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Saccadic eye movements and face recognition performance in patients with central glaucomatous visual field defects

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ABSTRACT

Patients with more advanced glaucoma are likely to experience problems with everyday visual tasks such as face recognition. However, some patients still perform well at face recognition despite their visual field (VF) defects. This study investigated whether certain eye movement patterns are associated with better performance in the Cambridge Face Memory Test. For patients with bilateral VF defects in their central 10° of VF, making larger saccades appeared to be associated with better face recognition performance ($\rho = 0.60$, $p = 0.001$). Associations were less apparent for the patients without significant 10° defects. There were no significant associations between saccade amplitude and task performance in people with healthy vision ($\rho = -0.24$; $p = 0.13$). These findings suggest that some patients with likely symptomatic glaucomatous damage manifest eye movements to adapt to VF loss during certain visual activities.

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1. Introduction

Patient-reported measures have repeatedly suggested that glaucoma leads to problems with performing everyday activities and a poorer perceived quality of life (Glen, Crabb, & Garway-Heath, 2011; Ramulu, 2009). However, the subjective nature of these studies mean that results are susceptible to bias, and as such, studies involving more objective ‘performance-based measures’ of visual disability have begun to complement these research findings. Such studies involve the direct assessment of a person’s ability to perform activities such as reading, mobility tasks, driving, searching for objects and face recognition, using standardised conditions and predetermined criteria (Glen et al., 2012; Haymes et al., 2008; Kotecha et al., 2009; Ramulu et al., 2009; Smith, Crabb, & Garway-Heath, 2011; Turano, Rubin, & Quigley, 1999). These findings suggest that the performance of patients with glaucoma is significantly reduced on average, compared with people with healthier vision. However, a common feature in data reported in these studies is the high between-patient variability in task performance; simply put, some patients continue to perform well at visual tasks despite the severity of their visual field (VF) loss. For example, patients with significant damage to the central 10° of VF performed worse, on average, at a face recognition task compared to people with normal vision of a similar age, but some patients still performed well at the task (Glen et al., 2012). We

hypothesise that eye movements, an element of visual function not typically considered in glaucoma, may explain some of this variability in visual task performance.

Eye movements are a vital tool for processing visual information; since acuity naturally attenuates with increasing eccentricity from the point of regard, an individual must move their eyes to bring new information onto the fovea in order to analyse details of a visual scene. Prior studies have suggested that some patients with glaucoma may be forced to sample information differently during everyday tasks, and that these changes may therefore underlie any apparent functional deficits. For example, when patients were shown dynamic movies of road traffic scenes, they were found to produce more fixations and saccades than controls with healthy vision (Crabb et al., 2010). Other research suggests that VF loss may lead to restrictions in eye movements in less dynamic tasks, with patients shown to produce fewer saccades and to view different locations of static naturalistic scenes than visually healthy people (Smith et al., 2012). Evidence in people with normal vision suggests that the type and difficulty of task influences the manner in which people move their eyes (for a review see Rayner, 2009), suggesting the importance of considering eye movements in different contexts. There is some compelling evidence that ‘training’ in eye movement control can improve task performance in subjects with age-related macular degeneration (AMD) (Seiple, Grant, & Szlyk, 2011; Seiple et al., 2005) and hemianopia (Pambakian et al., 2004). It has also been suggested that eye movements play a functional role in normal face recognition; for example, scanning behaviour may underlie some of the face recognition deficits seen in older adults, with the way faces are sampled at first

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viewing influencing subsequent recognition accuracy (Chan et al., 2011; Firestone, Turk-Browne, & Ryan, 2007).

This report aims to examine data from a ‘performance-based’ task in order to see if there is a link between eye movement behaviour and performance in glaucoma. Specifically we test the hypothesis that better performance at a face recognition task is associated with aspects of saccadic eye movements in patients with bilateral glaucomatous VF loss in the central 10° and that this association is not apparent in people with normal vision.

