS (p=0.042) to be the easier machine to have the test conducted on. The ROS was considered to be the most comfortable machine to have the test carried out on for those with VFL (p=0.002) but this was not specific to those with CFD (p=0.074), or to those with NFD (p=0.197). No difference was found for controls (p=0.846). Those with VFL may consider it more comfortable than the controls due to being more likely to have undergone more visual field tests than other members of the population, and have a dislike of the constraints a chin-rest and forehead rest implements. All those who preferred the ROS were spectacle wearers and 80% of participants who did not prefer the ROS were non-spectacle wearers. The preference may therefore be due to the use of habitual spectacles being preferred over a trial lens. Visual comfort presented no difference in any of the participants. None of the participant groups perceived any difference in duration of each test. This would be expected for the study participants who objectively had no difference in durations. However, the speedier nature of the ROS was not perceived by controls. When deciding on their overall preference for one perimeter over the other, none of the participant groups expressed any preference for either perimeter. Ergonomically therefore the ROS did not have any advantage over the HFA overall.

6.5.1. Conclusion.

The overall poor performance of the ROS perimeter questions its suitability for clinical examination of the visual field. The ROS perimeter has not been validated, and it is acknowledged that a validity study, to determine that it measures what it has been designed to measure, i.e. the visual field, would have been an appropriate starting point. In addition, it is acknowledged that the format of the examination is significantly different to that of the HFA, and therefore it can be considered that two very different tests are being compared. However, the ROS's objective is the same as the HFA, which is to measure the visual field, determine defective and non-defective fields and monitor progression in those with existing VFL. The results suggest that the ROS perimeter is not a suitable instrument for individuals with extensive VFL. Of the examinations that were attempted on the study participants, one third had to be excluded due to the participant being unable to see the green moveable target. This indicates that a large proportion of the population suffering VFL could not undergo examination with this perimeter. In addition, for those participants that were examined, the results suggest that ROS is not reliable in determining those who have VFL. The sensitivity values of the ROS FT program were consistently and significantly lower

than the HFA in those with VFL (p=<0.005) and in the controls (p=<0.005). This is likely to be due to the ROS presenting the stimuli at a pre-determined greyscale level obtained from five initial recordings of when a participant identifies the stimulus and the lack of point retesting. This strategy creates a ceiling effect and limits the dynamic range of this perimeter. The lack of retesting of locations means it is questionable that the perimeter is a threshold test and questions the manufacturers claim of this being called a FT examination. The lower sensitivity values did not translate to defective fields on the ROS Error Greyscale. There is no agreement in defect depth and pointwise analysis also demonstrated a significant difference (p=0.001) between the ROS Error Greyscale and the HFA Probability Plot in those with VFL indicating that the ROS is unlikely to accurately determine the depth and location of the defect in those with VFL as found be the HFA. There is a lack of agreement in the MD between perimeters. ROC generated by plotting MD of the ROS against known defect established by the HFA generated an AUC of 0.681 providing poor sensitivity (0.647) and acceptable specificity (0.737) compared to that of the HFA. When employing the HPA criteria (adapted) the ROS misses 66.67% of defective fields providing 33.33% sensitivity.

The significantly lower sensitivity values and lack of reproducible defective stimulus locations compared to the HFA defective stimulus locations, means this visual field program is not comparable to the HFA. This conclusion is supported by the lack of agreement determined by Bland and Altman plots. Bland and Altman plots found the bias for the controls to be furthest from zero than those with VFL establishing that the test has no validity if the sensitivity values are to be comparable to those of the HFA.

Participant preferences did not establish a preference for either perimetry method overall. Therefore, it is not superior ergonomically to the HFA.

In summary, these results suggest that the ROS cannot be used by a third of the population who have VFL. Results also suggest that it cannot determine VFL in two thirds of the population who have VFL as found by the HFA. The ROS is also unable to determine the depth and location of the defect in those with VFL as found by the HFA. Results do not currently support the ROS to be used in optometric practice to determine or monitor VFL. Results suggest that the ROS is not a suitable perimeter for those with VFL.

Due to the lack of agreement when compared to the HFA or establishment of a defective field in those known to have VFL it is recommended that the creators of the ROS look at algorithms used by other perimeters, that also present stimuli on a

monitor and employ a lap-top or personal computer, that have shown better results in terms of sensitivity and specificity. In particular how the current sensitivity values found on the ROS are translated to produce the Error Greyscale.

7. Conclusion.

Those with VFL possess a significant change in EES across visits. There is a need for repeat testing to establish an accurate result for these individuals. There is also significant variance in the location of the defect in those with VFL on repeat testing. However, the variation in results on retesting did not significantly impact upon driving status from pass to fail or vice-versa. Variability in pass/fail frequencies was 12% in those with VFL. This variability was not found to be significant and hence there is good agreement across visits utilising the current fitness-to-drive criteria. An overlap zone of EES scores whereby a person can fail on one visit or pass on another is unable to be established due to the criteria of the DVLA fitness-to-drive assessment being based upon location and not upon score nor are presenting variance in scores across visits a predictive factor. However, those who present with an EES less than 77% are likely to fail and those who present a score of 90% or more are likely to pass. The EVFT possesses poor repeatability in those with VFL, with significant differences in EES across visits and significant pointwise variation across visits. However, the pointwise test-retest variation does not impact upon the EES between visits overall. The pointwise variation and the variation in EES also had no impact on altering driving licence status. Therefore, the EVFT possesses good repeatability determining fitness-to-drive status. However, Repeat tests are recommended in particular if a participant presents with an EES of 77-90% where there is a possibility they could have a pass/fail change on a subsequent visit. These results show that variability in the pass/fail status on the EVFT can occur across three visits. However, all participants who had inconsistent pass/fail results on the EVFT who had failed on visit 1, passed on visit 2. All participants who had failed on both visit 1 and on visit 2, did not pass on visit 3. Therefore, it is recommended that a retest occurs where a patient fails on their first attempt to allow for the possibility of passing on their second attempt.

There is a significant lack of agreement in the EES between the EVFT performed on the HFA and the Henson. The latter providing significantly lower scores in those with and without VFL. This provides support that contrast sensitivity is reduced for the lower background luminance of the Henson. However, there is no significant difference in EES for those with CFD, which may be linked to the lack of central stimuli presented by the EVFT. Overall, participants find making a decision on whether they have seen a target on the Henson more difficult than the HFA. Those with VFL have more retest

variability in EES, driven by those with NFD, than the controls. The EVFT performed on the Henson records more points that the test considers defective than the EVFT performed on the HFA There is no agreement in defect locations between perimeters. One hundred percent of those with VFL and 90.32% of the controls do not have an exact replication of defects with more variability being present in those with VFL. This variability is more prevalent in the lower visual field. There is more variability within the peripheral field in all participants. However, the retest variability and the examination being performed on the Henson does not impact upon an individual's driving status and hence the choice of perimeter will not impact on a person's quality of life. An overlap zone of EES to establish where a participant will pass on one test and fail on another is of no value. Although established that it will not impact on an individual's fitness-to-drive result, it is recommended that the EVFT is performed on the HFA where possible. Although the EVFT on the Henson records more points it considers defective, which can be considered a benefit, it makes for a more stressful examination on an examination already considered stressful. It is therefore recommended that this examination is performed on the HFA or where a Henson is utilised it is limited to a newer model of the Henson perimeter family whereby the background luminance and stimulus presented matches that of the HFA. The Henson 9000 is the newest Henson perimeter. The background luminance is 10 cd/m^2 and the target stimulus used for the EVFT is 100 cd/m^2. This equates to 31.40 asb and 314 asb respectively. Utilising the Weber fraction (Appendix 3) this still provides a calculated difference in the luminance difference threshold via the use of known formula.

The preceding Henson perimeter to the Henson 9000, the Henson 8000 had specifications of 10 cd/m^2 for the background luminance for the EVFT and a target stimulus of 318.40 cd/m^2. This provides equivalent values of 31.40 asb. and 1000 asb. respectively, which is nearly exact to the HFA EVFT specifications (Elektron-Eye-Technology. 2017a). The Henson 8000 is no longer in production and neither is the Henson 5000. The 8000 being replaced by the 9000 (Elektron-Eye Technology. 2017b). However, when something is no longer in production it does not follow that they will not be found in practices. Therefore, where possible the EVFT is currently recommended to be performed on the Henson 8000 or the HFA to ensure a match in background luminance. However, using a perimeter with lower background luminance to match the Henson Pro 5000 Perimeter has shown not to impact on the fitness-to-drive status.

The ROS perimeter has not been previously validated, and it is acknowledged that in retrospect a validation study should have been carried out first to determine that it

measures what it has been designed to measure, i.e. the visual field. Nevertheless, the study presented here shows that the ROS is not a suitable test for patients with established VFL and therefore brings into question whether the test is of any utility in clinical examination of patients. Of the examinations that were attempted on the study participants, one third had to be excluded due to the participant being unable to see the green moveable target. The green moveable target is required to be seen in order to conduct the test. This indicates that a large proportion of the population suffering VFL would not be able to examined by this perimeter. In addition, for those who are examined, the results suggest that the ROS is not reliable in determining those who have VFL.

The sensitivity values of the ROS FT examination are consistently and significantly lower than the HFA by an average of 7.07 dB in those with VFL and these differences increase at higher sensitivity values. The difference is more pronounced with a mean underestimation of 10.74 dB in those who do not have defective fields. Subsequently there is only moderate correlation between the sensitivities of the ROS FT and the HFA SITA Standard examinations and Bland and Altman plots confirm the lack of agreement between the examinations. If the ROS were to be used as a subsequent test in monitoring individuals for VFL the differences would lead to unnecessary referrals to the hospital eye service if based upon the sensitivity values. There was more variability in those with VFL which was driven by those with NFD. Using Bland and Altman plots, the bias of the controls is the furthest from zero than either the study or the study sub-groups indicating that the examinations are generating differing results and the test has no validity if sensitivity values are to be comparable to the HFA. The average range of sensitivity peaked at 21 dB for the ROS with a maximum sensitivity achieved among all participants of 30 dB compared to average peak sensitivity of 29 dB and maximum achieved with this cohort of 39 dB for the HFA, indicating that the ROS does not have as great a dynamic range to match that of the HFA. The lower sensitivity values and lack of dynamic range is likely to be due to the ROS presenting the stimuli at a pre-determined greyscale level obtained from five initial recordings, of when a participant identifies the stimulus, and the lack of point retesting. This strategy creates a ceiling effect and limits the dynamic range of this perimeter. The lack of retesting of locations means it is questionable that the perimeter is a threshold test and questions the manufacturers claim of this being called a FT examination. The ROS although presenting lower sensitivity values does not translate this within its Error Greyscale plot and the ROS was unable to generate a replication of the defect or the depth of the scotoma found with the HFA Probability Plot for each of

the participants. The range of differences between perimeters was significantly more in those participants with VFL indicating that the ROS is unlikely to accurately determine the depth and location of the defect in those with VFL as found by the HFA. The algorithm that translates sensitivity to defect requires re-evaluation. Pointwise analysis demonstrated a significant difference in greyscales between perimeters in those with VFL. There is a significant difference in unweighted MD between perimeters with no logical relationship found. An MD of -5 dB on the HFA provided a lower MD on the ROS (more negative), at -8 dB the ROS provided a higher MD (less negative) and had a difference of -2 dB when MD of -8 to -6 dB were produced by the HFA. The plotting of MD to defect produced an AUC of 0.202. When using the defect found on the HFA and plotting the MD of the ROS the cut-off required to produce acceptable sensitivity equated to poor specificity and an MD that would not include many defective fields determined on the HFA. Only at an MD of -8.00 dB would the ROS be able to indicate a field as defective, above this value (less negative) the ROS provides an area of uncertainty supporting the notion that the test currently has no value. The ROS misses 66.67% of defective fields providing sensitivity of 33.33% when employing the criteria outlined in the HPA grading. The lower sensitivity values and the lack of defective fields found currently contradict each other. The ROS does provide good fixation (82.14% of participants) but there is no gain in the reduced time of the examination for those who have VFL. The ROS was not preferred over the HFA by the participants overall. There is therefore no current ergonomic advantage based upon the questionnaire within this study.

The results of this study do not currently support the ROS being used for establishing presence of disease or eliminating the presence of disease and cannot currently replace established methods, It is currently not in agreement with the established method of the HFA perimeter and it is currently not validated in identifying persons with known visual defects. Nor do the results of the study validate the use of this perimeter to establish depth of VFL or the monitoring of VFL for progression.

In summary, results suggest that the ROS cannot be used by a third of those participants who have VFL. For those participants who are able to conduct the test on the ROS, results also suggest that it cannot determine VFL in two thirds of the participants who have VFL. The ROS is also unable to determine the depth and location of the defect in those with VFL as found by the HFA. Results do not currently support the ROS to be used in optometric practice to determine or monitor VFL and suggest this is not a suitable perimeter for those with VFL. The overall poor

performance of the ROS perimeter questions the validity of the perimeters design and the current format it utilises for examination of the visual field.

Therefore, it is recommended that the ROS is not used within practice to determine or monitor VFL. It is recommended that there is re-evaluation of the method used to determine the measured sensitivity and in addition, how this is translated into the Error Greyscale. The ROS has potential advantages by being an examination that can be conducted in domicillary settings and enabling more frequent examinations if it is developed to produce good sensitivity and specificity to determine defective fields. However, further research looking at potential algorithms, the method of determining the initial greyscale level of the target presented, the need for retesting of points to determine threshold, the use of smaller stimuli, the benefits of ametropic and presbyopic correction, fixation monitoring, choice of background luminance and ambient room illumination is required with the aim of increasing sensitivity and specificity.

7.1. Limitations.

Limitations of these studies have been discussed throughout. There are some limitations that are common to all the aforementioned studies which will be outlined here. One limitation common to all studies is the study participants. The participants were actively participating and engaging. The studies were not funded, giving rise to participants who were highly motiviated without a fee incentive. This leads to natural bias and does not lend itself to include participants who do not wish to engage with research and has the potential to overlook members of the population who do not read leaflets, are not engaged in charities and do not read publications issued by the charities where advertisements were placed. The small sample sizes for some of the subgroups have made determining conclusions for these categories difficult and are likely to have resulted in the low powers found within some of the insignificant results for these groups. This can allow for incorrect acceptance of the null hypothesis and prevent the results from being extrapolated (Faber & Fonseca. 2014). Differing ways of dividing the participants were considered to include only central visual field loss and peripheral visual field loss but this did not lead to an increase in any sub-group sample sizes due to the variety of visual field loss present within individual participants. Measurement bias was controlled for when evaluating the repeatability of the EVFT by using the same instrumentation for all three visits. For the studies whereby reproducibility was to be determined then use of the same instrument for all measurements was not a possibility due to the nature of these studies. Measurement

bias can be controlled by double blinding, this was however not possible due to the instruments having a different appearance and participants would be able to establish where the machine is different. The studies were limited to one researcher conducting all the examinations, however, human beings are not robust, and particularly when monitoring fixation loss, the clinicians possible fatigue, or possible inattention, can lead to unreliable examinations being considered reliable and subsequently being included within the data analyses. Unreliable tests being included within the data analyses would have a bearing on the accuracy of the statistical results. The zones chosen to enable eccentricity to be analysed, may have provided different results if different degrees from fixation were chosen for these zones. In particular, the central zone chosen to evaluate the ROS was large and it is possible this would encapsulate various defects and result in the increased variance of the results found within this central visual field. The use of habitual spectacles, which included progressive power lenses, means that results may have been impacted by rim artefacts and aberrations within the visual field. In addition, the vertex distances of the spectacles worn were not measured between visual field examinations. Differing vertex distances can cause differences in the available field of view between perimeters. These factors cannot be ruled out as a causative factor of variability. The Henson perimeter failed to record any false negatives and the ROS perimeter does not determine these. This impacts on determining attention (Bengtsson & Heijl. 2000) and unreliable test results may have been used within the data analyses. Cognitive function was not assessed objectively and this can have a bearing on attention for all the visual field examinations, in particular, the reaction times when undertaking the ROS examination, leading to lower sensitivities being recorded. Pupil sizes were not measured and optical clarity was not assessed. Fankhauser & Switzerland (1986) state that unless these two parameters are not perfectly identical, then the data gathered from perimetry is not truly comparable (Fankhauser & Switzerland. 1986). The studies were conducted across three visits. The first visit was the most comprehensive in terms of examinations performed (figure 3-3). This may have led to fatigue on the last test performed (randomised) which can have an impact upon the results. To assist with increasing the reliability of the visual field results used in the data analyses, fixation could have been subjectively graded to determine the quality of the response. In addition, the method used to determine the percentage of fixation losses for the study evaluating the ROS, by dividing the number recorded with the mean of the HFA checks, does not reflect the exact percentage of fixation losses, but provides a close estimate at best. Both these factors regarding the fixation monitoring can lead to unreliable examinations being

included within the analyses with the potential of impacting upon the accuracy of the statistical test results.

Driving licence status was not requested from the participants for the studies examining the EVFT, this means that not all of these participants would be likely to undergo an EVFT in real-life or be impacted by the result, this can lead to inflation presented in the studies on who the results will actually impact upon.

The use of the combined grid, aimed to solve the differences in grid designs when comparing the EVFT on the HFA and Henson perimeters. However, the use of this combined grid led to some stimulus locations, which would not map to a likewise plot, having to be eliminated from the analysis. This means that not all points were compared and it is unknown if these points would have had a bearing on the results.

The format of the ROS examination is significantly different to that of the HFA. This makes data difficult to compare and can lead to comparison of aspects that are not designed to be similar, but still measures the same function, simply requiring a different interpretation of the output. The ROS perimeter has had no previous validation, and it is acknowledged that a validity study, to determine that it measures what it has been designed to measure, i.e. the visual field, prior to further evaluation would have been an appropriate starting point. A further limitation within the study evaluating the ROS is the lack of calibration of the spatial and temporal characteristics of the instruments display. Lack of calibration can impact on the observers perceived image, and luminance output of the liquid crystal display's light source can change over time necessitating a maintenance of calibration. The perceived contrast of an uncalibrated liquid crystal display can vary greatly (Fetterly *et al*. 2008) providing uncertainty in the accuracy in the sensitivity values and defects recorded. The lack of chin-rest and head-rest with the design of the ROS perimeter does not enable the examination distance to be reliably ensured throughout the examination. This can give rise to differences in the angular subtense of the stimulus at the eye and subsequently give rise to variability within the results. In addition, the participants, although not naïve to perimetry, were naïve to being examined on the ROS. This may cause delayed response times to the target and subsequently leading to lower sensitivities being recorded.