2. Methods

Patients with repeatable VF defects in both eyes as a result of Primary Open Angle Glaucoma (and no other ocular disease) were recruited from Moorfields Eye Hospital NHS Trust. People with healthy vision (controls) were selected from the Fight for Sight clinic at City University London. Prior to participation in the study, visual acuity (VA), measured in logMAR, of all participants was recorded using an Early Treatment Diabetic Retinopathy Study (ETDRS) chart. A requirement of the study was a binocular VA of at least 0.18 (Snellen 6/9). The contrast sensitivity (CS) of all patients was also recorded using a Pelli-Robson chart. Participants were verified as ‘within normal limits’ on the Oculus C-Quant (Oculus GmbH, Wetzlar, Germany), a measure of straylight indicating levels of lens opacity. In addition, visual fields (SITA Standard 24-2 and 10-2) in both eyes were recorded on a Humphrey Field Analyzer (HFA, Carl Zeiss Meditec, CA, USA) in all patients. The Glaucoma Hemifield Test (GHT), an algorithm which detects signs of glaucomatous damage, was flagged as “outside normal limits” in all recorded VFs, though patients were purposely recruited to have a range of VF defect severities. The HFA output also shows the mean deviation (MD); a standard summary measure of the overall severity of VF loss that takes the participant’s age into account. Following on from previously published research suggesting the presence of central glaucomatous defects may impact face recognition performance (Glen et al., 2012), patients were subsequently classified according to whether or not they had ‘significant’ defects in the 10-2 VF in both eyes using the MD values. As previously reported, a ‘significant’ defect was defined as one where the MD on the HFA output was flagged as being worse than the 1% normative value [$MD < 1\%$]. To determine the impact of binocular vision in the central 10° on task functioning, greyscales for integrated visual fields (IVF) were also constructed for each patient using their 10-2 VFs (as the central 10° was the primary focus of this investigation). This method involves combining monocular VFs by taking the best total deviation (TD) sensitivity value at each VF location to represent the state of the individual’s binocular vision (Crabb & Viswanathan, 2005). None of the control subjects (who completed SITA-FAST 24-2 VFs in both eyes to screen for VF defects) failed the GHT. All participants passed the Middlesex Elderly Assessment of Mental Status (MEAMS) test (Kutlay et al., 2007), indicating they were of sufficient cognitive health and did not show any signs of dementia or any other isolated cognitive deficit.

The study was approved by research governance committees of the participating institutions in addition to receiving approval from a UK National Health Service, National Research Ethics Service committee. The study conformed to the declaration of Helsinki, and all participants gave their informed written consent prior to taking part. Data was anonymised and stored in a secure database.

2.1. Procedure

Participants completed the Cambridge Face Memory Test (CFMT) (Duchaine & Nakayama, 2006) on a 22" monitor (Iiyama Vision Master PRO 514, Iiyama Corporation, Tokyo, Japan) at

resolution of 1600×1200 at 100 Hz. In the test, participants binocularly view six new faces at three different viewing angles for three seconds each ($n = 18$ “viewing trials”). Their recognition of these faces is subsequently tested in a series of forced-choice recognition trials ($n = 51$), whereby they are required to distinguish the previously seen face from an additional two unfamiliar faces. The CFMT is a freely available, validated test, initially designed to test for the neurological condition prosopagnosia but has also been used to investigate face recognition deficits in other clinical conditions (Hedley, Brewer, & Young, 2011; Wilson et al., 2010). It appears to have good reliability and is capable of measuring face recognition independent of IQ (Bowles et al., 2009; Wilmer et al., 2010) and has featured in a number of recent research studies (Bate et al., 2008; Degutis et al., 2007; Herzmann et al., 2008; Iaria et al., 2009). A full description of the methodology is described in the original paper by Duchaine and Nakayama in which the test validation is described (Duchaine & Nakayama, 2006). The outcome measure for the test is the percentage of correctly identified faces. Fig. 1 shows example images from the viewing and recognition stages of the task, in addition to the eye movements made by an example participant as they viewed these images during the task. Participants completed the CFMT at a viewing distance of 60 cm, and had their head mounted in a comfortable head-rest to minimise head movements. All participants wore trial frames with the correct refractive correction for the viewing distance. The images subtended a viewing angle of 7.4° horizontally and 11.1° vertically, which was calculated to be equivalent to viewing a real face at a distance of roughly 1 m in the real world.

2.2. Eyetracking

Eye movements during task performance were monitored using the Eyelink 1000 system (SR Research Ltd., Ontario, Canada). Pupil position was monitored monocularly at 1000 Hz (the chosen eye was alternated across participants). The Eyelink’s proprietary algorithm was used to calibrate and verify the subject’s point of regard in response to prompts shown at different locations of the screen. It was required that the system stated that accuracy was of a “good” level prior to beginning the task (signifying minimal

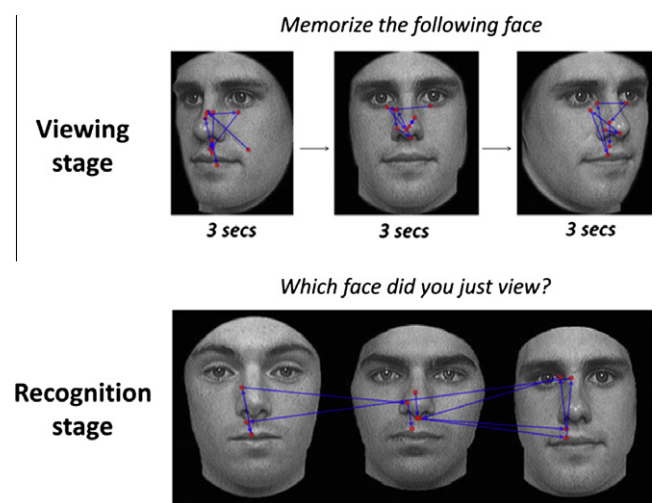


Fig. 1. Example trials from the CFMT. In the viewing stage of the study, participants are asked to memorise a face, which is shown at three different viewing angles for three seconds each. Participants are introduced to six different faces in total. In the recognition stage of the task, participants are given forced-choice trials whereby they must pick out the face they recognise from amongst the distractor faces. The scanpaths of saccades [blue] and fixations [red] made by an example participant as they carry out the task are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

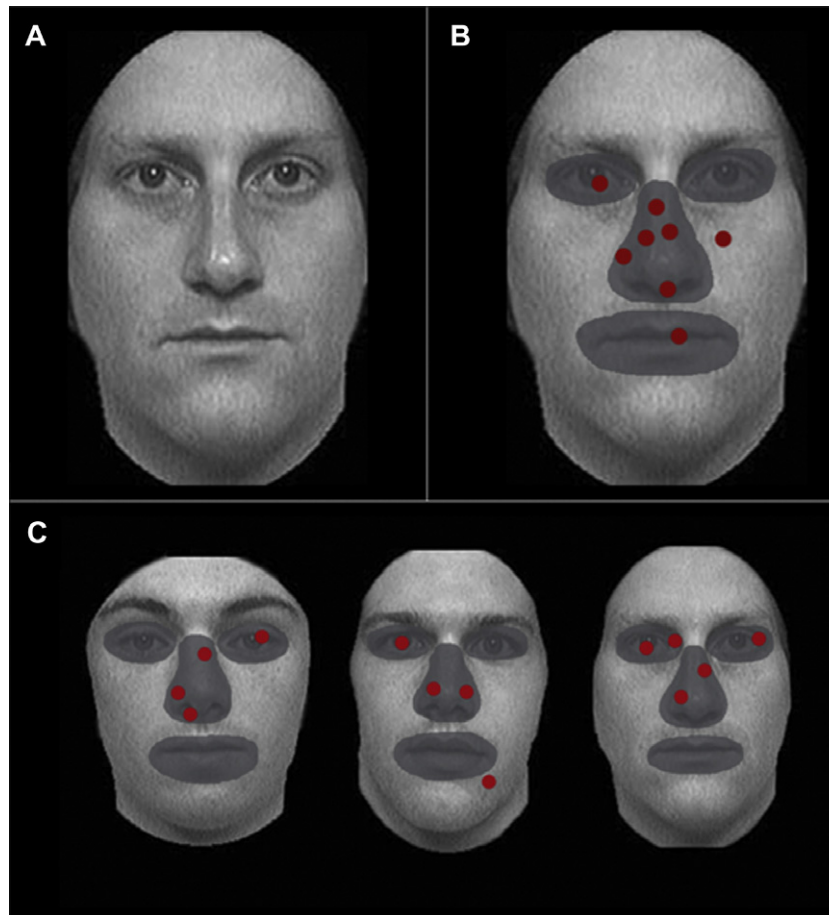


Fig. 2. Image A shows an example of one of the unmodified 'viewing trials' from the CFMT. In images B and C (depicting a viewing and recognition trial respectively), the ROIs used in the analysis are shaded. The locations of the fixations made by one of the participants as they looked at these images are indicated by the red dots. The number of fixations that fell within a mapped ROI was calculated using a specifically created computer program written in C#. In this example, the majority of fixations fell on the nose or eyes. Fixations outside the marked regions are classed as landing on 'other regions'. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