7.2. Future work.

There was significant difference in EES between visits for those with VFL. However, it could not be established which type of VFL drove this difference. No statistical

differences were found in any sub-categories of VFL participants. This lack of statistical difference may have resulted from the small sample sizes in the sub-categories for VFL participants. Future work with larger sample sizes for the sub-categories of VFL participants may establish which type of VFL drove the difference. A large effect size was located within those with PFD. It is a possibility that this type of VFL had impact within the pooled data but was not located due to the small sample size. A larger sample of this type of VFL can be investigated to determine if this has impact on EES and consequently on any variance in fitness-to-drive status. In addition, the change in EES was not found to be significant for those who presented with inconsistent results across visits, however, a large effect size was established here and it needs to be considered if inclusion of more participants who present with PFD would have a bearing on results. A medium effect size with no significant differences found was also located in the Un participants for differences in EES across visits and hence, a larger cohort of these participants can also be worthwhile investigating if they will impact upon variance in fitness-to-drive status.

There is a lack of agreement between EES on the HFA and EES on the Henson in those with VFL. This was driven mainly by those with NFD. No significant difference was found in those with CFD, PFD or classified as Un. However, medium to large effect sizes were found for these groups. The lack of significance may be due to the low sample sizes in these cohorts and hence larger samples may show more significance between results and is a factor to explore.

Overall, larger sample sizes within the sub-categories of VFL would assist in any future research into the repeatability of the EVFT indicated by the large effect sizes found and the inability to locate in what type of VFL drove the difference in the EES.

The study to determine reproducibility of the EVFT utilised the Henson 5000 Perimeter. There are newer models of the Henson Perimeter family. The EVFT examination on the Henson 8000 has the same stimulus and background luminance parameters as the HFA EVFT. To determine if the EVFT is reproducible on the HFA and Henson 8000 and subsequent models is still to be undertaken.

The EVFT has many limitations and many tests have been researched as valid replacements. The stimulus used for the EVFT is considered bright, and hence only determines deep defects (Rauscher *et al*. 2007). To solve the problem of only determining deep defects a FT examination could be considered to be more appropriate. However, the increased time of conducting the EVFT as a FT examination

is likely to increase fatigue. Another limitation of the EVFT is the sparse and uneven sampling across the visual field, in particular the lack of test points within the central field, which can mean CFDs go undetected (Owen *et al*. 2008). To solve this limitation it can be considered that inclusion of evenly spaced test areas, which include the largely untested central field, would be more appropriate. This however, would increase the number of test points examined, subsequently increasing the examination time. This would also have a bearing on fatigue. Therefore, further research is required to establish the appropriate level of the stimulus that needs to be presented, and in addition, the minimum amount of stimuli that needs to be presented to determine fitness-to-drive to limit increased duration of the test. A research project to determine these parameters utilising MVCs as the arbiter would appear appropriate for a fitness-to-drive examination. The use of vision in driving is not limited to the measured available visual field. It is also dependent on various other factors that have been previously discussed in section 1.9. Therefore, it would be more fitting to look at alternative examinations that examine more than the available visual field in an examination determining fitness-to-drive. The UFOV examination has demonstrated a link to MVCs and examines processing speed, divided attention and selective attention (Crabb *et al*. 2004). One of the limitations of the UFOV examination, and other examinations that have been researched to assess fitness-to-drive, lies in the lack of their fulfilment of the current DVLA criteria by not examining 120º of the visual field. Most of the tests researched limit examination of the visual field to the central 30º. Expanding the UFOV examination to include examination of 120º of visual field may allow this examination to be considered as a replacement to the EVFT. The effect of this expansion would need further research to validate the expanded examination, and again further research using MVCs as the arbiter to determine the point of pass/fail for this expanded field examination.

The ROS perimeter has had no previous validation. This perimeter requires further research to determine that it measures what it has been designed to measure, i.e. the visual field. A new strategy of determining threshold is required with the aim to create a valid staircase procedure. This has been achieved in the AFOV examination, which records the threshold presentation time via a staircase method (Coekelbergh *et al*. 2004). It is recommended that the strategy used by the AFOV is considered to avoid a ceiling effect and to increase the dynamic range. The ROS also needs to determine how the sensitivity values recorded should translate to the Error Greyscale plot. To do this it needs further investigation against an established perimeter such as the HFA to determine what sensitivity value locates the same level of defect. The natural variance

of the examination also needs to be established. Therefore, the repeatability of the examination needs to also be established, prior to reproducibility. In addition, the benefits of ametropic and presbyopic correction, fixation monitoring, use of head and chin-rests and the choice of background luminance and ambient room illumination should be considered and investigated with the aim of increasing sensitivity and specificity.

7.3. Summary.

7.3.1. What was known before?

Visual fields suffer from variability. Variability is increased where sensitivity is reduced.

Losing a driving licence is a significant life event and can lead to depression and reduce quality of life.

There is some evidence to support a link to VFL and MVCs.

The EVFT is to be conducted with a uniform stimulus of 10 dB.

There is a rise in threshold as the luminance of the background rises.

Larger stimuli increase dynamic range and decrease variability, but have less resolution than smaller stimuli for detecting small scotomas.

7.3.2. What these studies add?

The EVFT has poor repeatability of EES and defect location in those with VFL.

The EVFT has poor reproducibility of EES and defect location for those with and without VFL when comparing perimeters with differing background luminance.

The EVFT has good repeatability of fitness-to-drive status on subsequent visits.

The EVFT has good reproducibility of fitness-to-drive status when using perimeters with differing background luminance.

The poor repeatability and poor reproducibility in EES and defect location of the EVFT does not impact upon an individuals driving licence status and hence would not contribute to depression, reduced quality of life or an increase in MVCs due to VFL.

Conducting the EVFT on the Henson 5000 records more defective points than those found by the HFA but does not impact upon driving licence status.

The ROS is unlikely to be able to be utilised by a third of those with VFL, and if used, is likely to miss 66.67% of visual field defects.

Where the ROS records defects, they are unlikely to be recorded to the same depth or at the same location as found on the HFA.

7.3.3. Clinical Recommendations.

The EES alters significantly at differing testing sessions leading to a clinical recommendation that where a person fails the EVFT on their first test, they are retested, particularly when their score is within the 77-90% EES range. Within this range, they are more likely to pass on a second examination.

It is also recommended that the EVFT examination is performed on the HFA to account for variance in EES and defect location between perimeters to avoid unnecessary difficulty to an already stressful examination.

Overall, the ROS perimeter is unsuitable for use in those with VFL and possesses low sensitivity of 33.33%. It is therefore recommended that this perimeter is not used in practice.

References

Acton, J., (2010). *Visual field and structural alterations in age-related macular degeneration*. Ph.D. thesis. Aston University.

Alberti, C., Horowitz, T., Bronstad, M. & Bowers, A., (2014). Visual Attention Measures Predict Pedestrian Detection in Central Field Loss: A Pilot Study. *Plos One*. [online]. **9**(2). 1-7. [Viewed 05 November 2016]. Available from: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0089381

Alberti, C., Peli. E. & Bowers, A., (2014). Driving with hemianopia: III. Detection of stationary and approaching pedestrians in a simulator. *The Association of Research in Vision and Ophthalmology*. [online]. **55**. 368-374. [Viewed 05 January 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/24346175

Alencar, L. & Medeiros, F., (2011). The role of standard automated perimetry and newer functional methods for glaucoma diagnosis and follow-up. *Indian Journal of Ophthalmology*. [online]. **59**(1). 53-58. [Viewed 17 October 2014]. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3038506/

Akoglu, H., (2018). User's guide to correlation coefficients. *Turkish Journal of Emergency Medicine*. [online]. **18**(3). 91-93. [Viewed 27 October 2019]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6107969/

Alqudah, A., Mansberger, S., Gardiner, S. & Demirel, S., (2016). Vision-related Quality of Life in Glaucoma Suspect or Early Glaucoma Patients. *Journal of Glaucoma*. [online]. **25**(8). 629-633. [Viewed 14 August 2018]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/27483331

Argus, W. & Brenton, R., (1986). Background illumination and perimetry. *Archives of Ophthalmology*. **104**.1124.

Armstrong, R. & Eperjesi, F., (2005). Data analysis methods in optometry. Part 5: correlation. *Optometry Today*. **Feb 25**. 34-37.

Artes, P., Henson, D. & Chaudry, S., (2001). Pointwise pass/fail criteria in suprathreshold perimetry. In: M. Wall, R. Mills, eds. *14th International Perimetric Society Visual Field Symposium. 06-09 September, Halifax, Canada.* Amsterdam, Netherlands: Kugler Publications. pp. 283-291.

Artes, P., Henson, D., Harper, R. & McLeod, D., (2003). Multisampling suprathreshold perimetry: a comparison with conventional suprathreshold and full-threshold strategies by computer simulation. *Investigative Ophthalmology and Visual Science*. [online]. **44**(6). 2582-2587. [Viewed 29 October 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/12766060

Artes, P., Iwase, A., Ohno, Y., Kitazawa, Y. & Chauhan, B., (2002). Properties of Perimetric Threshold Estimates from Full Threshold, SITA Standard, and SITA Fast Strategies. *Investigative Ophthalmology and Visual Science*. [online]. **43**(8). 2654-2659. [Viewed 08 May 2017]. Available from: http://iovs.arvojournals.org/article.aspx?articleid=2124008

Artes, P., McLeod, D. & Henson, D., (2002). Response time as a discriminator between true- and false-positive responses in suprathreshold perimetry. *Investigative*

Ophthalmology and Visual Science. [online]. **43**(1). 129-132. [Viewed 29 October 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/11773022

Aslam, T., (2011). A novel paediatric game-based visual-fields assessor. *British Journal of Ophthalmology*. [online]. **95**(7). 921-924. [Viewed 01 November 2016]. Available from: http://bjo.bmj.com/content/95/7/921

Asman, P., Fingeret, M., Robin, A., Wild, J., Pacey, I., Greenfield, D., Liebmann, J. & Ritch, R., (1999). Kinetic and Static Fixation Methods in Automated Threshold Perimetry. *Journal of Glaucoma*. [online]. **8**(5). 290-6. [Viewed 07 June 2017]. Available from: https://www.growkudos.com/publications/10.1097%25252F00061198-199910000-00003/reader

Atchley, P. & Chan, M., (2011). Potential benefits and costs of concurrent task engagement to maintain vigilance: a driving simulator investigation. *Human Factors*. [online]. **53**. 3-12. [Viewed 04 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/21469529

Authié, C. & Mestre, D., (2011). Optokinetic nystagmus is elicited by curvilinear optic flow during high speed curve driving. *Vision Research*. [online]. **51**. 1791-1800. [Viewed 01 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/21704061

Ayala, M., (2012). Comparison of the monocular Humphrey Visual Field and the binocular Humphrey Esterman Visual Field test for driver licensing in glaucoma subjects in Sweden. *Biomed Central Ophthalmology.* [online]. **12**(35). 1-7. [Viewed 08 May 2017]. Available from: https://www.researchgate.net/publication/230628711_Comparison_of_the_monocular_Humphrey_Visual_Field_and_the_binocular_Humphrey_Esterman_Visual_Field_test_for_driver_licensing_in_glaucoma_subjects_in_Sweden

Bach, K., Jaegar, M., Skov, M. & Thomassen, N., (2009). Interacting with in-vehicle systems: understanding, measuring and evaluating attention. In: A. Blackwell, ed. *Proceedings of the 23rd british HC1 group animal conference on people and computers: celebrating people and technology*, *01-05 September 2009, Cambridge, U.K.* [online]. London: The British Computer Society. pp. 453-462. [Viewed 09 October 2016]. Available from: https://pdfs.semanticscholar.org/8973/43e1a63761c7dd1b156f2d92ac07e6cd1fa7.pdf

Ball, K. & Owsley, C., (1993). The useful field of view test: a new technique for evaluating age-related declines in visual function. *Journal of the American Optometric Association*. **64**(1). 71-9. [Viewed 08 April 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/8454831

Ball, K., Roenker, D., Wadley, V., Edwards, J., Roth, D., McGwin, G., Raleigh, R., Joyce, J., Cissell, G. & Dube, T., (2006). Can high-risk older drivers be identified through performance-based measures in a Department of Motor Vehicles setting. *The American Geriatrics Society*. [online]. **54**. 77-84. [Viewed 11 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16420201

Barton, K., Nolan, W. & Strouthidis, N., (2015). Clinical and management strategies in glaucoma practice perspectives from international glaucoma specialists. *Eyenews*. **21**(6): 14-20.

Bengtsson, B. & Heijl, A., (2000). False negative responses in glaucoma perimetry: Indicators of patient performance or test reliability? *Investigative Ophthalmology and*

Visual Science. [online]. **41**(8). 2201- 2204. [Viewed 20 April 2018]. Available from: http://iovs.arvojournals.org/pdfaccess.asbx?url=dara/journals/iovs/932908/

Bengtsson, B., Olsson, J., Heijl, A. & Rootzen, H., (1997). A new generation of algorithms for computerised threshold perimetry, SITA. *Acta Ophthalmologica Scandinavica*. [online]. **75**. 368-375. [Viewed 21 April 2015]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/9374242

Bentley, S., Le Blanc, R., Nicolela, M. & Chauhan, B., (2012). Validity, reliability, and repeatability of the useful field of view test in persons with normal vision and patients with glaucoma. *Investigative Ophthalmology and Visual Science*. [online] **55**(11). 6793-6769. [Viewed 05 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/22956614

Bergin, C., (2011). *Improving measurements in perimetry for glaucoma*. Ph.D. thesis, City University London. [Viewed 24 September 2016]. Available from: http://openaccess.city.ac.uk/930/1/Bergin_PhD_Thesis.pdf

Betz-Stablin, B., Morgan, W., House, P. & Hazelton, M., (2013). Spatial modelling of visual field data for assessing glaucoma progression. *Investigative Ophthalmology and Visual Science*. [online]. **54**(2). 1544-1553. [Viewed 09 September 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/23341021

Bhargava, J., Patel, B., Foss, A., Avery, A. & King, A., (2006). Views on glaucoma patient aspects of their treatment: an assessment of patient preference by conjoint analysis. *Investigative Ophthalmology and Vision Science*. [online]. **47**(7). 2885-2888. [Viewed 07 April 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16799029

Bhorade, A., Yom, V., Barco, P., Wilson, B., Gordon, M. & Carr, D., (2016). On-road Driving Performance of Patients with Bilateral Moderate and Advanced Glaucoma. *American Journal of Ophthalmology*. [online]. **166**. 43-51. [Viewed 09 June 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/26949136

Birch, M., Wishart, P. & O'Donnell, N., (1995). Determining progressive visual field loss in serial humphery visual fields. *Ophthalmology*. [online]. **102**. 1227-1235. [Viewed 02 September 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/9097752

Birmingham, E., Bischof, W. & Kingstone, A., (2009). Saliency does not account for fixations to eyes within social scenes. *Vision Research*. [online]. **49**. 2992-3000. [Viewed 02 October 2016]. Available from: http://www.sciencedirect.com/science/article/pii/S0042698909004325

Bland, J. & Altman, D., (2003). Applying the right statistics: Analyses of measurement studies. *Ultrasound in Obstetrics and Gynecology*. [online]. **22**. 85-93. [Viewed 07 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/12858311

Bland, J. & Altman. D., STATISTICAL METHODS FOR ASSESSING AGREEMENT BETWEEN TWO METHODS OF CLINICAL AGREEMENT. [online]. 1-9. [Viewed 08 May 2018]. Available from: https://www-users.york.ac.uk/~mb55/meas/ba.pdf

Blane, A., (2016). Through the Looking Glass: A Review of the Literature Investigating the Impact of Glaucoma on Crash Risk, Driving Performance, and Driver Self-Regulation in Older Drivers. *Journal of Glaucoma*. [online]. **25**(1). 113-121. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/25493623

Bowers, A., Elgin, J., McGwin, G. & Owsley, C., (2005). On-Road Driving with Moderate Visual Field Loss. *Optometry and Vision Science*. [online]. **82**(8). 657-667. [Viewed 06 January 2017]. Available from: http://serinet.meei.harvard.edu/faculty/peli/papers/vfe_paper_ovs_published.pdf

Bowers, R., Mandel, A., Goldstein, R. & Peli, E., (2009). Driving with hemianopia, I: Detection performance in a driving simulator. *Investigative Ophthalmology and Visual Science*. [online]. **50**(11). 5137-5147. [Viewed 04 January 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19608541

Bowers, A., Mandel, A., Goldstein, R. & Peli, E., (2010). Driving with Hemianopia, II: Lane Positioning and Steering in a Driving Simulator. *Investigative Ophthalmology and Visual Science*. [online]. **51**(12). 6605-6613. [Viewed 11 February 2016]. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3055772/

Bozzani, F., Alavi, Y., Jofre-Bonet, M. & Kuper, H., (2012). A comparison of the sensitivity of EQ-5D, SF-6D and TTO utility values to changes in vision and perceived visual function in patients with primary open-angle glaucoma. *Biomed Central Ophthalmology*. [online]. **12**(43). 1-9. [Viewed 01 November 2017]. Available from: https://bmcophthalmol.biomedcentral.com/articles/10.1186/1471-2415-12-43

Bronstad, P., Albu, A., Bowers, A., Goldstein, R. & Peli, E., (2015). Driving with Central Visual Field Loss II: How Scotomas Above or Below the Preferred Retinal Locus (PRL) Affect Hazard Detection in a Driving Simulator. *Plos One*. [online]. 1-11. [Viewed 05 November 2016]. Available from: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0136517

Bronstad, P., Bowers, A., Albu, A. & Goldstein, R., (2013). Driving with central vision loss I: effect of central scotomas on responses to hazards. *Jama Ophthalmology*. **131**(1). 303-309. [Viewed 07 March 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23329309

Brouzas, D., Tsapakis, S., Nitoda, E. & Moschas, M., (2014). Visual field examination using a video projector: comparison with Humphrey perimeter. *Clinical Ophthalmology*. [online]. **8**. 523-526. [Viewed 01 April 2018]. Available from: https://www.researchgate.net/publication/260950676_Visual_field_examination_using_a_video_projector_comparison_with_Humphrey_perimeter

Brunn-Jensen, J., (2011). Visual screening with a laptop computer system. *Optometry*. [online]. **82**. 519-527. [Viewed 18 November 2016]. Available from: https://www.sciencedirect.com/science/article/pii/S1529183911003885

Brusini, P., Salvetat, M. & Zeppieri, M., (2005). Probing glaucoma visual damage by rarebit perimetry. *British Journal of Ophthalmology*. [online]. **89**. 180-184. [Viewed 02 September 2016]. Available from: https://bjo.bmj.com/content/89/2/180

Castro, D., Kawasw, J. & Melo, L., (2008). Learning effect of standard automated perimetry in healthy individuals. *Arquivos Brasileiros de Oftalmologia*, [online] **71**(4):523-528. [Viewed 08 January 2018]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/18797662