non-linearity when fixating different target positions). Between the presentations of each new set of images, participants were required to fixate on a centralized stimulus and a drift correction was performed. If a large drift was detected, the eyetracker was recalibrated using the original algorithm. Throughout the task, the Eyelink system automatically recorded each saccade and fixation and the size of saccades (saccade amplitude) made.

2.3. Analysis

Significant VF defects in the central 10° of vision are detrimental for face recognition (Glen et al., 2012). Patients were therefore classified according to whether or not they had significant defects in the central 10° of vision. A VF defect was classed as being 'significant' in the central 10° if both MDs in their 10–2 VFs were flagged as being worse than the 1% normative value ($MD p < 1\%$): from this point onwards, such cases will be referred to as having "significant 10° defects". Those patients who did not have $MD p < 1\%$ for both 10–2 VFs were classed as not having significant 10° defects. The third group consisted of the visually healthy control subjects who had no VF defects.

The performance measure for the task was the percentage of correctly identified faces. Eye movements were investigated separately for the trials when the participant first viewed the faces, and for the 'recognition' trials, where they were given a selection of three faces and required to pick out the face they recognised (see Fig. 1). The eye movement response variables were the mean

number of saccades made per second and mean saccade amplitude across trials for each participant. Spearman's rho was used to investigate associations between eye movements and task performance in each of the study groups. The contributions of age, VA and CS were also investigated using partial correlations controlling for the effects of these factors. Fisher's r to z transformation was used to determine whether correlations for the patient groups and the controls were statistically different from one another. A multiple regression analysis was used to consider the contributions of all measured eye movements (saccade rate, saccade amplitude in viewing and recognition task stages), visual (VA, CS, best eye 24–2 MD and 10–2 MD) and personal (age, % score in MEAMS) variables for overall performance in the face recognition task (percentage correctly identified faces).

2.3.1. Regions of Interest (ROI) analysis

Where people look is also useful for understanding how people process visual information. The secondary analysis therefore considered the fixation locations of the participants in relation to key regions of interest (ROI) on the face. Key facial features were manually marked out on each image trial using Adobe Photoshop (Adobe Photoshop CS5, Adobe Systems Incorporated, CA, USA). These were the regions occupied by each eye (combined to form 1 region), nose and mouth. All other areas were classed as 'other regions' (Fig. 2). The number of fixations that fell on each of the mapped out areas was then calculated using a specifically created computer program written in C#. The results were expressed in

terms of the relative proportion of the fixations that fell within each ROI (meaning the sum of fixations across the ROIs would be one for each trial). This procedure coincides with other published work (Watanabe et al., 2011).

A multivariate General Linear Model (GLM) Analysis of Variance (ANOVA) was used to calculate differences in the proportion of fixations allocated to each of the ROIs between the three study groups. Spearman's rho correlations were used to examine the relationship between proportion of fixations allocated to a particular region and overall task performance within each study group.

2.4. Inclusion and exclusion information

All data recorded by the Eyelink system for the participants was included in the analysis except for misclassified blinks (i.e. theoretically impossible saccade amplitudes recorded that were larger than the maximum size of the screen [66.8°]). Furthermore, all saccades of amplitude less than 0.5° were excluded. This criteria has been used in several studies using Eyelink software as a method of excluding noise within the eye tracking data (Foulsham, Teszka, & Kingstone, 2011; Smith, Glen, & Crabb, 2012; Smith et al., 2012; Tatler & Vincent, 2008) and meant that 4.8% of each patient's data and 5.6% of the controls' data on average was subsequently removed (the proportion of exclusions between groups was not statistically significant; independent *t*-test $p = 0.39$).

Data was analysed using the statistical software package SPSS 18 (IBM Corporation, Somers, NY, USA), with figures produced using the *ggplot2* package in the open source environment R (version 2.12.1) (R Development Core Team, 2008).