Cengiz, C., Puolakka, M. & Halonen, L., (2015). Reaction time measurements under mesopic light levels: Towards estimation of the visual adaption field. *Lighting Research*. [online]. **47**. 828-844. [Viewed 06 January 2016]. Available from: http://journals.sagepub.com/doi/abs/10.1177/1477153514554494

Chaudhuri, A. & Behan, P., (2004). Fatigue in neurological disorders. *The Lancet*. [online]. 363(9413). 978-988. [Viewed 24 September 2019]. Available from: https://www.sciencedirect.com/science/article/pii/S0140673604157942?via%3Dihub

Chauhan, B. & Johnson, C., (1999). Test-retest variability of frequency-doubling perimetry and conventional perimetry in glaucoma patients and normal subjects. *Investigative Ophthalmology and Visual Science*. [online]. **40**. 648-656. [Viewed 17 January 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/10067968

Cheung, S., Klein, H., Bartsch, D., Kozak, I., Marcotte, T. & Freeman, W., (2011). Relationship between retinal nerve fiber layer thickness and driving ability in patients with human immunodeficiency virus infection. *Graefes Archive of Clinical Experimental Ophthalmology*. [online]. **249**. 1643-1647. [Viewed 10 March 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21732109

Chisholm, C., (2008b). Visual requirements for driving. *Optometry Today*. [online]. **25/01/08**. 40-44. [Viewed 28 August 2014]. Available from: http://www.optometry.co.uk/uploads/articles/Jan%2025%2008%20Clinical%20driving.pdf

Chisholm, C., Rauscher, F., Crabb, D., Davies, L., Dunne, M., Edgar, D., Harlow, J., James-Galton, M., Petzold, A., Plant, G., Viswanathan, A., Underwood, G. & Barbur, J., (2008a). Assessing visual fields for driving in patients with paracentral scotoma. *British Journal of Ophthalmology*. [online]. **92**. 225-230. [Viewed 23 March 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/17962396

Chun, M. & Jiang, Y., (1999). TOP-DOWN ATTENTIONAL GUIDANCE BASED IN IMPLICIT LEARNING OF VISUAL COVARIATIONS. *Psychological Science*. [online]. **10**(4). 360-365. [Viewed 08 October 2016]. Available from: http://journals.sagepub.com/doi/abs/10.1111/1467-9280.00168

Church, A., (2014). Henson_9000_manual_english. *Elektron Technology*. [online]. 1-137. [Viewed 14 July 2017]. Available from: https://www.dropbox.com/s/47gfbcz8y5maigv/Henson_9000_Manual_English.pdf?dl=0

Clay, O., Wadley, V., Edwards, J., Roth, D., Roenker, D. & Ball, K., (2005). Cumulative meta-analysis of the relationship between useful field of view and driving performance in older adults: current and future implications. *Optometry and Vision Science*. [online]. **82**(8). 724-731. [Viewed 03 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16127338

Cubbidge, R., (2005). *Visual Fields.* London: Butterworth and Heinemann.

Cochran, M., Mahabadi, N., Czyz, C., (2019). *Branch Retinal Vein Occlusion (BRVO)*. Treasure Island, Florida: StatPearl Publishing.

Coeckelbergh, T., Brouwer, W., Cornelisson, F. & Kooijman, A., (2004). Predicting practical fitness to drive in drivers with visual field defects caused by ocular pathology. *Human Factors*. [online]. **46**(4). 748-760. [Viewed 04 January 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/15709335

Coeckelbergh, T., Brouwer, W., Cornelissen, F., Wolffelaar, P. & Kooijman, A., (2002b) The Effect of Visual Field Defects on Driving Performance. *Archives of Ophthalmology* [online].**120**. 1509-1516. [Viewed 04 February 2015]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/12427065

Coeckelbergh, T., Cornelissen, F., Brouwer, W. & Kooijman, A., (2002a) The effect of visual field defects on eye movements and practical fitness to drive. *Vision Research* [online]. **42**. 669-677. [Viewed 03 February 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/11853783

The College of Optometrists, (2017). Assessing and managing patients with low vision. [online]. *The College of Optometrists*. [Viewed 09 August 2019]. Available from: https://guidance.college-optometrists.org/guidance-contents/knowledge-skills-and-performance-domain/assessing-and-managing-patients-with-low-vision/#open:120,121

The College of Optometrists, (2019). The domicillary eye exam. [online]. *The College of Optometrists*. [Viewed 29 August 2019]. Available from: https://guidance.college-optometrists.org/guidance-contents/knowledge-skills-and-performance-domain/the-domiciliary-eye-examination/

Conway, M., Hosking, S., Zhu, H. & Cubbidge, R., (2014). Does Swedish Interactive Threshold Algotithm (SITA) accurately map visual field loss attributed to vigabatrin? *Biomed Central Ophthalmology*. [online]. **14**. 1-10. [Viewed 02 November 2017]. Available from: https://bmcophthalmol.biomedcentral.com/articles/10.1186/1471-2415-14-166

Costa, M., Simone, A., Vignali, V., Lantieri, C., Bucchi, A. & Dondhi, G., (2014). Looking behaviour for vertical road signs. *Transportation Research Part F*. [online]. **23**. 147-155. [Viewed 02 October 2016]. Available from: http://www.sciencedirect.com/science/article/pii/S1369847814000126

Crabb, D., Edgar, D., Fitze, F., Mcnaught, A. & Wynn, H., (1995). New approach to estimating variability in visual field data using an image processing technique. *British Journal of Ophthalmology*. [online]. **79**. 213-217. [Viewed 01 September 2015]. Available from: http://bjo.bmj.com/content/bjophthalmol/79/3/213.full.pdf

Crabb, D., Fitzke, F., Hitchings, R. & Visawanathan, A., (2004). A practical approach to measuring the visual field component of fitness to drive. *British Journal of Ophthalmology*. **88**. 1191-1196. [Viewed 02 September 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/15317714

Crabb, D., Smith, N., Rauscher, F., Chisholm, C., Barbur, J., Edgar, D. & Garway-Heath, D., (2010). Exploring eye movements in patients with glaucoma when viewing a driving scene. *Plos One.* [online]. **5**(3). 1-10. [Viewed 09 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/20300522

Crabb, D. & Viswanathan, A., (2005). Integrated visual fields: a new approach to measuring the binocular field of view and visual disability. *Graefe's Archive of Clinical and Experimental Ophthalmology*. [online]. **243**. 210-216. [Viewed 06 November 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/15806374

Crabb, D., Viswanathan, A., McNaught, A., Poinoosawmy, D., Fitzke, F. & Hitchings, R., (1998). Simulating binocular visual field status in glaucoma. *British Journal of Ophthalmology*. [online]. **82**. 1236-1241. [Viewed 22 March 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/9924324

Cross, J., McGwin, G., Rubin, G., Ball, K., West, S., Roenker, D. & Owsley, C., (2009). Visual and Medical Risk Factors for Motor Vehicle Involvement among Older Drivers. *British Journal of Ophthalmology*. [online]. **93**. 400-404. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2747632/

Crundall, D., Underwood, G. & Chapman, P., (1999). Driving experience and the functional world. *Perception*. **26**. 1075-1087.

Cubbidge, R., (1997). *Examination variability in short-wavelength automated perimetry*. Ph.D. thesis. Aston University.

Cubbidge, R., (2005). *Visual Fields.* London: Butterworth and Heinemann.

Cubbidge, R., (2012). 'Visual fields' [PowerPoint presentation].

Daniel, M. & Jacobson, M., (1997). The Localising Value of a Quadrantanopia. *Archives of Neurology.* [online]. **54**(4). 401-404. [Viewed 10 August 2017]. Available from: https://jamanetwork.com/journals/jamaneurology/article-abstract/594510?redirect=true

de Vries, M., Stoutenbeek, R., Müskens, R. & Jansonius, N., (2012). Glaucoma screening during regular optician visits: the feasibility and specificity of screening in real life. *Acta Ophthalmologica.* [online]. **90**. 115-121. [Viewed 06 September 2016]. Available from: https://www.ncbi.nlm.nih.gov/m/pubmed/22268769/

Delgado, M., Nguyen, N., Cox, T., Singh, K., Lee, D., Dueker, D., Fechtner, R., Juzych, M., Lin, S., Netland, P., Pastor, S., Schuman, J. & Samples, J., (2002). Automated perimetry: a report by the American Academy of Ophthalmology.*The American Academy of Ophthalmology*. [online]. **109**. 2362-2374. [Viewed 02 September 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/12466186

Deng, L., Demirel, S. & Gardiner, S., (2014). Reducing variability in visual field assessment of glaucoma through filtering that combines structural and functional information. *The Association for Research in Vision and Ophthalmology*. [online]. **55**(7). 4593-4602. [Viewed 09 September 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/24970252

Dengler-Harles. M. (1991). *The detection of automated perimetric stimuli in ocular disease*. Ph.D. thesis, Aston University. [Viewed 02 September 2014]. Available from: https://research.aston.ac.uk/portal/en/theses/the-detection-of-automated-perimetric-stimuli-in-ocular-disease(34245878-fd44-457e-bac3-693c1f613539).html

Dengler-Harles, M., Wild, J., Cole, M., O'Neill, E. & Crews, S., (1990). The influence of forward light scatter on the visual field indices in glaucoma. *Graefe's Achive of Ophthalmology*. [online]. **228**. 326-331. [Viewed 05 September 2014]. Available from: https://link.springer.com/article/10.1007/BF00920056

Department of Transport, (2014). Reported Road Casualties Great Britain: 2014 Annual Report. Contributing factors to reported road accident 2014. [online]. London: Department of Transport. [Viewed 03 January 2017]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/463043/rrcgb2014-02.pdf

Department of Transport, (2017). Reported Road Casualties Great Britain: 2016 annual report. Moving Britain Ahead. [online]. London: Department of Transport. [Viewed 07 January 2018]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/668504/reported-road-casualties-great-britain-2016-complete-report.pdf

Department of Transport, (2016). Transport Statistics Great Britain 2016. [online]. London: Department of Transport. [Viewed 07 January 2018]. Available from: fingertips.phe.org.uk/documents/Transport-stats-2016-DfT.pdf

Di Stasi, L., McCamy, M., Pannasch, S., Renner, R., Catena, A., Canas, J., Velichkovsky, B. & Martinez-Conde, S., (2015). Effects of driving time on microsaccadic dynamics. *Experimental Brain Research*. [online]. **233**. 599-605. [Viewed 04 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/25417191

Donaldson, B., (2016a). *Re: Ros*. Email: wbmdonaldson@doctors.org.uk

Donaldson, B., (2016b). *Ring of Sight*. Email. wbm.donaldson@doctors.org.uk

Dorosz, J., Dybezynski, W. & Rafalowski, M., eds. (2003). *Lightmetry 2002: Metrology & Testing Techniques Using Light, 14-16 May 2002, Warsaw, Poland* [online]. SPIE. The International Society for Optics and Photonics. [Viewed 10 October 2016]. Available from: http://adsabs.harvard.edu/abs/2003SPIE.5064...22D

Doshi, A. & Trivedi, M., (2012). Head and eye gaze dynamics during visual attention shifts in complex environments. *Journal of Vision*. [online]. **12**(2). 1-16. [Viewed 01 October 2016]. Available from: http://jov.arvojournals.org/article.aspx?articleid=2121395

Dow, J., (2011). Visual field defects may not affect safe driving. *Traffic injury Prevention*. [online]. **12**. Abstract only. [Viewed 27 April 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21972859

Doyle, M. & Walker, R., (2001). Curved saccadic trajectories: voluntary and reflective saccades curve away from irrelevant distractions. *Experimental Brain Research*. [online]. **139**(3). 333-344. [Viewed 09 October 2016]. Available from: https://link.springer.com/content/pdf/10.1007/s002210100742.pdf

Drance, S., (1972). The glaucomatous visual field. *British Journal of Ophthalmology*. [online]. **56**. 186-200. [Viewed 30 September 2019]. Available from: https://bjo.bmj.com/content/bjophthalmol/56/3/186.full.pdf

Driver and Vehicle Licensing Agency, (2011). Static visual field defects-new process. *Driver and Vehicle Licensing Agency*. [online]. [Viewed 07 April 2016]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/207075/Govuk_-_Static_visual_field_defect.pdf

Driver and Vehicle Licensing Agency, (2014). For medical practitioners at a glance guide to the current medical standards of fitness to drive. *Driver and Vehicle Licensing Agency.* [online]. 50-52. [Viewed 24 September 2014]. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/351444/aagv1.pdf

ECOO, (2011). Report on Driver Vision Screening in Europe. *EC Directives*. [online]. 1-12. [Viewed 23 September 2014]. Available from: http://www.ecoo.info/wp-content/uploads/2012/07/ReportonDriverVisionScreeninginEurope.pdf

Edwards, J., Vance, D., Wadley, V., Cissell, G., Roenker, D. & Ball, K., (2005). Reliability and Validity of Useful Field of View Test Scores as Administered by Personal Computer. *Journal of Clinical and Experimental Neurophysiology*. **27**(5). 529-543. [Viewed 12 October 2016]. Available from: https://www.tandfonline.com/doi/abs/10.1080/13803390490515432

Elektron-Eye-Technologies, (2017b). Henson 9000: Technical Profile. [online]. *Elektron-Eye-Technologies*. [Viewed 11 July 2017]. Available from:

https://www.elektron-eye-technology.com/products/henson-9000-perimeter/henson-9000-technical-profile/#tech-spec

Elektron-Eye-Technologies, (2017a). Henson Perimeter User Manual. *Elektron Technology*. [online]. 1-159. [Viewed 13 July 2017]. Available from: https://www.elektron-eye-technology.com/wp-content/uploads/2017/03/Henson_8000_manual_1.4.pdf

Elliot, A. & Newman, B., (2013). Royal College of Ophthalmologists. Vision Standards for Driving. *Royal College of Ophthalmologists*. [online]. [Viewed 25 April 2016]. Available from: https://www.rcophth.ac.uk/wp-content/uploads/2014/12/2013_PROF_216_Vision_Standards_for_Driving_April_2013.pdf

Eloholma, M., Viikari, M., Halonan, L., Walkey, H., Goodman, T., Alferdinck, J., Freiding, A., Bodrogi, P. & Várady, G., (2005). Mesopic-models-from brightness matching to visual performance in night-time driving: a review. *Lighting Research and Technology.* [online]. **37**(2), 155-175. [viewed 09 October 2016]. Available from: http://journals.sagepub.com/doi/abs/10.1191/1365782805li135oa?journalCode=lrtd

Ernest, P., Schouten, J., Beckers, H., Hendrikse, F., Prins, M. & Webers, C., (2012). The evidence base to select a method for assessing glaucomatous visual field progression. *Acta Ophthalmologica*. [online]. **90**. 101-108. [Viewed 06 January 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/21812943

Esterman, B., (1967). Grid for scoring visual fields: I. Tangent screen. *Archives of Ophthalmology.* [online]. **77**. 780-786. [Viewed 10 October 2014]. Available from: http://archopht.jamanetwork.com/

Esterman, B., (1968). Grid for scoring visual fields. *Archives of ophthalmology*. **79**. 400-406.

Esterman, B., (1981). Grids for functional scoring of visual fields. *Documenta Ophthalmologica Proceeding Series*. **26**. 373-380.

Esterman, B., (1982). Functional scoring of the binocular field. *Ophthalmology*. **89**. 1226-1240.

Esterman. B., (1983). Functional scoring of the binocular visual field. In: E. Greve, A. Heijl, eds. *Fifth international visual field symposium, 20-23 October 1982, Sacramento.* The Netherlands: Dr W. Junk Publishers. 187-192.

Esterman, B., (1984). The functional visual field in abnormal conditions. In: A. Heijl, E. Greve, eds. *Proceedings of the 6th international visual fields symposium, 27-31 May 1984, Santa Margherita Ligure*. The Netherlands: Dr W. Junk Publishers. 281-292.

Esterman, B., (1985). The occupational visual field: II. Practical aspects: the functional visual fields in abnormal conditions and its relationship to visual ergonomics. Visual impairment and job fitness. In: G, Verriest, ed. *Visual field: 6th international symposium: papers, 27-31 May 1984, Santa Margherita Ligure*. The Netherlands: Dr W. Junk Publishers. 281-326.

Faber, J. & Fonseca, L., (2014). How sample sizes influence research outcomes. *Dental Journal Press of Orthodontics*. [online]. **19**(4). 27-29. [Viewed 30 October 2019]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4296634/

Falkmer, T., Nilsson, L. & Törnos, J., (2000). Detection and identification of information presented peripherally inside the car. *Swedish National road and Transport Research Institute*. [online]. [Viewed 02 October 2016]. Available from: https://www.vti.se/en/Publications/Publication/detection-and-identification-of-information-presen_670545

Fankhauser, F., (1979). Problems related to the design of automatic perimeters. *Documenta Opthalmologica*. **47**(1). 89-138.

Fankhauser, F. & Bebie, H., (1978). Threshold fluctuations, Interpolations and Spatial Resolution in Perimetry. In: E. Greve, ed. (1978). *Third International Visual Symposium, May 3-6 1978, Tokyo* [online]. Netherlands: Springer Netherlands. Volume 19. [Viewed 27 August 2016]. Available from: https://link.springer.com/chapter/10.1007%2F978-94-009-9611-3_33

Fankhauser, F. & Haeberlin, H., (1980). DYNAMIC RANGE AND STRAY LIGHT. AN ESTIMATE OF THE FALSIFYING EFFECTS OF STRAY LIGHT IN PERIMETRY. *Documenta Ophthalmologica*. **50**. 143-167. [Viewed 30 October 2015]. Available from: https://link.springer.com/article/10.1007/BF00161159

Fankhauser, F. & Switzerland, B., (1986). Background illumination and perimetry. *Archives of Ophthalmology*. **104**(8). 1126.

Faul, F., Erdfelder, E., Lang, A. & Buchner, A., (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*. [online]. **39**. 175-191. [Viewed 13 March 2016]. Available from: https://link.springer.com/content/pdf/10.3758/BF03193146.pdf

Fellman, R., (1995). Discussion of Determining progressive visual field loss in serial Humphrey visual fields by Ronald L. Fellman, MD. *Ophthalmology.* [online]. **102**(8). 1234-1235. [Viewed 02 September 2014]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/9097752

Fetterly, K., Blume, H., Flynn, M. & Samei, E., (2008). Introduction to grayscale calibration and related aspects of medical imaging grade liquid crystal displays. *Journal of Digital Imaging*. [online]. **21**(2). 193-207 [Viewed 05 November 2019]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/17333412

Fonda, S., Wallace, R. & Herzog, A., (2001). Changes in Driving Patterns and Worsening Depressive Symptoms in Older Adults. *Journal of Gerontology Series B: Social Sciences.* [online]. **56**(6): S343-S351. [Viewed 26 October 2018]. Available from: https://academic.oup.com/psychsocgerontology/article/56/6/S343/610648

Foster, P., Buhrmann, R., Quigley, H. & Johnson, G., (2002). The definition and classification of glaucoma in prevalence surveys. *British Journal of Ophthalmology*. [online]. **86**(2). 238-242. [Viewed 25 November 2014]. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1771026/

Fotios, S., Cheal, C. & Boyce, P., (2005). Light source spectrum, brightness perception and visual performance in pedestrian environments: a review. *Lighting Research and Technology.* [online]. **37**(4), 271-294. [Viewed 09 October 2016]. Available from: http://journals.sagepub.com/doi/abs/10.1191/1365782805li139oa

Freeman, D., Grana, G. & Passaglia. C., (2010). Retinal ganglion cell adaption to small luminance fluctuations. *Journal of Neurophysiology*. [online]. **104**. 704-712. [Viewed 11 October 2014]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/20538771

Freeman, E., Munoz, B., Turano, K. & West, S., (2006). Measures of Visual Function and Their Association with Driving Modification in Older adults. *Investigative Ophthalmology and Visual Science*. [online]. **47**. 514-520. [Viewed 07 May 2017]. Available from: http://iovs.arvojournals.org/article.aspx?articleid=2163847

Friedman, D., O'Colmain, B., Muñoz, B., Tomany, S., McCarty, C., de Jong, P., Nemesure, B., Mitchell, P., Kempden, J. & Congdon, N., (2004). Prevalence of Age-Related Macular Degeneration in the United States. *Archives of Ophthalmology*. [online]. **122**. 564-572. [Viewed 07 May 2017]. Available from: http://jamanetwork.com/journals/jamaophthalmology/fullarticle/416232

Garcia-Perez, M., (2005). Is the DeVries-Rose to Weber Transition Empirically Possible with Sine-Wave Gratings? *The Spanish Journal of Psychology*. [online]. **8**(2). 113-118. [Viewed 08 September 2016]. Available from: https://www.cambridge.org/core/journals/spanish-journal-of-psychology/article/is-the-devriesrose-to-weber-transition-empirically-possible-with-sinewave-gratings/F3F7FA2358B314BB0E68D75BDE3867B4

Garcia-Perez, M. & Peli, E., (1997). The transition from DeVries-Rose to Weber's law: Comments on Rovamo, Mustonen and Nasanen. *Vision Research*. [online]. **37**(18). 2573-2576. [Viewed 11 June 2016]. Available from: http://www.sciencedirect.com/science/article/pii/S0042698997000710

Gardiner, S., (2003). *STATISTICAL METHODS FOR THE ANALYSIS OF VISUAL FIELDS DATA IN GLAUCOMA*. Ph.D. thesis, The Nottingham Trent University. [Viewed 28 September 2016]. Available from: http://www.staff.city.ac.uk/d.crabb/PhD%20Thesis%20-%20Stuart%20Gardiner.pdf

Gardiner, S., Crabb, D., Fitzke, F. & Hitchings, R., (2004). Reducing noise in suspected glaucomatous visual fields by using a new spatial filter. *Vision Research*. [online]. **44**. 839-848. [Viewed 09 September 2016]. http://www.sciencedirect.com/science/article/pii/S0042698903004747

Gardiner, S., Demirel, S. & Johnson, C., (2006a). Modelling the sensitivity to variability relationship in perimetry. *Vision Research*. [online]. **46**. 1732-1745. [Viewed 03 September 2014]. Available from: http://www.sciencedirect.com/science/article/pii/S0042698905006607

Gardiner, S., Johnson, C. & Spry, P., (2006b). Normal Age-Related Sensitivity Loss for the Variety of Visual Functions Throughout the Visual Field. *Optometry and Vision Science*. [online]. **83**(7). 438-443. [Viewed 10 September 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16840869

Gasper, J., Ward, N., Neider, M., Cromwell, J., Carbonari, R., Kaczmarski, H., Ringer, R., Johnson, A., Kramer, A. & Loschky, L., (2016). Measuring the Useful Field of View During Simulated Driving With Gaze-Contingent Displays. *Human Factors*. [online]. **58**(4). 630-641. [Viewed 02 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/27091370

Gedik, S., Akman, A. & Akova, Y., (2007). Efficiency of rarebit perimetry in the evaluation of homonymous hemianopia in stroke patients. *British Journal of Ophthalmology*. [online]. **91**. 1065-1069. [Viewed 19 October 2016]. Available from: https://bjo.bmj.com/content/91/8/1065

Glen, F., Smith, N. & Crabb, D., (2015). Impact of superior and inferior visual field loss on hazard detection in a computer-based driving test. *British journal of Ophthalmology*.

[online]. **99**. 613-617. [Viewed 05 November 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/25425712

Gloriani, A., Matesanz, B., Barrionuevo, P., Arranz, I., Issolio, L., Mar, S. & Aparicio, J., (2016). Influence of background size, luminance and eccentricity on different adaption mechanisms. *Vision Research*. [online]. **125**. 12-22. [Viewed 11 July 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/27210038

Gondalez-Hernandez, M., de la Rosa, M., de la Vega, R. & Hernandez-Vidal, A., (2007). Long-term fluctuation of standard automatic perimetry, pulsar perimetry and frequency-doubling technology in early glaucoma diagnosis. *Ophthalmic Research*. [online] 39(6). 338-343. [Viewed 08 January 2018]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/17952009

GOV.UK, (2014). DVLA's current medical guidelines for professionals – Vision appendix. *GOV.UK.* [Viewed 23 September 2014]. Available from: https://www.gov.uk/current-medical-guidelines-dvla-guidance-for-professionals-vision-chapter-appendix

Gracitelli, C., Tatham, A., Boer, E., Abe, R., Diniz-Filho, A., Rosen, P. & Medeiros, F., (2015). Predicting Risk of Motor Vehicle Collisions in Patients with Glaucoma: A Longitudinal Study. *Plos One*. [online]. 1-14. [Viewed 09 October 2016]. Available from: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0138288

Gray, S., Spencer, I., Spry, P., Brookes, S., Baker, I., Peters, T., Sparrow, J. & Easty, D., (1997). The Bristol Shared Care Glaucoma Study--validity of measurements and patient satisfaction. *Journal of Public Health Measurement*. [online]. **19**(4). 431-436. [Viewed 02 September 2014]. Available from: http://pubhealth.oxfordjournals.org

Gruber, N., Moismann, U., Muri, R. & Nef, T., (2013). Vision and Night Driving Abilities of Elderly Drivers. *Traffic Injury Prevention*. [online]. **14**. 477-485. [Viewed 06 October 2016]. Available from: https://www.tandfonline.com/doi/abs/10.1080/15389588.2012.727510

Gupta, N., Krishnadev, N., Hamsha, S. & Yucel, Y., (2006). Depth perception deficits in glaucoma suspects. *British Journal of Ophthalmology*. [online]. **90**(8). 979-981. [Viewed 07 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1857183/

Haan, G., Melis-Dankes, B., Brouwer, W., Bredewoud, R., Tucha, O. & Heutink, J., (2014). Car driving performance in hemianopia: an on-road driving study. *Investigative Ophthalmology and Visual Science*. [online]. **55**(10). 6482-6489. [Viewed 03 January 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25212777

Halonen, L. & Bizjak, G., *CIE mesopic photometry-implementation for outdoor lighting*. [PowerPoint presentation]. [Viewed 05 August 2017]. Available from: http://www.sdr.si/dokumenti/p01.pdf

Hamel, J., Kraft, A., Ohl, S., De Beukelaer, S., Audebert, H. & Brandt, S., (2012). Driving simulation in the clinic: testing visual exploratory behaviour in daily life activities in patients with visual field defects. *Journal of Visualized Experiments*. [online]. **67**. 1-6. [Viewed 30 December 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23023223

Hatt, S., Wormald, R. & Burr, J., (2006). Screening for prevention of optic nerve damage due to chronic open angle glaucoma (review). *Cochrane Database of*

Systemic Reviews. [online]. **4**. 1-16. [Viewed 30 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/17054274

Hayreh, S. & Zimmerman, M., (2017). OCULAR ARTERIAL OCCLUSIVE DISORDERS AND CAROTID ARTERY DISEASE. *Ophthalmology Retina*. [online]. **1**(1). 12-18. [Viewed 14 September 2019]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5439962/

Heijl, A., (2010). Concept and importance of visual field measurements to detect glaucoma progression. *Glaucoma Now*. [online]. **2**. 1-12. [Viewed 01 November 2017]. Available from: http://glaucomanow.com/media/5367/gn%20no2.pdf

Heijl, A. & Bengtsson, B., (1996). The effect of Perimetric experience in patients with glaucoma. *Archives of Ophthalmology*. [online]. **114**(1). 19-22. [Viewed 17 May 2016]. Available from: https://lup.lub.lu.se/search/publication/e9366f25-aa13-4e3c-865b-85c5cc2de921

Heijl, A., Lindgreen, A. & Lindgren, G., (1989). Test-retest variability in glaucomatous visual fields. *American Journal of Ophthalmology*. [online]. **108**(2). 130-135. [Viewed 17 January 2018]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/2757094

Heijl, A., Lindgren, G. & Olsson, J., (1987). A package for the statistical analysis of visual fields. In: E. Greve, A. Heijl, eds. *Seventh International Visual Field Symposium*, *September 1986, Amsterdam* [online]. Dordrecht: Springer. 153-168. [Viewed 04 November 2017] Available from: https://link.springer.com/chapter/10.1007/978-94

Heijl, A. & Patella, V., (2002). *The Field Analyzer Primer. Effective Perimetry.* 3rd ed. California: Carl Zeiss Meditec, Inc

Heijl, A., Patella, V. & Bengtsson, B., (2012). *The Field Analyzer Primer. Effective Perimetry.* 4th ed. California: Carl Zeiss Meditec, Inc.

Henson, D., (2001). *Visual Fields.* 2nd ed. Oxford: Butterworth-Heinemann.

Henson, D., Chaudry, S., Artes, P., Faragher, E. & Ansons, A., (2000). Response Variability in the Visual Field: Comparison of Optic Neuritis, Glaucoma, Ocular Hypertension, and Normal Eyes. *Investigative Ophthalmology and Visual* Science. [online]. **41**(2). 417-421. [Viewed 01 September 2015]. Available from: http://invibe.net/biblio_database_dyva/woda/data/att/1ccc.file.pdf

Hills, B., (1980). Vision, visibility and perception in driving. *Perception*. [online]. **9**. 183-216. [Viewed 09 October 2016]. Available from: http://journals.sagepub.com/doi/abs/10.1068/p090183

Hirasawa, K., Murata, H., Hirasawa, H., Mayama, C. & Asaoka, R., (2014). Clustering visual field test points based on rates of progression to improve prediction of future damage. *Investigative Ophthalmology and Visual Science*. [online]. **55**. 7681-7685. [Viewed 05 October 2017]. Available from: http://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/933042/

Hitchings, R., (1994). Perimetry--back to the future? *British Journal of Ophthalmology*. [online]. **78**. 805-806. [Viewed 01 September 2014]. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC504957/

Ho, G., Scialfa, C., Caird, J. & Graw, T., (2001). Visual search for traffic signs: the effects of clutter, luminance, and aging. *Human Factors*. [online]. **43**(2). 194-207.

[Viewed 05 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/11592661

Hofeldt, A., (2015). *BINARY CHOISE SELF-TESTING*. Inventor: Albert John Hofeldt. 22 January 2015. Appl: 18 July 2013. US Patent 20150022782.

Hoffmann, J. & Subramaniam, B., (1995). The role of visual attention in saccadic eye movements. *Perception and Psychophysics*. [online]. **57**(6). 787-795. [Viewed 04 October 2016]. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.211.3955&rep=rep1&type=pdf

Hollander, D., Volpe, N., Moster, M., Liu, G., Baker, L., Judy, K. & Galetta, S., (2000). Use of a portable head mounted perimetry system to assess bedside visual fields. *British Journal of Ophthalmology*. [online]. **84**. 1185-1190. [Viewed 02 November 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/11004108

Horani, A., Frenkel, S., Yahalom, C., Farber, M., Ticho, U. & Blumenthal, E., (2002). The Effect in Visual Field Testing of Healthy Subjects Using Frequency Doubling Technology. *Journal of Glaucoma*. [online]. **11**. 511-516. [Viewed 09 April 2016]. Available from: http://glaucoma.org.il/wp-content/uploads/J-Glaucoma-2002-Learning-effect-with-FDT.pdf

Houston, S., Weber, E., Koga, S. & Newman, S., (2010). Rarebit Perimetry for Bedside Testing: Comparison With Standard Automated Perimetry. *Journal of Neuro-ophthalmology*. [online]. **30**. 243-247. [Viewed 01 November 2016]. Available from: https://insights.ovid.com/pubmed?pmid=20548245

Huestegge, L. & Böckler, A., (2016). Out of the corner of the driver's eye: Peripheral processing of hazards in static traffic scenes. *Journal of Vision*. [online]. **16**(2). 1-15. [Viewed 02 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/27488848

Humphrey Instruments Inc, (1993). Basic Principles of Perimetry. In: M. Haley, ed. *The field Analyser Primer*. 2nd edition. San Leandro, California: Humphrey Instruments Inc. pp. 3-11.

IbisVision, (2019). Introducing RING of SIGHT. A New Standard in Visual Field Testing. *IbisVision*. [Viewed 26.07.2019]. Available from : https://www.ibisvision.co.uk/ringofsight.html

IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 23.0, Armonk, NY: IBM Corp.

Imaging and Perimetry Society, (2010). IPS standards and guidelines 2010. [online]. *Imaging and Perimetry Society*. [Viewed 26 December 2015]. Available from: http://www.perimetry.org/gen-info/standards/standards2010/IPS-Standards2010.pdf

Itkonen, T., Pekkanen, J. & Lappi, O., (2015). Driver Gaze Behaviour is Different in Normal Curve Driving and when Looking at the Tangent Point. *Plos One*. [online]. 1-19. [Viewed 02 October 2016]. Available from: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0135505

Jalie, M., (1988). *The Principles of Ophthalmic Lenses*. London: The Association of British Dispensing Opticians.

Jampel, H., Friedman, D., Quigley, H. & Miller, R., (2002b). Correlation of the Binocular Visual Field with Patient Assessment of Vision. *Investigative Ophthalmology and Visual Science*. [online]. **43**(4). 1059-1067. [Viewed 25 January 2016]. Available from: http://iovs.arvojournals.org/article.aspx?articleid=2200185

Jampel, H., Schwartz, A., Pollack, I., Abrams, D., Weiss, H. & Miller, R., (2002a) Glaucoma patients' assessment of their visual function and quality of life. *Journal of Glaucoma*. [online]. **11**(2). 154-163. [Viewed 26 January 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/11912364

Johnson, C., (2013). Psychophysical factors that have been applied to clinical perimetry. *Vision Research*. [online]. **90**. 25-31. [Viewed 30 October 2016]. Available from: https://www.sciencedirect.com/science/article/pii/S0042698913001715

Johnson, C. & Keltner, J., (1983). Incidence of visual field loss in 20,000 eyes and its relationship to driving performance. *Archives of Ophthalmology*. [online]. **101**. 371-376. [Viewed 04 September 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/6830485

Kaleem, M., Munoz, B., Munro, C., Gower, E. & West, S., (2012). Visual characteristics of elderly night drivers in the Salisbury Eye Evaluation Driving Study. *Investigative Ophthalmology and Visual Science*. [online]. **53**(9). 5161-5167. [Viewed 06 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/22743327

Kalloniatis, M. & Khuu, S., (2016). Equating spatial summation in visual field testing reveals greater loss in optic nerve disease. *Ophthalmic and Physiological Optics*. [online] **36**. 439-452. [Viewed 14 November 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/27197562

Kandil, F. & Rotter, A., (2010). Car drivers attend to different gaze tangents when negotiating closed vs. open bends. *Journal of Vision*. [online]. **10**(4). 1-11. [Viewed 01 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/20465342

Kang, I., Reem, R., Kaczmarowski, A. & Malpeli, J., (2009). Contrast sensitivity of cats and humans in scotopic and mesopic conditions. *Journal of Neurophysiology*. [online]. **102**. 831-840. [Viewed 03 September 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/19458146

Kanski, J., (2007) *Clinical Ophthalmology. A Systematic Approach.* 6th ed. London: Butterworth and Heinemann.