3. Results

Fifty-one patients and 39 controls with healthy vision took part in the study. Of the patients, 28 were classed as having significant 10° defects in both eyes (10–2 MD $p < 1\%$) whilst 23 did not have significant 10° defects (10–2 MD $p > 1\%$). Descriptive statistics for the three study groups are displayed in Table 1.

The previously reported differences (Glen et al., 2012) in average performance (percentage of correctly identified faces) between these groups was confirmed in this smaller sample of participants, with the patients with significant 10° defects performing worse on average (mean = 68% correctly identified faces, SD = 14%) than those without significant 10° defects (mean = 77%, SD = 11) and controls (mean = 77%, SD = 11%). These average differences were statistically significant (univariate ANOVA $F = 4.56$; $p = 0.01$), with post hoc comparisons revealing that the difference in scores between patients with significant 10° defects and controls was statistically significant ($p = 0.02$). Boxplots displaying the range of face recognition scores within each group are displayed in Fig. 3. It is apparent that whilst patients with significant 10° defects

performed worse on average in the task than those patients without significant 10° defects, and the controls, there was still a large amount of variability in performance between individuals.

3.1. Eye movements when first viewing faces

Spearman's rho correlations were used to consider the relationship between the percentage of correctly identified faces and the average number of saccades made per second, and the average saccade amplitude respectively, within each defect group. The results of the correlations are displayed in Table 2: none of the correlations for the viewing stage reached statistical significance.

Partial correlations (controlling simultaneously for age, VA and CS) between saccades per second and face recognition performance were -0.37 ($p = 0.07$) for the patients with significant 10° defects, -0.18 ($p = 0.46$) for those without significant 10° defects and -0.14 ($p = 0.40$) for the controls. The partial correlations for the relationship between saccade amplitude and performance in the viewing stage of the task were -0.10 ($p = 0.62$) for the patients with 10° defects and 0.14 ($p = 0.55$) and -0.04 ($p = 0.84$) for the patients without significant 10° defects and controls respectively.

3.2. Eye movements during 'recognition'

Spearman's rho correlations between eye movement parameters and task performance for the recognition stage of the task, for each group, are also displayed in Table 2. Within the group of patients classed as having significant 10° defects, a significant association was found between the number of saccades made per second and percentage of correctly identified faces. There was an even stronger relationship between performance and average saccade amplitude of these patients ($\rho = 0.60$; $p = 0.001$; Fig. 4). These relationships remained significant when accounting for age, VA and CS within the correlation (saccades per second coefficient: -0.44 , $p = 0.03$; saccade amplitude: 0.57 , $p = 0.003$). Cook's distance measure was used to investigate the influence of each point on the correlations and revealed that no points had an influence exceeding 0.2 (values above 1 are usually considered indicative of excessive influence).

The relationship between saccades per second and performance was less apparent for those patients without significant 10° defects. Spearman's rho correlation between saccade amplitude and performance within this patient group was significant; however, the relationship was no longer statistically significant when controlling for age, VA and CS within the correlation (partial $r = 0.40$;

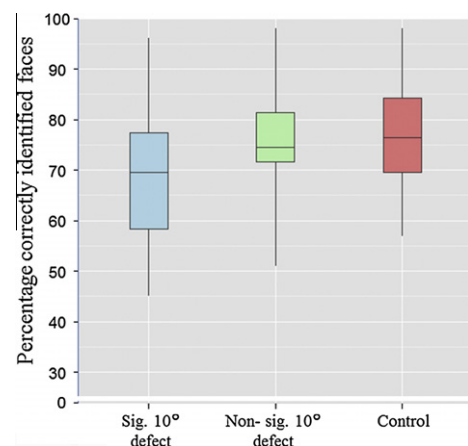


Fig. 3. Boxplots of face recognition scores for those patients with, and without, significant defects to the central 10°, and controls. (Boxes represent interquartile range (IQR) and whiskers depict maximum and minimum values.)

Table 1
Mean (SD) visual and personal information for participants in each study group.