Kasahara, S., Okabe, S., Nakazato, N. & Ohno, Y., (2007). Eye movement Patterns of the Elderly during Stair Descent: Effect of Illumination. *Journal of Light and Visual Environment*. [online]. **31**(3). 134-140. Abstract only. [Viewed 07 May 2017]. Available from: https://www.jstage.jst.go.jp/article/jlve/31/3/31_3_134/_article/-char/en

Kasneci, E., Sippel, K., Aehling, K., Heister, M., Rosenstiel, W., Schiefer, U. & Papageorgiou, E., (2014). Driving with Binocular Visual Field Loss? A Study on a Supervised On-Road Parcours with Simultaneous Eye and Head Tracking. *Plos One*. [online]. **9**(2). 1-13. [Viewed 06 September 2014]. Available from: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0087470

Keay, L., Munoz, B., Duncan, D., Hahn, D., Baldwin, K., Turano, K., Munro, C., Bandeen-Roche, K. & West, S., (2013). Older Drivers and Rapid Deceleration Events: Salisbury Eye Evaluation Driving Study. *Accident Analysis and Prevention*, [online]. **58**. 279-285. [Viewed 02 October 2015]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3465526/

Keltner, J. & Johnson, C., (1980). Mass Visual Field Screening in a Driving Population. *American Academy of Ophthalmology*. [online]. **87**(8). 785-792. [Viewed 12 October 2015]. Available from: https://www.sciencedirect.com/science/article/pii/S0161642080351610

Keltner, J., Johnson, C., Cello, K., Dontchev, M., Gal, R. & Beck, R., (2010). Visual Field Profile of Optic Neuritis: A Final Follow-up Report From the Optic Neuritis Treatment Trial From Baseline Through 15 Years. *Archives of Ophthalmology*. [online]. **128**(30). 330-337. [Viewed 01 November 2015]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4107874/pdf/nihms598071.pdf

Kim, K., Jeoung, J., Kim, D., Ahn, S., Park, K. & Kim, S., (2015). Long-term follow-up in preperimetric open-angle glaucoma: progression rates and associated factors. *American Journal of Ophthalmology*. [online]. **159**(1). 160-168. [Viewed 13 September 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25448320

Klewin, K. & Radius, R., (1986). Background illumination and automated perimetry. *Archives of Ophthalmology*. [online]. **104**(3). 395-397. [Viewed 02 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/3754130

Koenderink, J., Van de Grind, W. & Bouman, M., (1970). Models of retinal signal processing at high luminances. *Biological Cybernetics*. [online]. **6**(6). 227-237. [Viewed 24 March 2016]. Available from: https://link.springer.com/article/10.1007/BF00276723

Konstantopoulos, P., (2009). Investigating drivers' visual search strategies: towards an efficient training intervention. Ph.D. thesis, University of Nottingham. [Viewed 25 November 2016]. Available from: http://eprints.nottingham.ac.uk/10845/

Krader, C., (2014). Visual field loss impacts driving performance. *Ophthalmology Times*. [online]. 1-3. [Viewed 15 May 2016]. Available from: http://www.modernmedicine.com/sites/default/files/legacy/mm/digital/OT/ot080114_ezine.pdf

Kubler, T., Kasneci, E., Rosenstiel, W., Heister, M., Achling, K., Nagel, K., Schiefer, U. & Papageorgiou, E., (2015). Driving with Glaucoma: Task Performance and Gaze Movements. *Optometry and Visual Science*. [online]. **92**(11). 1037-1046. [Viewed 08 March 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/26501733

Kunimatsu-Sanuki, S., Iwase, A., Ariaie, M., Aoki, Y., Hara, T., Nakazawa, T., Yamaguchi, T., Ono, H., Sanuki, T. & Itoh, M., (2015). An assessment of driving fitness in patients with visual impairment to understand the elevated risk of motor vehicle accidents. *British Medical Journal Open*. [online]. **5**(2). 1-11. [Viewed 05 November 2016]. Available from: http://bmjopen.bmj.com/content/5/2/e006379

Kwon, M., Huisingh, C., Rhodes, L., McGwin, G., Wood, J. & Owsley, C., (2016). Association between glaucoma and at-fault motor vehicle collision involvement among older drivers: A Population Based Study. *Ophthalmology*. [online]. **123**. 109-116. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4695303/

Labrique, A., Palmer, A., Healy, K., Mehra, S., Sauer, T., West Jr, K. & Sommer, A., (2015). A novel device for assessing dark adaption in field settings. *Biomed Central Ophthalmology*. [online]. **15**(74). 1-9. [Viewed 03 September 2016]. Available from: https://bmcophthalmol.biomedcentral.com/track/pdf/10.1186/s12886-015-0062-7

Lamble, D., Summala, H. & Hyvarinen, L., (2002). Driving performance of drivers with impaired central visual field acuity. *Accident Analysis and Prevention*. [online]. **34**. 711-

716. [Viewed 05 November 2016]. Available from: http://www.sciencedirect.com/science/article/pii/S0001457501000719

Land, M. & Lee, D., (1994). Where we look when we steer. *Nature*. [online]. **369**. 742-744. [Viewed 04 October 2016]. Available from: http://www.nature.com/nature/journal/v369/n6483/abs/369742a0.html

Landers, J., Sharma, A., Goldberg, I. & Graham, S., (2007). A comparison of global indices between the Medmont Automated Perimeter and the Humphrey Field Analyser. *British Journal of Ophthalmology*. [online]. **91**. 1285-1287. [Viewed 15 November 2016]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2001002/

Lappi, O., (2014). Future path and tangent point models in the visual control of locomotion in curve driving. *Journal of Vision*. [online]. **14**(12). 1-22. [Viewed 02 October 2016]. Available from: http://jov.arvojournals.org/article.aspx?articleid=2193909

Lappi, O., Lehtonen, E., Pekkanen, J. & Itokonen, T., (2013). Beyond the tangent point: Gaze targets in naturalistic driving. *Journal of Vision*. [online]. **13**(13). 1-18. [Viewed 01 October 2016]. Available from: http://jov.arvojournals.org/article.aspx?articleid=2193829

Latham, K., Katsou, M. & Rae, S., (2014). Advising patients on visual fitness to drive: implications of revised DVLA regulations. *British Journal of Ophthalmology*. [online]. **99**. 545-548. [Viewed 01 November 2016]. Available from: https://bjo.bmj.com/content/bjophthalmol/99/4/545.full.pdf

Lee, R., Wong, T., Sabanayagam, C., (2015). Epidemiology of diabetic retinopathy, diabetic macular edema and related vision loss. *Eye and Vision*. [online]. **2**(17). 1-25. [Viewed 15 September 2019]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4657234/pdf/40662_2015_Article_26.pdf

Legge, G., (2013). Driving with central field loss. *Jama Ophthalmology*. [online]. **131**(3). 393-395. [Viewed 13 October 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23329348

Lehtonen, E., Lappi, O., Kotkanen, H. & Summala, H., (2013). Look-ahead fixations in curve driving. *Ergonomics*. [online]. **56**(1). 34-44. [Viewed 04 October 2016]. Available from: https://www.researchgate.net/publication/233392593_Look-ahead_fixations_in_curve_driving

Lehtonen, E., Lappi, O., Koirikivi, L. & Summala, H., (2014). Effect of driving experience on anticipatory look-ahead fixations in real curve driving. *Accident Analysis and Prevention*. [online]. **70**. 195-208. [Viewed 02 October 2016]. Available from: http://www.sciencedirect.com/science/article/pii/S0001457514001079

Lema, S. & Blake, R., (1977). Binocular summation in normal and stereoblind humans. *Vision Research*. [online]. **17**. 691-695. [Viewed 02 August 2019]. Available from: file:///C:/Users/bartlaea/AppData/Local/Packages/Microsoft.MicrosoftEdge_8wekyb3d8bbwe/TempState/Downloads/1-s2.0-S0042698977800047-main.pdf

Lennie, P., (1979). Scotopic increment thresholds in retinal ganglion cells. *Vision Research*. [online]. **19**(4). 425-430. [Viewed 18 November 2016]. Available from: https://www.sciencedirect.com/science/article/pii/0042698979901081

Lim, J. & Liu, Y., (2009). Modelling the Influences of Top-Down and Bottom-Up Processes. *IEEE Transactions on Systems, Management and Cybernetics part A: Systems and Humans*. [online]. **39**. 706-714. [Viewed 09 October 2016]. Available from: http://ieeexplore.ieee.org/document/5076145/?reload=true

Lin, Z., Lu, Z. & He, S., (2016). Decomposing experience-driven attention: Opposite attentional effects of previously predictive cues. *Attention, Perception and Psychophysics*. [online]. **78**. 2185-2198. [Viewed 02 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/27068051

Liu, T., Heeger, D. & Carrason, M., (2006). Neural correlates of the visual vertical meridian asymmetry. *Journal of Vision* [online]. **6**(11). 1294-1306. [Viewed 07 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1864963/

Lo, P., Chen, L. & Chi Ho, T., (2010). *Apparatus and method for objective perimetry visual field testing*. Inventors: Patrick Lo, Liang Chen and Chi Ho To. 08 January 2013. Appl: 07 March 2008. US Patent US8500278B2.

Lowry, E., Hou, J., Hennein, L., Chang, R., Lin, S., Keenan, J., Wang, S., Ianchulev, S., Pasquale, L. & Han, Y., (2016). Comparison of Peristat Online Perimetry with the Humphrey Perimetry in a Clinic-Based Setting. *Transitional Vision Science and* Technology. [online]. **5**(4). 1-9. [Viewed 01 November 2017]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4959820/

MacDougall, H. & Moore, S., (2005). Functional assessment of head-eye coordination during vehicle operation. *Optometry and Vision Science*. [online]. **82**(8). 706-715. [Viewed 03 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16127336

MacInnes, W., Hunt, A., Hilchey, M. & Klein, R., (2014). Driving forces in free visual search: An ethology. *Attention, Perception and Psychophysics*. [online]. **76**. 280-295. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/24385137

Macnaughton, J., (2005). *Low Vision Assessment*. Kent: ABDO College.

Malik, R., Swanson, W. & Garway-Heath, D., (2005). Development and evaluation of a linear staircase strategy for the measurement of perimetric sensitivity. *Vision Research*. [online]. **46**. 2956-2967. [Viewed 18 November 2015]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16764899

Manji, H. & Plant, G., (2000). Epilepsy surgery, visual fields, and driving: a study of the visual field criteria for driving in patients after temporal lobe epilepsy surgery with a comparison of Goldmann and Esterman perimetry. *Journal of Neurology, Neurosurgery and Psychiatry*. [online]. **68**. 80-82. [Viewed 13 October 2015]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/10601407

Manor, B. & Gordon, E., (2003). Defining the temporal threshold for ocular fixation in free-viewing visuocognitive tasks. *Journal of Neuroscience Methods*. [online]. **123**(1-2). 85-93. [Viewed 06 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/12948551

Mars, F. & Navarro, J., (2012). Where We Look When We Drive with or without Active Steering Wheel Control. *Plos One*. [online]. **7**(8). 1-6. [Viewed 01 October 2016]. Available from: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0043858

Matza, L., Rousculp, M., Malley, K., Boye, K. & Oglesby, A., (2008). The longitudinal link between visual acuity and health-related quality of life in patients with diabetic retinopathy. *Health and Quality of Life Outcomes*. [online]. **6**(95). 1-10. [Viewed 03 November 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/18992161

Maynard, M., Zele, A. & Feigl, B., (2016). Mesopic Pelli-Robson contrast sensitivity and MP-1 microperimetry in healthy ageing and age-related macular degeneration. *Acta Ophthalmologia*. [online]. **94**. 772-778. [Viewed 07 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/27225020

McCourt, M., Leone, L. & Blakeslee, B., (2015). Brightness induction and suprathreshold vision: Effects of age and visual field. *Vision Research* [online]. **106**. 36-46. [Viewed 07 May 2017]. Available from: http://www.sciencedirect.com/science/article/pii/S0042698914002764

McGwin, G., Husingh, C., Jain, S., Girkin, C. & Owsley, C., (2013). Binocular visual field impairment in glaucoma and at-fault motor vehicle collisions. *Journal of Glaucoma*. [online]. **24**(2). 138-143. [Viewed 26 April 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25642648

McKendrick, A., (2005). Recent developments in perimetry test stimuli and procedures. *Clinical and Experimental Optometry*. [online]. **88**(2). 73-80. [Viewed 01 September 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/15807638

Medeiros, F., Weinreh. R., Boer, R. & Rosen, P., (2012). Driving simulation as a performance-based test of visual impairment in glaucoma. *Journal of Glaucoma*. [online]. **21**(4). 221-227. [Viewed 28 May 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21467952

Medeiros, N. & Curcio, C., (2001). Preservation of Ganglion Cell Layer Neurons in Age-Related Macular Degeneration. *Investigative ophthalmology and Visual Science*. [online]. **42**(3). 795-803. [Viewed 29 May 2016]. Available from: https://iovs.arvojournals.org/article.aspx?articleid=2123592

Miranda, M. & Henson, D., (2008). Perimetric sensitivity and response variability in glaucoma with single-stimulus automated perimetry and multiple-stimulus perimetry with verbal feedback. *Acta Ophthalmologica*. [online]. **86**. 202-206. [Viewed 02 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/18005269

Mitchell, J. & Bradley, C., (2006). Quality of life in age-related macular degeneration: a review of the literature. *Health and Quality of Life Outcomes.* [online]. **4**(97). 1-20. [Viewed 01 November 2017]. Available from: https://hqlo.biomedcentral.com/articles/10.1186/1477-7525-4-97

Molner, F., Marshall, S., Man-Son-Hing, M., Wilson, K., Byszewski, A. & Stiell, I., (2007). Acceptability and concurrent validity of measures to predict older driver involvement in motor vehicle crashes: an emergency department pilot case-control study. *Accident Analysis and Prevention*. [online]. **39**(5). 1056-1063. [Viewed 06 October 2016]. Available from: https://www.sciencedirect.com/science/article/pii/S000145750700022X

Moore, A., Fitze, F., Kemp, C., Arden, G., Keen, T., Inglehearn, C., Bhattacharya, S. & Bird, A., (1992). Abnormal dark adaption kinetics in autosomal dominant sector retinitis pigmentosa due to rod opsin mutation. *British Journal of Ophthalmology* [online]. **76**. 465-469. [Viewed 08 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/1390527

Morgan, D., (2016). *FOI. Licenses revoked in the UK.* [Data set]. Swansea: DVLA.

Muira, T., (1990). Active function of eye movement and useful field of view in a realistic setting. In: R. Groner, G. d'Ydewalle, R. Parham, eds. *From eye to the mind: information acquisition in perception, search and reading*. Abstract only. Oxford: North-Holland. pp. 119-127. [Viewed 06 October 2016]. Available from: https://psycnet.apa.org/record/1990-98322-009

Muqit, M., Wakely, L., Stanga, P., Henson, D. & Ghanchi, F., (2010). Effects of conventional argon panretinal laser photocoagulation on retinal nerve fibre layer and driving visual fields in diabetic retinopathy. *Eye*. [online]. **24**. 1136-1142. [Viewed 11 August 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/20019760

Murray, I., Fleck, B., Brash, H., MacRae, M., Tan, L. & Minns, R., (2009). Feasibility of saccadic vector optokinetic perimetry: a method of automated static perimetry for children using eye tracking. *Ophthalmology*. [online]. **116**. 2017-2026. [Viewed 22 April 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/19560207

Mutlukan, E. & Damato, B., (1992). The dark perimetric stimulus. *British Journal of Ophthalmology*. [online]. **76**. 264-267. [Viewed 25 March 2015]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC504252/pdf/brjopthal00053-0008.pdf

National Health Service Dorset Clinical Commissioning Group, (2019). Glaucoma Shared Care. *National Health Service Dorset Clinical Commissioning Group*. [online]. 1. [Viewed 10 August 2019]. Available from: https://www.dorsetccg.nhs.uk/Downloads/aboutus/finance/02_GMS_0074%20Glaucoma%20Shared%20Care/02_GMS_0074%20Glaucoma%20Shared%20Care%20v2.pdf

Nazemi, P., Fink, W., Sadun, A., Francis, B. & Minckler, D., (2007). Early detection of glaucoma by means of a novel 3D computer-automated visual field test. *British Journal of Ophthalmology*. [online]. **91**. 1331-1336. [Viewed 05 September 2015]. Available from: https://bjo.bmj.com/content/91/10/1331

Neelam, K., Nolan. J., Chakravarthy, U. & Beatty, S., (2009). Psychophysical function in age-related maculopathy. *Survey of Ophthalmology*. [online]. **54**. 167-210. [Viewed 07 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/19298899

Nelson-Quigg, J., Cello, K. & Johnson, C., (2000). Predicting Binocular Visual Field Sensitivity from Monocular Visual Field Results. *Investigative Ophthalmology and Visual Science*. [online]. **41**. 2212-2221. [Viewed 28 September 2016]. Available from: http://iovs.arvojournals.org/article.aspx?articleid=2123192

NEMA, (2009). Digital Imaging and Communications in Medicine (DICOM) Part 14: Grayscale Standard Display Function. PS 3.14-2009. *National Electrical Manufacturers Association*. [online]. 1-55. [Viewed 09 October 2016]. Available from: http://dicom.nema.org/dicom/2004/04_14pu.pdf

NHS.UK., (2017). Free NHS eye tests and optical vouchers. [online]. *NHS.UK*. [Viewed 10 August 2019]. Available from: https://www.nhs.uk/using-the-nhs/help-with-health-costs/free-nhs-eye-tests-and-optical-vouchers/

Nieves, J., Valero, E. & Herandez-Andres, J., (2002). Influence of the mean luminance on the detection threshold for red-green chromatic gratings. In: R. Chung, A. Rodrigues, eds. *9th congress of the international colour association*, *24-29 June 2001*, *Rochester, New York* [online]. Washington: SPIE—The International Society for Optical Engineering. 4421. [Viewed 28 October 2014]. Available from: http://spie.org/Publications/Proceedings/Paper/10.1117/12.464582

Nouri-Mahdavi, K., Brigatti, L., Weitzman, M. & Caprioli, J., (1997). Comparison of Methods to Detect Visual Field Progression in Glaucoma. *Ophthalmology*. [online]. **104**. 1228-1236. [Viewed 01 September 2014]. Available from: http://www.sciencedirect.com/science/article/pii/S0161642097301535

Nouri-Mahdavi, K., Nassiri, N., Giangiacomo, A. & Caprioli, J., (2011). Detection of visual field progression in glaucoma with standard achromatic perimetry: a review and practical implications. *Graefe's Archive for Experimental and Clinical Ophthalmology*. [online]. **249**. 1593-1616. [Viewed 04 September 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21870086

Nowakowski, R., (1994). *Primary Low Vision Care.* Michigan: Appleton and Lange.

Ong, E., Zheng, Y., Aung, T., Tan, L., Cheng, C. & Wong, T., (2014). Performance of the Moorfields Motion Displacement Test for Identifying Eyes with Glaucoma. *American Academy of* Ophthalmology. [online]. **121**. 88-92. [Viewed 30 October 2016]. Available from: https://www.sciencedirect.com/science/article/pii/S0161642013007963

Ono, T., Yuki, K., Awano-Tanabe, S., Fukagawa, K., Shimoyama, M., Ozawa, Y., Ozeki, N., Shiba, D. & Tsubota, K., (2015). Driving self-restriction and motor vehicle collision occurrence in glaucoma. *Optometry and Visual Science*. [online]. **92**(3). 357-364. [Viewed 28 January 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25551687

Ophthaclass, Glaucoma Grading Scale (Hodapp-Parish-Anderson). [online]. *Ophthaclass*. [Viewed 27 September 2014]. Available from: http://ophthaclassification.altervista.org/glaucoma-grading-scale-hodapp-parrish-anderson/

Optical Radiation Group, (2016). Colour rendering of light sources. [online]. *Optical Radiation Group*. [Viewed 18 October 2016]. Available from: https://www.nist.gov/pml/sensor-science/optical-radiation/color-rendering-light-sources

Owen, V., Crabb, D., White, E., Viswanathan, A., Garway-Heath, D. & Hitchings, R., (2008). Glaucoma and fitness to drive: using binocular visual fields to predict a milestone to blindness. *Investigative Ophthalmology*. [online]. **49**(6). 2449-2455. [Viewed 25 October 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/18515585

Owsley, C., Ball, K., McGwin, G., Sloane, M., Roenker, D., White, M. & Overley, T., (1998). Visual processing impairment and risk of motor vehicle crash among older adults. *Jama*. [online]. **279**(14). 1083-1088. [Viewed 16 May 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/9546567

Owsley, C., Ball, K., Sloane, M., Roenker, D. & Bruni, J., (1991). Visual/cognitive correlates of vehicle accidents in older drivers. *Psychology and Ageing*. [online]. **6**(3). 403-415. [Viewed 03 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/1930757

Owsley. C., McGwin. G., Jackson, G., Kallies. K. & Clark. M., (2007). Cone- and Rod-Mediated Dark Adaptation Impairment in Age-Related Maculopathy. *Ophthalmology*. [online]. **114**(9). 1728-1735. [Viewed 07 May 2017]. Available from: http://www.aaojournal.org/article/S0161-6420(06)01673-3/abstract

Palmer, S., (1999). *Photons to Phenomenology*. 3rd ed. Cambridge, MA: MIT press.

Papageorgiou, E., Hardiess, G., Ackermann, H., Wiethoelter, H., Dietz, K., Mallot, H. & Schiefer, U., (2012). Collision avoidance in persons with homonymous visual field defects under virtual reality conditions. *Vision Research*. [online]. **52**. 20-30. [Viewed 01 February 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/22100816

Parker, W., McGwin, G., Wood, J., Elgin, J., Vaphiades, M., Kline, L. & Owsley, C., (2011). Self-reported driving difficulty by persons with hemianopia and quadrantanopia. *Current Eye Research*. [online]. **36**(3). 270-277. [Viewed 05 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/21275522

Parkhurst, D. & Niebur, E., (2003). Scene content selected by active vision. *Spatial vision*. [online]. **16**(2). 125-154. [Viewed 10 October 2016]. Available from: http://www.ini.uzh.ch/~peterk/Lectures/AttentionSeminar/Parkhurst.SpatialVision.03.pdf

Patel, A., Wollstein, G., Ishikawa, H. & Schuman, J., (2007) Comparison of Visual Field Defects Using Matrix Perimetry and Standard Achromatic Perimetry. *The American Journal of Ophthalmology*. [online].**114**(3). 480-487. [Viewed 03 November 2017]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1945823/pdf/nihms24614.pdf

Pfau, M., Lindner, M., Muller, P., Birtel, J., Finger, R., Harmening, W., Fleckenstein, M., Holz, F. & Schmitz-Valckenberg, S., (2017). Effective Dynamic Range and Retest Reliability of Dark-Adapted Two-Color Fundus-Controlled Perimetry in Patients With Macular Diseases. *Investigative Ophthalmology and Visual Science*. [online]. **58**(6). 158-167. [Viewed 13 November 2018]. https://iovs.arvojournals.org/article.aspx?articleid=2643490

Phillip, D., (2016). *Henson.* Email: DavidPhilip.Thomas@dvla.gsi.gov

Phu, J., Khuu, S., Zanger, B. & Kalloniatis, M., (2017). A comparison of goldman III, V and spatially equated test stimuli in visual field testing: the importance of complete and partial spatial summation. *Ophthalmic and Physiological Optics*. [online]. **37**. 160-176. [Viewed 27 December 2017]. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/opo.12355

Prajapati, B., Dunne, M. & Armstrong, R., (2010). Sample size estimation and statistical power analyses. *Optometry Today*. [online]. **16/07/10.** [Viewed 06 September 2015]. Available from: http://www.floppybunny.org/robin/web/virtualclassroom/stats/basics/articles/gpower/Gpower_tutorial_Prajapati_2010-.pdf

Quigley, H., Enger, C., Katz, J., Sommer, A., Scott, R. & Gilbert, D., (1994). Risk factors of the development of glaucomatous visual field loss in ocular hypertension. *Archives of Ophthalmology*. [online].**112**(5). 664-669. [Viewed 23 December 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/8185522

Racette, L. & Casson, E., (2005). The impact of visual field loss on drving performance: evdence from on-road driving assessments. *Optometry and Vision Science* [online]. **82**(8). 668-674. [Viewed 30 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16127331

Rae, S., Latham, K. & Katsou, M., (2016). Meeting the UK driving vision standards with reduced contrast sensitivity. *Eye*. [online]. **30**. 89-94. [Viewed 02 November 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/26471119

Ragland, D., Satariano, W. & MacLeod, K., (2005). Driving cessation and increased depressive symptoms. *Journal of Gerontology*. [online]. **60A**(3): 399-403. [Viewed 23 March 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/15860482

Raj, R., Geisler, W., Frazer, R. & Bovik, A., (2009). Contrast statistics for foveated visual systems: fixation selection by minimizing contrast entropy. *Journal of the Optical Society of America*. [online]. **22**(10). 2039-2049. [Viewed 06 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16277275

Ramulu, P., Hochberg, C., Maul, E., Chan, E., Ferrucci, L. & Friedman, D., (2014). Glaucomatous visual field loss associated with less travel from home. *Optometry and Vision Science*. [online]. **91**(2). 187-193. [Viewed 26 January 2015]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/24374635

Ramulu, P., West, S., Munoz, B., Jampel, H. & Friedman, D., (2009). Driving cessation and driving limitation in glaucoma: the Salisbury Eye Evaluation Project. *American Academy of Ophthalmology*. [online]. **116**. 1846-1853. [Viewed 24 January 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19592110

Rao, P., Munoz, B., Turano, K., Munro, C. & West, S., (2013). The decline in attentional visual fields over time among older participants in the Salisbury Eye Evaluation Driving Study. *Ophthalmology and Visual Science*. [online]. **54**(3). 1839-1844. [Viewed 13 January 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23361510

Rasengane, T., Palmer, J. & Teller, D., (2001). Infant light adaption shows Weber's law at photopic illuminances. *Vision Research*. **41**. 359-373. [Viewed 28 October 2014]. Available from: http://www.sciencedirect.com/science/article/pii/S0042698900002649

Rauscher, F., Chisholm, C., Crabb, D., Barbur, J., Edgar, D., Plant, G., James-Galton, M., Petzold, A., Dunne, M., Davies, L., Underwood, G., Phelps, N. & Viswanathan, A., (2007). *Road safety research report. Central scotoma and driving. Department for Transport. Report number: 79.* London: Queen's Printer & Controller of Her Majesty's Stationary Office.

Ren, Y., Li, X., Zheng, X., Li, Z., Zhai, Q. & Chen, X., (2014). Analysis and Modelling of Driver's Gaze Trajectories in Curves Driving. *Advances in Mechanical* Engineering. [online]. 1-12. [Viewed 10 October 2016]. Available from: https://www.researchgate.net/publication/273179372_Analysis_and_Modeling_of_Driver's_Gaze_Trajectories_in_Curves_Driving

Rensink, R., O'Regan, J. & Clark, J., (1997). TO SEE OR NOT TO SEE: The Need for Attention to Perceive Changes in Scenes. *Psychological Science*. [online]. **8**(5). 368-373. [Viewed 08 October 2016]. Available from: http://www2.psych.ubc.ca/~rensink/publications/download/PsychSci97-RR.pdf

Reyes, M., Gallagher, S. & Sammarco, J., (2013). Evaluation of Visual Performance when Using Incandescent, Fluorescent and LED Machine Lights in Mesopic Conditions. *IEEE Transactions on Industry Applications*. [online]. **49**(5). 1992-1999. [Viewed 07 May 2017]. Available from: https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/eovpw.pdf

Reyes, M., Sammarco, J., Gallahger, S. & Srednicki, J., (2014). Comparative evaluation of Light Emitting Diode cap lamps with an emphasis on visual performance in mesopic lighting conditions. *IEEE Transactions on Industry Applications*. **50**(1). 127-133. [Viewed 07 May 2017]. Available from: http://ieeexplore.ieee.org/document/6074389/

Rijn, L., (2002). *Binocular visual field measurement for driving assessment: comparison of Esterman and Goldmann techniques*. 61-80. [online]. Amsterdam: Amsterdam: The Netherlands Ophthalmic Research Institute (NORI) of The Royal Netherlands Academy of Arts and Sciences. [Viewed 04 October 2016]. Available from: https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/pdf/projects_sources/glare_eu_report2002.pdf

Rittger, L., Kiesel, A., Schmidt, G. & Maag, C., (2014). Masking Action Relevant Stimuli in dynamic environments- The MARS method. *Transportation Research Part F*. [online]. **27**. 150-173. [Viewed 07 October 2016]. Available from: http://www.sciencedirect.com/science/article/pii/S136984781400151X

RNIB, (2014). Key information and statistics. [online]. *RNIB*. [Viewed 17 October 2014]. Available from: http://www.rnib.org.uk/knowledge-and-research-hub/key-information-and-statistics

Robertshaw, K. & Wilkie, R., (2008). Does gaze influence steering around a bend? *Journal of Vision*. [online]. **8**(4). 1-13. [Viewed 01 October 2016]. Available from: http://jov.arvojournals.org/article.aspx?articleid=2122187

Roenker, D., Cissell, G., Ball, K., Wadley, V. & Edwards, J., (2003). Speed-of-processing and driving simulator training result in improved driving performance. *Human Factors*. [online]. **45**(2). 218-233. [Viewed 10 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/14529195

Rogers, S., Kadar, E. & Costall, A., (2016). Driver's Gaze Patterns in Braking From Three Different Approaches to a Crash Barrier. *Ecological Psychology*. [online]. **17**(1). 39-53. [Viewed 10 October 2016]. Available from: http://www.tandfonline.com/doi/abs/10.1207/s15326969eco1701_3

Rovamo, J., Koljonen, T. & Nasanen, R., (1996). A New Psychophysical Method for Determining the Photopic Spectral-luminosity Function of the Human Eye. *Vision Research*. [online]. **36**(17). 2675-2680. [Viewed 08 September 2016]. Available from: https://www.sciencedirect.com/science/article/pii/0042698996000284

Rovamo, J., Nasanen, R. & Mustonen, J., (1997). Transition from DeVries-Rose to Weber's law: reply to Garcia Perez and Peli. *Vision Research*. [online]. **37**(18). 2576-2578. [Viewed 07 September 2016]. Available from: https://www.deepdyve.com/lp/elsevier/transition-from-devries-rose-to-weber-s-law-reply-to-garc-a-p-rez-and-1C7OtH4lST

Rowe, F., (2016). *Visual Fields via the Visual Pathway*. 2nd Edition. Boca Raton: CRC Press. Taylor and Francis Group.

Royal College of Ophthalmologists, (2013). Vision Standards for Driving. *Ophthalmic services guidance*. [online]. 1-10. [Viewed 23 September 2014]. Available from: https://www.rcophth.ac.uk/wp-content/uploads/2014/12/2013_PROF_216_Vision_Standards_for_Driving_April_2013.pdf

Rubin, G., Ng, E., Bandeen-Roche, K., Keyl, P., Freeman, E. & West, S., (2007). SEE Project Team. A prospective, population-based study of the role of visual impairment in motor vehicle crashes among older drivers: the SEE study. *Investigative Ophthalmology and Visual Science*. [online]. **48**(4). 1483-1491. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/17389475

Rudd, M. & Rieke F., (2016). Brightness in human rod vision depends on slow neural adaption to quantum statistics of light. *Journal of Vision*. [online]. 16(14), 1-25. [viewed 14 August 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/27903008

Rumar, K., (1990). The basic driver error: lane detection. *Ergonomics*. [online]. **33**(10-11). 1281-1290. [Viewed 08 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/2286189

Sakai, H., Shin, D., Kohama, T. & Uchiyama, Y., (2012). Attentional effects on gaze preference for salient loci in traffic scenes. *Ergonomics*. [online]. **55**(7). 743-751. [Viewed 02 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/22506809

Salvucci, D. & Liu, A., (2002). The time course of a lane change: Driver control and eye-movement behaviour. *Transportation Research part F: Traffic Psychology and Behaviour*. [online]. **5**(2). 123-132. [Viewed 04 October 2016]. Available from: http://www.sciencedirect.com/science/article/pii/S1369847802000116

Sammarco, J., Gallagher, S. & Reyes, M., (2010). Visual Performance for Trip Hazard Detection when Using Incandescent and LED Miner Cap Lamps. *Journal of Safety Research*. [online]. **41**.85-91. [Viewed 09 October 2016]. Available from: https://www.cdc.gov/niosh/mining/works/coversheet432.html

Sammarco, J., Reyes, M., Bartels, J. & Gallagher, S., (2009). Evaluation of Peripheral Visual Performance When Using Incandescent and LED Miner Cap Lamps. *IEEE Transactions on Industry Applications.* [online]. **45**(6), 1923-1929. [viewed 07 May 2017]. Available from: http://ieeexplore.ieee.org/document/4659125/

Sandlin, D., McGwin, G. & Owsley, C., (2014). Association between vision impairment and driving exposure in older adults aged 70 years and over: a population-based examination. *Acta Ophthalmologica*. [online]. **92**: e207-e212. [Viewed 29 October 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23601553

Schell, G., Lavien, M., Stein, J. & Musch, D., (2013). Filtering data from the collaborative initial glaucoma treatment study for improved identification of glaucoma progression. *BMC Medical Information and Decision Making*. [online]. **13**(137). 1-8. [Viewed 09 September 2016]. Available from: http://www.biomedicalcentral.com/147-6947/13/137

Schiefer, U., Strasburger, H., Becker, S., Vonthein, R., Schiller, J., Dietrich, T. & Hart, W., (2001). Reaction time in automated kinetic perimetry: effects of stimulus luminance, eccentricity, and movement direction. *Vision Research*. [online]. **41**. 2157-2164. [Viewed 07 May 2017]. Available from: http://www.sciencedirect.com/science/article/pii/S0042698901000888

Sebastion, S., Abrams, J. & Geisler, W., (2017). Constrained sampling experiments reveal principles of detection in natural scenes. In: B. Randolph, ed. *Proceedings of the National Academy of Science United States of America, 11 July 2017, Texas U.S.A.* [online]. Nashville Tennessee: Vanderbilt University, E5731-E5740. [Viewed 30 October 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/28652323

Seim, T. & Valberg, T., (2016). A neurophysiologically-based analysis of lightness and brightness perception. *Color Research and Application*. [online]. **41**(4). 339-351. [Viewed 03 September 2017]. Available from: https://www.deepdyve.com/lp/wiley/a-neurophysiologically-based-analysis-of-lightness-and-brightness-pvYPdOhO0p

Sharpe, L., Fach. C. & Stockman, A., (1992). The field adaption of the human rod visual system. *Journal of Physiology*. [online]. **445**. 319-343. [Viewed 10 September 2016]. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1179984/

Sheth, V., Gottlab, I., Mohammad, S., McLean, R. & Proudlock, F., (2014). Visual field deficits in albinism. *Investigative Ophthalmology and Visual Science*. [online]. **55**(13). Abstract only. [Viewed 06 October 2016]. Available from: http://iovs.arvojournals.org/article.aspx?articleid=2268017

Shinar, D., (2008). Looks are (almost) everything: where drivers look to get information. *Human Factors*. [online]. **50**(3). 380-384. [Viewed 25 November 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/18689042

Shinoda, H., Hayhoe, M. & Shrivastava, A., (2001). What controls attention in natural environments? *Vision Research*. [online]. **41**. 3535-3545. [Viewed 02 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/11718793

Shirato, S., Inoue, R., Fukushima, K., & Suzuki, Y., (1999). Clinical evaluation of SITA: a new family of perimetric testing strategies. *Graefe's Archives of Clinical and Experimental Ophthalmology*. [online]. **237**:29-34. Abstract only. [Viewed 08 May 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/9951638

Shute, C., (2018). A case report of branch retinal vein occlusion in a teenager due to hyperhomocysteinaemia; the interplay of genetic and nutritional defects. *BMC Ophthalmology*. [online]. **18**((suppl 1)220)). 41-58. [Viewed 14 September 2019]. Available from: https://bmcophthalmol.biomedcentral.com/articles/10.1186/s12886-018-0859-2

Siatkowski, R., Lam, B., Anderson, D., Feuer, W. & Halikman, A., (1996). Automated Suprathreshold Static Perimetry Screening for Detecting Neuro-ophthalmological Disease. *Ophthalmology*. [online]. **103**(6). 907-911. [Viewed 07 September 2016]. Available from: https://www.sciencedirect.com/science/article/pii/S0161642096305885

Siegal, S. & Castellan, N., (1998). *Nonparametric Statistics.* 2nd Edition. New York: McGraw-Hill Book Company.

Silva, M., Mateus, C., Reis, A., Nunes, S., Fonseca, P. & Castelo-Branco, M., (2010). Asymmetry of visual sensory mechanisms: Electrophysiological, structural, and psychophysical evidences. *Journal of Vision* [online]. **10**(6). 1-11. [Viewed 07 May 2017]. Available from: http://jov.arvojournals.org/article.aspx?articleid=2191712

Smith, N., (2011). *Eye movements, search and perception of visual field defects in glaucoma*. Ph.D. thesis, City University of London. [Viewed 10 April 2017]. Available from: http://openaccess.city.ac.uk/1132/

Smith, T., (1989). The effect of regression towards the mean on visual disability. *Documenta Ophthalmologica*. [online]. **70**. 331-337. [Viewed 27 August 2016]. Available from: https://link.springer.com/article/10.1007/BF00157063

Snell, R. & Lemp, M., (1998). *Clinical anatomy of the eye.* 2nd Edition. Oxford: Blackwell science ltd.