	Group			p-Value
	Significant 10° defects N = 28	Non-significant 10° defects N = 23	Controls N = 39	
24-2 MD (dB)	−9.9 (5.7)	−3.1 (3.1)	0.0 (1.1)	<0.000001
10-2 MD (dB)	−11.7 (5.3)	−1.4 (1.5)	N/A	<0.000001
VA (logMAR)	0.08 (0.08)	0.03 (0.12)	−0.06 (0.09)	<0.000001
CS (log)	1.78 (0.21)	1.90 (0.11)	1.95 (0.00)	<0.000001
Age (years)	70 (7)	68 (8)	66 (9)	0.12
Score in MEAMS (%)	98.1 (2.7)	98.4 (3.9)	98.1 (3.7)	0.93

N/A: not available.

Table 2
Spearman's rho correlations (*p*-values) between eye movements and performance within each group for the viewing and recognition stages of the face recognition task. Significant correlations are highlighted.

	Percentage correctly identified faces		
	Significant 10° defects	Non significant 10° defects	Controls
Viewing stage			
Saccades per sec	−0.26 (<i>p</i> = 0.31)	−0.29 (<i>p</i> = 0.19)	−0.18 (<i>p</i> = 0.29)
Saccade amplitude	−0.15 (<i>p</i> = 0.51)	0.18 (<i>p</i> = 0.40)	−0.11 (<i>p</i> = 0.52)
Recognition stage			
Saccades per sec	−0.37* (<i>p</i> = 0.05)	−0.19 (<i>p</i> = 0.39)	−0.24 (<i>p</i> = 0.15)
Saccade amplitude	0.60* (<i>p</i> = 0.001)	0.49* (<i>p</i> = 0.02)	−0.24 (<i>p</i> = 0.13)

* *p* < 0.05.

p = 0.07). There were no significant relationships between task performance and saccades per second, nor saccade amplitude, in the

controls. Partial correlations controlling for age, VA, and CS in the controls were not statistically significant (coefficient for saccade rate and performance was −0.21; *p* = 0.21; and for performance and saccade amplitude −0.19; *p* = 0.25).

Fisher's R to Z transformation, accounting for the differences in sample size in each group, was then used to determine whether the significant partial correlations obtained for the patients with significant 10° defects were actually significantly different from those yielded in the controls. For the correlations between saccade rate and performance, *z* was −0.87 (*p* = 0.19). The correlation between performance and saccade amplitude obtained in the patient group was statistically different from the correlation observed in the controls (*z* = 3.26; *p* = 0.002).

The relative contributions of all measured variables (age, VA, CS,% in MEAMS, best eye 24-MD and 10-2 MD) and eye movement parameters (saccades per second and saccade amplitude in the viewing and recognition stage respectively) on overall face recognition performance (percentage of correctly identified faces) were investigated in a multiple regression analysis. For the patients with significant 10° defects, these variables combined were found to account for 62% of the total variance in performance (adjusted