Softpedia, G*Power3 Version 3.1.9.2. [online]. *Softpedia.* [Viewed 01 January 2015]. Available from: http://www.softpedia.com/get/Science-CAD/G-Power.shtml

Sotimehin, A. & Ramulu., P., (2018). Measuring Disability in Glaucoma. *Journal of Glaucoma.* [online]. **27**(11). 939-949. [Viewed 30 December 2018]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/30161076

Spry, P., Bates A., Johnson, C. & Chauhan, B., (2000). Simulation of longitudinal threshold visual field data. *Investigative Ophthalmology and Visual Science*. [online]. **41**(8). 2192-2200. [Viewed 01 August 2018]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/10892862

Spry, P., Hussin, H. & Sparrow, J., (2005). Clinical evaluation of frequency doubling technology perimetry using the humphrey matrix 24-2 threshold strategy. *British Journal of Ophthalmology*. [online]. **89**. 1031-1035. [Viewed 03 September 2014]. Available from: https://bjo.bmj.com/content/89/8/1031

Spry, P., Johnson, C., McKendrick, M. & Turpin, A., (2003). Measurement error of visual field tests in glaucoma. *British Journal of Ophthalmology*. [online]. **87**. 107-112. [Viewed 11 September 2016]. Available from: http://europepmc.org/articles/PMC1771451

Stabell, U. & Stabell, B., (2003). Effects of light and dark adaption of rods on specific-hue threshold. *Vision Research*. [online]. **43**. 2905-2914. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/14568378

Sund, P., Bath, M. & Mansson, L., (2010). Investigation of the effect of ambient lighting on contrast sensitivity using a novel method for conducting visual research on LCD's. *Radiation Protection Dosimetry*. [online]. **139**(1). 62-70. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/20211917

Suzuki, Y., Kitazawa, Y., Araie, M., Yamagami, J., Yamamoto, T., Ishida, K., Funaki, S., Mishima, H., Tsukamoto, H., Okada, K. & Shibata, T., (2001). Mathematical and Optimal Clustering of Test Points of the Central 30-Degree Visual Field of Glaucoma. *Journal of Glaucoma*. [Online]. **10**(2). 121-128. [Viewed 03 September 2016]. Available from: https://journals.lww.com/glaucomajournal/pages/author.aspx?firstName=Junkichi&lastName=Yamagami

Swanson, W., Dul, M. & Fischer, S., (2005). Quantifying Effects of Retinal Illumination on Frequency Doubling Perimetry. *Investigative Ophthalmology and Visual Science*. [online]. **46**(1). 235-240. [Viewed 07 May 2017]. Available from: http://iovs.arvojournals.org/article.aspx?articleid=2163342

Swanson, W., Dul, M., Horner, D., Liu, T. & Tran, I., (2014). Assessing spatial and temporal properties of perimetric stimuli for resistance to clinical variations in retinal illumination. *Investigative Ophthalmology and Vision Science*. [online]. **55**(1). 353-359. [Viewed 08 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/24370832

Szinte, M., Carrasco, M., Cavanagh, P. & Rolfs, M., (2015). Attentional trade-offs maintain the tracking of moving objects across saccades. *Journal of Neurophysiology*. [online]. **113**. 2220-2231. [Viewed 10 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/25609111

Szlyk, J., Mahler, C., Seiple, W., Edward, D. & Wilensky, J., (2005). Driving performance of glaucoma patients correlates with peripheral visual field loss. *Journal of Glaucoma*. [online]. **14**(2). 145-150. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/15741817

Szlyk, J., Taglia, D., Paliga, J., Edward, D. & Wilensky, J., (2002). Driving performance in patients with mild to moderate glaucomatous clinical vision changes. *Journal of Rehabilitation Research and Development*. [online]. **39**(4). 467-495. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/17638144

Tanabe, S., Yuki, K., Ozeki, N., Shiba, D., Abe, T., Kouyama, K. & Tsubota, K., (2011). The association between primary open-angle glaucoma and motor vehicle collisions. *Investigative Ophthalmology and Visual Science*. [online]. **52**(7). 4177-4181. [Viewed 27 November 2015]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21447677

Tattersall, C., Vernon, S. & Menon, G., (2007). Mean deviation fluctuation in eyes with stable Humphery 24-2 visual fields. *Eye*. [online]. **21**. 362-366. [Viewed 04 September 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/16424913

Taylor, T., Pradhan, A., Divekar, G., Romoser, M., Muttart, J., Gomez, R., Pollatsek, A. & Fisher, D., (2013). The view from the road: the contribution of on-road glance-monitoring technologies to understand driver behaviour. *Accident Analysis and Prevention*. [online]. **58**. 175-186. [Viewed 01 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/23548549

Tchoudomira, M. & Passaglia, C., (2015). Contrast adaption in the *Limulus* lateral eye. *Journal of Neurophysiology*. [online]. **114**. 3234-3241. [Viewed 02 August 2016]. Available from: https://www.physiology.org/doi/full/10.1152/jn.00593.2015

Thang, J., Beckman, C., Abrahamsson, M. & Sjostrand, J., (1995). The 'light scattering factor' the importance of geometry, contrast definition and adaption. *Investigative Ophthalmology and Visual Science*. [online]. **36**(11). 2313-2317. [Viewed 02 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/7558726

Timms, A., (2015). Motorists banned in error after DVLA eyesight test fails. *The Guardian* [online]. 17 October. Updated 17 October 2015, 06:59. [Viewed 12 September 2016]. Available from: https://www.theguardian.com/money/2015/oct/17/motorists-banned-dvla-eyesight-test-faulty-equipment

Trento, M., Passera, P., Trevisan, M., Schellino, F., Sitia, E., Albani, S., Montanaro, M., Bandello, F., Scoccianti, L., Charrier, L., Cavallo, F. & Porta, M., (2013). Quality of life, impaired vision and social role in people with diabetes: a multicenter observational study. *Acta Diabetologica*. [online] **50**. 873-877. [Viewed 06 September 2016]. Available from: https://link.springer.com/article/10.1007%2Fs00592-013-0470-1

Tunnacliffe, A., (1993). *Introduction to Visual Optics.* Surrey: The Gresham Press.

Turpin, A., Jankovic, D. & McKendrick, A., (2007). Retesting visual fields: utilising prior information to decrease test-retest variability in glaucoma. *Investigative Ophthalmology and Visual Science*. [online]. **48**(4). 1627-1634. [Viewed 29 October 2014]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/17389493

Uchida, T. & Ohno, Y., (2015). Defining the visual adaption field for mesopic photometry: How does a high-luminance source affect peripheral adaption? *Lighting Research and Technology*. [online]. **47**. 845-858. [Viewed 07 May 2017]. Available from: http://journals.sagepub.com/doi/abs/10.1177/1477153514558963

Ullman, S., (1984). Visual routines. *Cognition*. [online]. **18**. 97-157. [Viewed 05 October 2016]. Available from: https://www.cs.cmu.edu/afs/cs/academic/class/15494-s16/readings/ullman-visual-routines.pdf

Underwood, G., Chapman, P., Brocklehurst, N., Underwood, J. & Crundall, D., (2003). Visual attention while driving: sequences of eye fixation made by experienced and novice drivers. *Ergonomics*. [online]. **46**(6). 629-646. [Viewed 08 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/12745692

Underwood, G., Crundall, D. & Chapman, P., (2002). Selective searching while driving: the role of experience in hazard detection and general surveillance. *Ergonomics*. [online]. **45**(1). 1-12. [Viewed 04 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/11964191

Underwood, G., Humphrey, K. & van Loon, E., (2011). Decisions about objects in real-world scenes are influenced by visual saliency before and during their inspection. *Vision Research*. [online]. **51**. 2031-2038. [Viewed 01 October 2016]. Available from: http://www.sciencedirect.com/science/article/pii/S0042698911002665

van Landingham, S., Hochberg, C., Massof, R., Chan. E., Friedman. D. & Ramulu. P., Driving patterns in older adults with glaucoma. *Biomed Central Ophthalmology*. [online]. **13**(4). 1-7. [Viewed 25 January 2015]. Available from: http://www.biomedcentral.com/1471-2415/13/4

Vega, R., Leeuwen, P., Velez, E., Lemij, H. & Winter, J., (2013). Obstacle Avoidance, Visual Detection Performance, and Eye-scanning Behaviour of Glaucoma Patients in a Driving Simulator: A Preliminary Study. *Plos One*. [online]. **8**(10). 1-14. [Viewed 14 December 2014]. Available from: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0077294

Vercher, J., Lazzari, S. & Gauthier, G., (1997). Manuo-ocular coordination in target tracking. II. Comparing the model with human behaviour. *Biological Cybernetics*. [online]. **77**. 267-275. [Viewed 04 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/9394444

Vesti, E., Johnson, C. & Chauhan, B., (2003). Comparison of Different Methods for Detecting Glaucomatous Visual Field Progression. *Investigative Ophthalmology and Visual Science*. [online]. **44**. 3873-3879. [Viewed 03 October 2016]. Available from: https://iovs.arvojournals.org/article.aspx?articleid=2123925

Virsu, V., (1978). Retinal mechanisms of visual adaption and afterimages. *Medical Biology*. [online]. **56**(2). 84-96. Abstract only. [Viewed 09 August 2017]. Available from: http://europepmc.org/abstract/med/661403

Virsu, V. & Lee, B., (1983). Light adaption in cells of macaque lateral geniculate nucleus and its relation to human light adaption. *Journal of Neurophysiology*. [online]. **30**(4). 864-878. [Viewed 14 August 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/6631467

Viswanathan, A., Crabb, D., Fitzke, F. & Hitchings, R., (2003). Prevalence and characteristics of central binocular visual field defects in patients attending a glaucoma perimetry service. In: M. Wall, A. Heijl, eds. *Perimetry Update 2002/2003*. New York: Kuglar Publications. Pp. 83-85.

Viswanathan, A., Fitzke, F. & Hitchings, R., (1997). Early detection of visual field progression in glaucoma: a comparison of PROGRESSOR and STATPAC 2. *British Journal of Ophthalmology*. [online]. **81**. 1037-1042. [Viewed 26 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/9497460

Wall, M., Brito, C., Woodward, K., Doyle, C., Kardon, R. & Johnson, C., (2008). Total deviation probability plots for stimulus size V perimetry. A comparison with size III

perimetry. *Archives of Ophthalmology*. [online]. **126**(4). 473-479. [Viewed 04 July 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/18413515

Wall, M., Johnson, C., Kutko, K., Nguyen, R., Brito, C. & Keltner, J., (1998). Long- and short-term variability of automated perimetry results in patients with optic neuritis and healthy subjects. *Archives of Ophthalmology*. [online]. **116**. 53-61. [Viewed 03 July 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/9445208

Wall, M., Punke, S., Stickney, T., Brito, C., Withrow, K. & Kardon, R., (2001). SITA standard in optic neuropathies and hemianopias: a comparison with full threshold testing. *Investigative Ophthalmology and Visual Science*. [online]. **42**(2). 528-557. [Viewed 05 July 2017]. Available from: https://www.ncbi.nlm.nih.gov/m/pubmed/11157893

Wall, M., Woodward, K., Doyle, C. & Zamba, G., (2010). The effective dynamic ranges of standard automated perimetry sizes III and V and motion and matrix perimetry. *Archives of Ophthalmology*. [online]. **128**(5). 570-576. [Viewed 05 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/20457977

Wang, Y., Toor, S., Gautam, R. & Henson, D., (2011). Blink Frequency and Duration During Perimetry and Their Relationship to Test-retest Threshold Variability. *Investigative Ophthalmology and Visual Science*. [online]. **52**(7). 4546-4550. [Viewed 11 October 2016]. Available from: http://iovs.arvojournals.org/article.aspx?articleid=2188061

Wanvik, P., (2009). Effects of road lighting: An analysis based on Dutch accident statistics 1987-2006. *Accident Analysis and Prevention*. [online]. **41**. 123-128. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/19114146

Werneke, J. & Vollrath, M., (2012). What does the driver look at? The influence of intersection characteristics on attention allocation and driving behaviour. *Accident Analysis and Prevention*. [online]. **45**. 610-619. [Viewed 01 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/22269548

Werner, S. & Theis, B., (2000). Is “Change Blindness” Attenuated by Domain-Specific Expertise? An Expert-Novices Comparison of Change Detection in Football Images. *Visual Cognition*. [online]. **7**(1-3). 163-173. [Viewed 09 October 2016]. Available from: http://www.tandfonline.com/doi/abs/10.1080/135062800394748

Werring, D., Bullmore, E., Toosy, A., Miller, D., Barker, G., MacManus, D., Brammer, M., Giampieto, V., Brusa, A., Brex, P., Moseley, I., Plant, G., McDonald, W. & Thompson, A., (2000). Recovery from optic neuritis is associated with a change in the distribution of cerebral response to visual stimulation: a functional magnetic resonance imaging study. *Journal of Neurology, Neurosurgery and Psychiatry*. [online] **68**. 441-449. [Viewed 01 November 2015]. Available from: https://jnnp.bmj.com/content/jnnp/68/4/441.full.pdf

West, C., Gildengorin, G., Haegerstrom-Portney, G., Lott, L., Schneck, M. & Brabyn, J., (2003). Vision and driving self-restriction in older adults. *Journal of the American Geriatrics Society*. [online]. **51**(10).1348-1355. [Viewed 07 May 2017]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/14511153

Wilson, M., Stephenson, S., Chattington, M. & Marple-Horvat, D., (2007). Eye movements coordinated with steering benefit performance even when vision is denied. *Experimental Brain Research*. [online]. **176**(3). 397-412. [Viewed 01 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/16896979

Winther, C. & Frisen, L., (2007). New rarebit vision test captures macular deficits hidden to acuity tests. *Acta Ophthalmologica* [online]. **93**(5):481-485. [Viewed 30 October 2017]. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/aos.12659

Wolfe, J. & Horowitz, T., (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neurosciences*. [online]. **5**. 495-501. [Viewed 09 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/15152199

Wong, T. & Scott, I., (2010). Retinal-Vein Occlusion. *The New England Journal of Medicine*. [online]. **363**(2). 2135-2144. [Viewed 14 September 2019]. Available from: https://www.nejm.org/doi/full/10.1056/NEJMcp1003934

Wood, J., (1987). *The investigation of the sensitivity gradient of the visual field, as a function of stimulus dynamic range, in the normal and abnormal eye*. Ph.D. thesis. Aston University. [Viewed 09 September 2016]. Available from: https://publications.aston.ac.uk/view/year/1987.html#group_W

Wood, J., (2011). Driving and Vision Series. Part 10- Ageing and Driving. *The Optician*. [online]. **Aug**. 19:24. [Viewed 13 February 2015]. Available from: http://www.opticianonline.net/driving-and-vision-series/

Wood, J. & Black, A., (2013). Older drivers: implications of visual changes with age. *Points du Vue*. **Spring**. 11-13.

Wood, J. & Black, A., (2016). Ocular disease and driving. *Clinical and Experimental Optometry*. [online]. **99**. 395-401. [Viewed 01 November 2017]. Available from: https://onlinelibrary.wiley.com/doi/full/10.1111/cxo.12391

Wood, J., Chaparro, A., Carberry, T. & Chu, B., (2010). Effect of simulated visual impairment on nighttime driving performance. *Optometry and Vision Science*. [online]. **87**. 379-386. [Viewed 05 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/20386352

Wood, J., Chaparro, A. & Hickson, L., (2009). Interaction between visual status, driver age and distractors on daytime driving performance. *Vision Research*. [online]. **49**. 2235-2231. [Viewed 05 October 2016]. Available from: http://www.sciencedirect.com/science/article/pii/S0042698909003101

Wood, J., Collins, M., Chaparro, A., Marszalek, R., Carberry, T., Lacherez, P. & Chu, B., (2014). Differential effects of refractive blur on day and nighttime driving performance. *Investigative Ophthalmology and Visual Science*. [online]. **55**. 2284-2289. [Viewed 05 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/24618322

Wood, J., McGwin, G., Elgin, J., Vaphiades, M., Braswell, R., DeCarlo. D., Kline, L., Meek, C., Searcey, K. & Owsley, C., (2009). On-road driving performance in persons with hemianopia and quadrantanopia. *Investigative Ophthalmology and Visual Science*. [online]. **50**(2). 577-585. [Viewed 02 May 2016]. Available from: http://www.ncbi.nlm.nih.gov/pubmed/18936138

World Health Organisation, (2014). Prevention of Blindness and Visual Impairment. [online]. *World Health Organisation*. [Viewed 17 November 2014]. Available from: http://www.who.int/blindness/causes/priority/en/index6.html

World Health Organisation, (2017). Prevention of blindness and visual impairment: Priority eye diseases. [online] *World Health Organisation.* [Viewed 02 December 2017]. Available from: http://www.who.int/blindness/causes/priority/en/

Wroblewski, D., Francis, B., Sadun, A., Vakili, G. & Chopra, V., (2014). Testing of visual fields with virtual reality goggles in manual and visual grasp modes. *Hindawi*. [online].1-10. [Viewed 02 September 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/25050326

Wyatt, H., Dul, M. & Swanson, W., (2007). VARIABILITY OF VISUAL FIELD MEASUREMENTS IS CORRELATED WITH THE GRADIENT OF VISUAL SENSITIVITY. *Vision Research*. [online]. **47**. 925-936. [Viewed 04 September 2014]. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2094527/

Xuan, J., Kirchdoefer, L. & Boyer, J., (1999). Effects of comorbidity on health-related quality-of-life scores: an analysis of clinical trial data. *Clinical Therapeutics*. [online]. **21**(2). 383-403. [Viewed 29 August 2019]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/10211540

Yan, Y., Yuan, H., Wang, X., Xu, T. & Liu, H., (2014). Study on Driver's Fixation Variation at Entrance and Inside Sections of Tunnel on Highway. *Advances in Medical Engineering*. [online]. 1-10. [Viewed 10 October 2016]. Available from: http://journals.sagepub.com/doi/abs/10.1155/2014/273427

Yuki, K., Asaoka, R. & Tsubota, K., (2014). The Relationship between Central Visual Field Damage and Motor Vehicle Collisions in Primary Open-Angle Glaucoma Patients. *Plos One*. [online]. 1-15. [Viewed 09 October 2016]. Available from: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0115572

Zeiss, (2014). Humphrey field analyser II-I The gold standard in perimetry. [online]. *Zeiss,* [Viewed 27 October 2014]. Available from: http://www.zeiss.com/meditec/en_us/products/ophthalmology-optometry/glaucoma/diagnostics/perimetry/humphrey-hfa-ii-i.html#technical-data

Zhao, N., Chen, W., Xuan, Y., Mehler, B., Reimer, B. & Fu, X., (2014). Drivers' and non-drivers' performance in a change detection task with static driving scenes: is there a benefit of experience? *Ergonomics*. [online]. **57**(7). 998-1007. [Viewed 08 October 2016]. Available from: https://www.ncbi.nlm.nih.gov/pubmed/24787715

Appendix 1. Location of the Esterman Stimuli Coordinates on the HFA.

Location	X	Y	Location	X	Y	Location	X	Y	Location	X	Y
1	-21	38	**30**	-12	3	**59**	-7	-7	**88**	-30	-20
2	21	38	**31**	-7	3	**60**	-3	-7	**89**	-20	-20
3	-56	21	**32**	7	3	**61**	3	-7	**90**	-12	-20
4	-33	21	**33**	12	3	**62**	7	-7	**91**	-7	-20
5	-18	21	**34**	20	3	**63**	12	-7	**92**	-3	-20
6	-5	21	**35**	30	3	**64**	20	-7	**93**	3	-20
7	5	21	**36**	40	3	**65**	30	-7	**94**	7	-20
8	18	21	**37**	55	3	**66**	40	-7	**95**	12	-20
9	33	21	**38**	74	3	**67**	55	-7	**96**	20	-20
10	56	21	**39**	-75	-2	**68**	75	-7	**97**	30	-20
11	-72	10	**40**	-55	-2	**69**	-74	-13	**98**	40	-20
12	-55	10	**41**	-40	-2	**70**	-55	-13	**99**	55	-20
13	-40	10	**42**	-30	-2	**71**	-55	-13	**100**	72	-20
14	-30	10	**43**	-20	-2	**72**	-40	-13	**101**	-68	-30
15	-19	10	**44**	-12	-2	**73**	-30	-13	**102**	-48	-30
16	-10	10	**45**	-7	-2	**74**	-20	-13	**103**	-32	-30
17	-3	10	**46**	7	-2	**75**	-12	-13	**104**	-18	-30
18	3	10	**47**	12	-2	**76**	-7	-13	**105**	-5	-30
19	10	10	**48**	20	-2	**77**	-3	-13	**106**	5	-30
20	19	10	**49**	30	-2	**78**	3	-13	**107**	18	-30
21	30	10	**50**	40	-2	**79**	7	-13	**108**	32	-30
22	40	10	**51**	55	-2	**80**	12	-13	**109**	48	-30
23	55	10	**52**	75	-2	**81**	20	-13	**110**	68	-30
24	72	10	**53**	-75	-7	**82**	30	-13	**111**	-53	-43
25	-74	3	**54**	-55	-7	**83**	40	-13	**112**	-28	-43
26	-55	3	**55**	-40	-7	**84**	74	-13	**113**	-8	-43
27	-40	3	**56**	-30	-7	**85**	-72	-20	**114**	8	-43
28	-30	3	**57**	-20	-7	**86**	-55	-20	**115**	28	-43
29	-20	3	**58**	-12	-7	**87**	-40	-20	**116**	53	-43

Location	X	Y	Location	X	Y	Location	X	Y	Location	X	Y
117	-32	-58	**118**	-8	-58	**119**	8	-58	**120**	32	-58

Table A1-1. The x and y coordinates of the 120 presented stimuli of the HFA Esterman Visual Field Test grid. Location numbers are representative of the stimuli left to right and top to bottom.