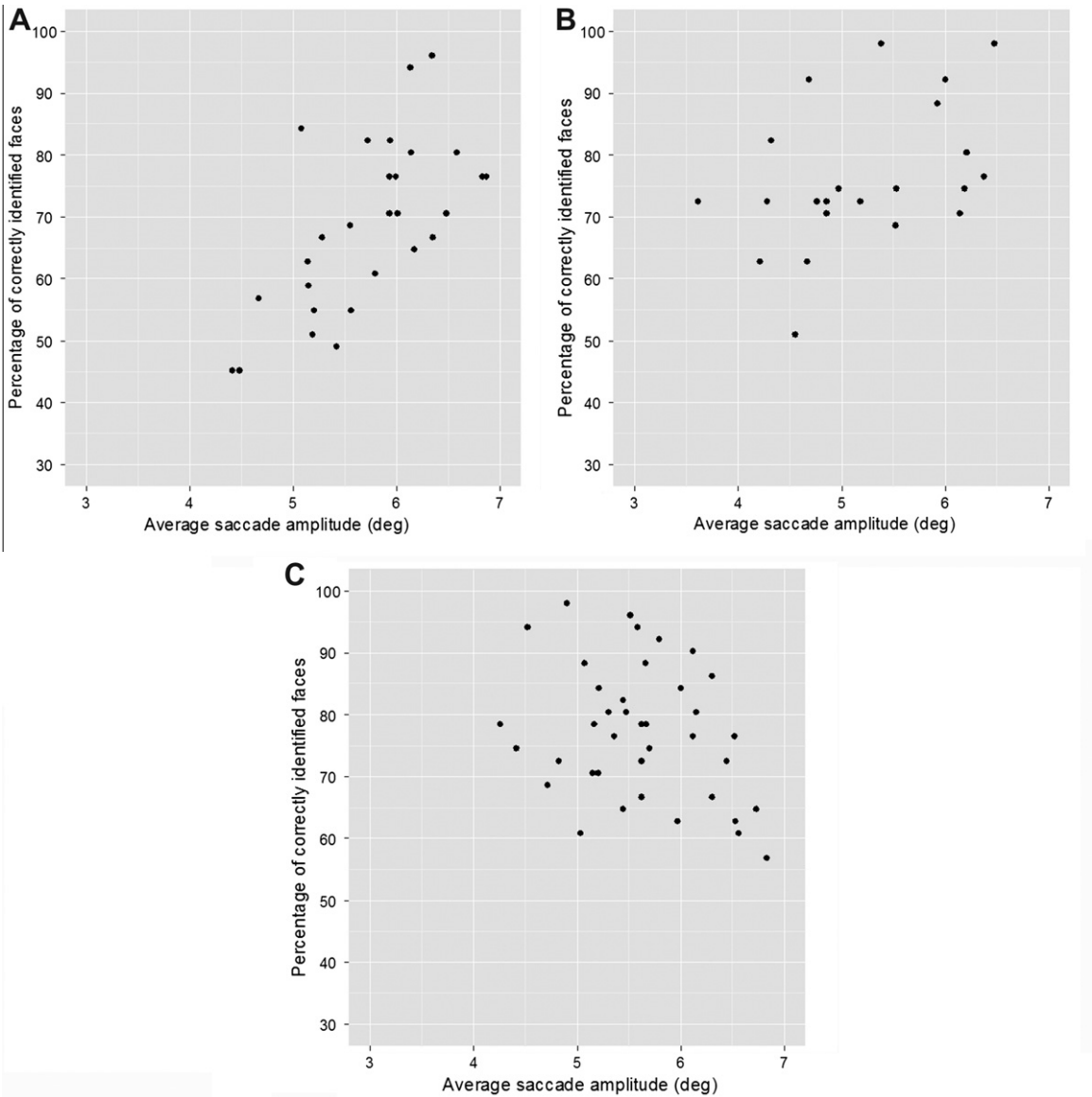


Fig. 4. Scatterplots showing the relationship between saccade amplitude when recognising faces and subsequent task performance for the patients with significant 10° defects (A), patients without significant 10° defects (B), and controls (C).

Table 3

Results of multiple linear regression of all measured vision, demographic and eye movement variables on percentage of correctly identified faces for the patients with significant 10° defects.

Parameter	Estimate	S.E.	p-Value
Average saccade amplitude in recognition stage	9.4	3.6	0.02
Contrast sensitivity	21.6	10.6	0.06
Average saccades per sec in viewing stage	−11.1	6.1	0.14
Best eye 24-2 MD	0.9	0.6	0.15
Age	−0.5	0.4	0.21
Average saccade amplitude in viewing stage	−5.6	4.5	0.23
Cognitive ability (MEAMS%)	1.1	0.8	0.20
Best eye 10-2 MD	−0.4	0.7	0.59
Average saccades per sec in recognition stage	−1.3	6.1	0.83
Visual acuity	−0.7	23.6	0.97

$r^2 = 0.62$). The most (and only) statistically significant predictor of percentage correctly identified faces in the model was average saccade amplitude during the recognition stage ($\beta = 9.4$; $p = 0.02$; Table 3). Severity of VF defect did not appear to be an important factor: this is illustrated further in Fig. 5 showing how patients with similar defects often behaved differently in the task.

When considering the same variables for those patients without significant 10° defects, they were found to explain 24% of the total variance in task performance within this group (adjusted $r^2 = 0.24$). Average saccade amplitude was no longer a significant predictor of face recognition performance ($\beta = 1.05$; $p = 0.81$). Whilst no single variable was a significant predictor of task performance, some p -values were close to significance (i.e. age $\beta = -0.80$; $p = 0.06$; best eye 24-2 MD $\beta = -3.84$; $p = 0.07$).

In the controls, the entered variables (excluding VF information as this was not measured) accounted for 19% of the variance in performance (adjusted $r^2 = 0.19$). None of the variables alone were significant predictors of performance.