Appendix 2. Standardised Verbal Instructions Provided to Each Participant.
(Adapted from Heijl *et al*. 2012 and Cubbidge. 2005).

Participants were informed/instructed:

How long the test is likely to take.

To place chin on left chin rest (Esterman visual field test on the Humphrey Field Analyser)/ To place chin in the middle of the chin rest (Esterman visual field test on the Henson Perimeter)/To place chin on the left/right chin rest, dependent upon eye under examination (HFA Sita Standard 24-2).

To maintain contact with chin and forehead rest.

To look at the fixation light at all times during the test.

To press the response button should they see a light in the edge of their visual field.

To keep both eyes open.

To blink as normal during the test.

To hold the response button down to pause the test should they feel they need a break and to release when they were ready to resume.

Participants had a demonstration of/were directed to:

How to utilise the response button when they see a light.

The fixation light.

How to hold the response button down when they wish to pause test and to release when they wish to resume testing.

Appendix 3. Calculation of EVFT differences between the HFA and the Henson Perimeter using known formulae.

Calculations for Henson 5000.

Utilising the formula below (Eqn.5) which determines sensitivity (dB), the k value of the Henson can be found. k is a constant dependent upon the state of retinal adaption.

$$sensitivity(dB) = k + \log\left(\frac{L}{\Delta L}\right)$$ (Cubbidge. 2005). Eqn. 5.

k calculates to be 40- 10logL for the HFA (Cubbidge. 2005)

Knowing the value of k for the HFA then sensitivity (dB) can then be calculated by Eqn 6 for the HFA.

$dB = 40 - \log \Delta L$ (Cubbidge. 2005) Eqn. 6.

Using the same method the k value for the Henson Pro Perimeter is found.

Using the following formula:

$0dB = k + 10logL - 10log\Delta L$ Eqn. 7.
$0 = k + 10logL - 10log3140$
$k = 34.97 - 10logL$

Substituting k into equation Eqn. 7,

$dB = 34.97 - 10\log \Delta L$ for the Henson Pro Perimeter.

The resultant sensitivity (dB) calculated for each perimeter with Eqn. 7 is presented in table A3-1.

HFA EVFT sensitivity (dB)	**Henson EVFT sensitivity (dB)**
EVFT ΔL HFA = 1000asb.	EVFT ΔL Henson = 31.8asb
$dB = 40 - 10\log 1000$ $= 40 - 30$ $= 10dB$	$dB = 34.97 - 10\log 31.8$ $= 34.97 - 15.024$ $= 19.95dB$

Table A3-1. Calculated sensitivity (dB) using known formulae. Values provided for the HFA and Henson Pro Perimeter.

The decibel measurement is an attenuation value from the maximum intensity. Each perimeter also presents with different background luminance and hence the decibel value for one perimeter will not necessarily mean the same for another perimeter.

Weber's law (Gardiner e*t al*. 2006. P.440, Virsu & Lee. 1983. P. 865) calculates sensitivity and the luminance difference threshold. These use the solid unit of asb, and hence the result is not an attenuation of the maximum stimulus.

Utilising this formula, sensitivity for the HFA EVFT is found to be

$$\frac{L}{\Delta L} = \frac{31.5}{1000} = 0.03$$ Eqn. 3.

and sensitivity for the Henson Pro Perimeter EVFT is found to be

$$\frac{L}{\Delta L} = \frac{10}{31.8} = 0.31$$

The contrast (luminance difference threshold) for the HFA EVFT is found to be

$$\frac{\Delta L}{L} = \frac{1000}{31.5} = 31.75$$ Eqn. 2.

and log (31.75) = 1.5

The contrast (luminance difference threshold) for the Henson Pro Perimeter EVFT is found to

$$\frac{\Delta L}{L} = \frac{31.8}{10} = 3.18$$

and log (3.215) =0.5

Substituting the two to consider a stimulus in asb for the HFA to match the ratio calculated for the Henson Pro Perimeter, provides the following value,

$$\Delta L = 3.18 \times 31.5$$
$$\Delta L = 100.17 asb.$$ Eqn. 8.

The presentation of a stimulus of 100 asb on the HFA would be the same as the HFA presenting at 20 dB (2 log units).

Calculations for Henson 9000.

The sensitivity for the Henson EVFT with the Henson 9000 values it is found to be

$$\frac{L}{\Delta L} = \frac{10}{100} = 0.1$$

The luminance difference threshold for the Henson EVFT with the Henson 9000 values it is found to be.

$$\frac{\Delta L}{L} = \frac{100}{10} = 10$$

and log (10)=1

Appendix 4. Measured Coordinates of the Henson Esterman Visual Field Test.

X	Y	X	Y	X	Y	X	Y
-48	36	48	12	24	0	18	-18
-36	36	60	12	36	0	30	-18
-24	36	72	12	48	0	-60	-24
-12	36	-42	6	60	0	-48	-24
0	36	-30	6	72	0	-36	-24
12	36	-18	6	-42	-6	-24	-24
24	36	-6	6	-30	-6	12	-36
36	36	6	6	-18	-6	24	-36
48	36	18	6	-6	-6	36	-36
-60	24	30	6	6	-6	48	-36
-48	24	42	6	18	-6	-36	-48
-36	24	-72	0	30	-6	-24	-48
-24	24	-60	0	42	-6	-12	-48
-12	24	-48	0	-72	-12	0	-48
0	24	-36	0	-60	-12	12	-48
12	24	-24	0	-48	-12	24	-48
24	24	-12	0	-36	-12	36	-48
36	24	12	0	-24	-12	-24	-60
48	24	-12	-24	-12	-12	-12	-60
60	24	0	-24	0	-12	0	-60
-72	12	12	-24	12	-12	12	-60
-60	12	24	-24	24	-12	24	-60
-48	12	36	-24	36	-12		
-36	12	48	-24	48	-12		
-24	12	60	-24	60	-12		
-12	12	-48	-36	72	-12		
0	12	-36	-36	-30	-18		
12	12	-24	-36	-18	-18		
24	12	-12	-36	-6	-18		
36	12	0	-36	6	-18		

Table A4-1. Coordinates of the EVFT (Henson). X and Y coordinates representing each individual stimulus location.

Appendix 5. Creation of the Combined Stimuli Grid. The Henson Esterman Visual Field Test Coordinates Mapped to the Nearest Humphrey Visual Field Analyser Esterman Visual Field Test coordinates.

Humphrey		**Henson**								**Henson within functional zone of HFA**	**New plot value**		**Within original functional zone**	**Max difference**	
X	Y	X	Y	X	y	x	Y	X	Y		X	Y		X	Y
-21	38	-24	36	-12	36	0	36	-36	36	Yes	-18	37	Yes	3	-1
21	38	24	36	12	36	36	36	0	36	Yes	18	37	Yes	-3	-1
-56	21	-60	24	-48	24					Yes	-54	22.5	Yes	2	1.5
-33	21	-36	24							Yes	-34.5	22.5	Yes	-1.5	1.5
-18	21	-24	24	-12	24					Yes	-18	22.5	Yes	0	1.5
-5	21	0	24							Yes	-2.5	22.5	Yes	2.5	1.5
5	21	0	24							Yes	2.5	22.5	Yes	-2.5	1.5
18	21	24	24	12	24					Yes	18	22.5	Yes	0	1.5
33	21	36	24							Yes	34.5	22.5	Yes	1.5	1.5
56	21	60	24	48	24					Yes	54	22.5	Yes	-2	1.5
-72	10	-72	12							Yes	-72	11	Yes	0	1
-55	10	-60	12	-48	12					Yes	-54	11	Yes	1	1
-40	10	-36	12							Yes	-38	11	Yes	2	1
-30	10	-36	12	-24	12					Yes	-30	11	Yes	0	1
-19	10	-24	12	-18	6					Yes	-21	9	Yes	-2	-1
-10	10	-12	12							Yes	-11	11	Yes	-1	1

-3	10	0	12			Yes	-1.5	11	Yes	1.5	1
3	10	0	12			Yes	1.5	11	Yes	-1.5	1
10	10	12	12			Yes	11	11	Yes	1	1
19	10	24	12	18	6	Yes	21	9	Yes	2	-1
30	10	24	12	36	12	Yes	30	11	Yes	0	1
40	10	36	12			Yes	38	11	Yes	-2	1
55	10	60	12			Yes	57.5	11	Yes	2.5	1
72	10	72	12			Yes	72	11	Yes	0	1
-74	3	-72	0			Yes	-73	1.5	Yes	1	-1.5
-55	3	-60	0	-48	0	Yes	-54	1.5	Yes	1	-1.5
-40	3	-36	0	-42	6	Yes	-39	3	Yes	1	0
-30	3	-30	6			Yes	-30	4.5	Yes	0	1.5
-20	3	-24	0	-18	6	Yes	-21	3	Yes	-1	0
-12	3	-12	0			Yes	-12	1.5	Yes	0	-1.5
-7	3	-6	6			Yes	-6.5	4.5	Yes	0.5	1.5
7	3	6	6			Yes	6.5	4.5	Yes	-0.5	1.5
12	3	12	0			Yes	12	1.5	Yes	0	-1.5
20	3	24	0	18	6	Yes	21	3	Yes	1	0
30	3	30	6			Yes	30	4.5	Yes	0	1.5
40	3	36	0	42	6	Yes	39	3	Yes	-1	0
55	3	60	0	48	0	Yes	54	1.5	Yes	-1	-1.5
74	3	72	0			Yes	73	1.5	Yes	-1	-1.5
-75	-2	-72	0			Yes	-73.5	-1	Yes	1.5	1
-55	-2	-60	0			Yes	-57.5	-1	Yes	-2.5	1

-40	-2	-36	0	Yes	-38	-1	Yes	2	1
-30	-2	-36	0	Yes	-33	-1	Yes	-3	1
-20	-2	-24	0	Yes	-22	-1	Yes	-2	1
-12	-2	-12	0	Yes	-12	-1	Yes	0	1
-7	-2								
7	-2								
12	-2	12	0	Yes	12	-1	Yes	0	1
20	-2	24	0	Yes	22	-1	Yes	2	1
30	-2	36	0	Yes	33	-1	Yes	3	1
40	-2	36	0	Yes	38	-1	Yes	-2	1
55	-2	60	0	Yes	57.5	-1	Yes	2.5	1
75	-2	72	0	Yes	73.5	-1	Yes	-1.5	1
-75	-7								
-55	-7								
-40	-7	-42	-6	Yes	-41	-6.5	Yes	-1	0.5
-30	-7	-30	-6	Yes	-30	-6.5	Yes	0	0.5
-20	-7	-18	-6	Yes	-19	-6.5	Yes	1	0.5
-12	-7								
-7	-7	-6	-6	Yes	-6.5	-6.5	Yes	0.5	0.5
-3	-7	-6	-6	Yes	-4.5	-6.5	Yes	-1.5	0.5
3	-7	6	-6	Yes	4.5	-6.5	Yes	1.5	0.5
7	-7	6	-6	Yes	6.5	-6.5	Yes	-0.5	0.5
12	-7								
20	-7	18	-6	Yes	19	-6.5	Yes	-1	0.5

30	-7	30	-6			Yes	30	-6.5	Yes	0	0.5
40	-7	42	-6			Yes	41	-6.5	Yes	1	0.5
55	-7										
75	-7										
-74	-13	-72	-12			Yes	-73	-12.5	Yes	1	0.5
-55	-13	-60	-12	-48	-12	Yes	-54	-12.5	Yes	1	0.5
55	-13	60	-12			Yes	57.5	-12.5	Yes	1.5	-0.5
-40	-13	-36	-12			Yes	-38	-12.5	Yes	2	0.5
-30	-13	-36	-12			Yes	-33	-12.5	Yes	-3	0.5
-20	-13	-24	-12			Yes	-22	-12.5	Yes	-2	0.5
-12	-13	-12	-12			Yes	-12	-12.5	Yes	0	0.5
-7	-13										
-3	-13	0	-12			Yes	-1.5	-12.5	Yes	1.5	0.5
3	-13	0	-12			Yes	1.5	-12.5	Yes	-1.5	0.5
7	-13										
12	-13	12	-12			Yes	12	-12.5	Yes	0	0.5
20	-13	24	-12			Yes	22	-12.5	Yes	2	0.5
30	-13	36	-12			Yes	33	-12.5	Yes	3	0.5
40	-13	36	-12	48	-12	Yes	42	-12.5	Yes	2	0.5
74	-13	72	-12			Yes	73	-12.5	Yes	-1	0.5
-72	-20										
-55	-20	-60	-24			Yes	-57.5	-22	Yes	-2.5	-2
-40	-20	-36	-24			Yes	-38	-22	Yes	2	-2
-30	-20	-30	-18			Yes	-30	-19	Yes	0	1

-20	-20	-18	-18	-24	-24		Yes	-21	-21	Yes	-1	-1
-12	-20	-12	-24				Yes	-12	-22	Yes	0	-2
-7	-20	-6	-18				Yes	-6.5	-19	Yes	0.5	1
-3	-20	-6	-18	0	-24		Yes	-3	-21	Yes	0	-1
3	-20	6	-18	0	-24		Yes	3	-21	Yes	0	-1
7	-20	6	-18				Yes	6.5	-19	Yes	-0.5	1
12	-20	12	-24				Yes	12	-22	Yes	0	-2
20	-20	18	-18	24	-24		Yes	21	-21	Yes	1	-1
30	-20	30	-18				Yes	30	-19	Yes	0	1
40	-20	36	-24				Yes	38	-22	Yes	-2	-2
55	-20	60	-24				Yes	57.5	-22	Yes	2.5	-2
72	-20											
-68	-30	-60	-24				Yes	-64	-27	Yes	4	3
-48	-30	-48	-36				Yes	-48	-33	Yes	0	-3
-32	-30	-36	-36				Yes	-34	-33	Yes	-2	-3
-18	-30	-24	-36	-12	-36		Yes	-18	-33	Yes	0	-3
-5	-30	0	-36				Yes	-2.5	-33	Yes	2.5	-3
5	-30	0	-36				Yes	2.5	-33	Yes	-2.5	-3
18	-30	12	-36	24	-36		Yes	18	-33	Yes	0	-3
32	-30	24	-36	36	-36		Yes	30	-33	Yes	-2	-3
48	-30	48	-36				Yes	48	-33	Yes	0	-3
68	-30	60	-24				Yes	64	-27	Yes	-4	3
-53	-43	-48	-36				Yes	-50.5	-39.5	Yes	2.5	3.5
-28	-43	-24	-48	-36	-48		Yes	-30	-45.5	Yes	-2	-2.5

-8	-43	-12	-48	0	-48	Yes	-6	-45.5	Yes	2	-2.5
8	-43	12	-48	0	-48	Yes	6	-45.5	Yes	-2	-2.5
28	-43	36	-48	24	-48	Yes	30	-45.5	Yes	2	-2.5
53	-43	48	-36			Yes	50.5	-39.5	Yes	-2.5	3.5
-32	-58	-24	-60			Yes	-28	-59	Yes	4	-1
-8	-58	-12	-60	0	-60	Yes	-6	-59	Yes	2	-1
8	-58	12	-60	0	-60	Yes	6	-59	Yes	-2	-1
32	-58	24	-60			Yes	28	-59	Yes	-4	-1

Table A5-1. Creation of the combined stimuli grid. The Henson EVFT coordinates mapped to the nearest HFA EVFT coordinate. Original plots (degrees) of both the HFA and Henson EVFT. Included are details of whether the original Henson EVFT plot was within a HFA EVFT functional zone, new plot values of combined locations, details of whether combined locations are within the HFA EVFT original functional zone and the amount the plot varies (degrees) from the original HFA EVFT stimuli plot. - = direction down or left. + = direction up or right.

Appendix 6. Excluded Coordinates of Humphrey Visual Field Analyser or Henson Pro Perimeter Esterman Visual Field Test.

X coordinate	Y coordinate	Perimeter the coordinate originates. HFA/Henson
48	36	Henson
-48	36	Henson
-7	-2	HFA
7	-2	HFA
7	-13	HFA
7	-13	HFA
-12	-7	HFA
12	7	HFA
-55	-7	HFA
55	-7	HFA
-72	-20	HFA
72	20	HFA
-75	-7	HFA
75	-7	HFA

Table A6-1. Excluded coordinates. Listed are the Henson and Humphrey Visual Field Analyser Esterman Visual Field Test coordinates that do not map within a close range to a plot on the other perimeter, or the combined plot location did not enable it to fall within an Esterman Visual Field Test functional zone. Two (1.79%) coordinates were found not to map to the aforementioned criteria for the Henson Perimeter and twelve (10%) coordinates were found not to map to the aforementioned criteria for the Humphrey Visual Field Analyser.

Appendix 7. Questionnaire.

Subject number (to be completed by researcher):

_____ **Date:_____**

QUESTIONNAIRE

Please indicate with a tick your answer to the following questions.

		1st machine	2nd machine	No difference
Question 1	On which machine did you feel the test was easier on?			
Question 2	Which machine did you feel the test was easier to carry out in terms of your posture, head position and chin rest comfort?			
Question 3	On which machine did you feel the test was visually more comfortable?			
Question 4	On which machine did you feel the test was quicker to complete?			
Question 5	Overall, which machine did you prefer to be tested on?			

Thank you for your time in completing this questionnaire.

Table A7-1. Questionnaire. Provided to participants to compare participant experience between the Humphrey Field Analyser 24-2 SITA Standard and Ring of Sight 24-2 full threshold.

Appendix 8. The Hodapp-Parish-Anderson Glaucoma Grading Scale.

Table A8-1. The Glaucoma Grading Scale (Hodapp-Parish-Anderson).
PSD=Pattern Standard Deviation, POAG=Primary Open Angle Glaucoma.
http://ophthaclassification.altervista.org/glaucoma-grading-scale-hodapp-parrish-anderson/