3.3. Region of Interest (ROI) analysis

Table 4 shows the mean (SD) proportion of fixations that were allocated to the eyes, nose, mouth, and other regions for each of the three groups. For all groups, the most fixated ROI was the nose, followed by the eyes. The GLM ANOVA analysis showed that there were no statistical differences in terms of the proportion of fixations allocated to the ROIs between the groups in either stage of the task.

The relationship between overall task performance and the proportion of fixations allocated to face regions were investigated using spearman's rho correlations. No correlations for the relationship between proportion of fixations on a region and performance, in neither the viewing nor recognition stage, reached statistical significance for any of the groups (correlations are listed in Appendix A).

4. Discussion

Defects within the central 10° of the VF appear to be particularly detrimental for functioning in everyday tasks such as reading (Fujita et al., 2006) and a good predictor of self-reported limitations in vision related activities (Tabrett & Latham, 2012). Our previous research also showed the importance of the central 10°, as people with advanced glaucomatous VF defects (specifically within the central 10°) performed worse on average at face recognition than people with less advanced defects, and visually healthy controls of a similar age (Glen et al., 2012). However, as in other performance-based studies (Kotecha et al., 2009; Smith, Crabb, & Garway-Heath, 2011), those results were based on average effects between groups, and it was evident that there was still a large degree of variability in task performance within each group. For

instance, some patients classed as having advanced VF loss still managed to identify close to 100% of the faces correctly during the task. This implied the existence of some sort of 'optimal' strategy that may help some patients overcome their VF loss, and the evidence presented in the current study appears to suggest that this could be related to aspects of the patient's eye movement behaviour.

Evidence from some studies has suggested that the eye movements made when first viewing a face are important for successful face recognition (Chan et al., 2011; Firestone, Turk-Browne, & Ryan, 2007; Henderson, Williams, & Falk, 2005). However, in the current study, there was no real indication that the eye movements made by the patients when first viewing a single face in the CFMT were correlated with overall face recognition performance. Nevertheless, eye movements when 'recognising' a face (i.e. searching for the face they recognised) appeared to be related to overall success at this task. In particular there was a notable association between the size of saccades made and the percentage of correctly identified faces. This association was less apparent for the patients who did not have significant defects in their central 10° of vision, and was non-existent in the controls. The idea that certain eye movements were associated with better task performance for some people with glaucoma, but less so in controls with normal vision, also emerged in another study investigating the impact of glaucoma on visual search of targets in images of everyday scenes. In that case, an increased saccade rate appeared to be associated with faster search times within the patient group, but not in the controls (Smith, Glen, & Crabb, 2012). Taken together, these findings may suggest that changes in eye movements could offer a useful tool for improving performance in a number of visual tasks, but that the best strategy may depend on specific features of the task at hand.

In addition, the current study attempted to consider whether there were any differences between the patients and controls in terms of how they sampled facial features: specifically whether there may be any differences in terms of the proportion of fixations that were allocated to specific regions of the face. In support of other research it was found that the participants did not allocate equal numbers of fixations to all facial features (Janik et al., 1978; Klin et al., 2002; McCullough & Emmorey, 1997; Watanabe et al., 2011), with participants in this study allocating the majority of their fixations to the nose region, and then the eyes. However, there was no statistically significant difference between groups in terms of how frequently they fixated each face region. Furthermore, the proportion of fixations allocated to the eyes, nose, mouth, or other regions did not appear to be associated with overall task performance within any of the groups. So, the observed associations between eye movements and performance are unlikely to reflect specific sampling of parts of the face. Note, however, the high frequency of fixations to the nose region reported here may simply reflect the requirement of participants to fixate regularly at a central point for drift corrections to be applied throughout the task, introducing significant bias in terms of gaze position. Increased fixations to the nose regions may, on the other hand, indicate the use of a more holistic processing strategy (Bombardi, Mast, & Lobmaier, 2009); often seen in the processing of upright faces. The relatively small size of the faces for the viewing distance is also likely to be an issue here; since the features were quite small, participants may have been less likely to pay particular attention to individual features. Future studies may wish to investigate this idea further by manipulating the size of the images (Bullimore, Bailey, & Wacker, 1991; Lott et al., 2005).

Whilst it appeared that producing larger saccades was associated with better task performance, it is unclear at this stage what exactly was driving some patients to make different eye movements to others. Participant recruitment was deliberately

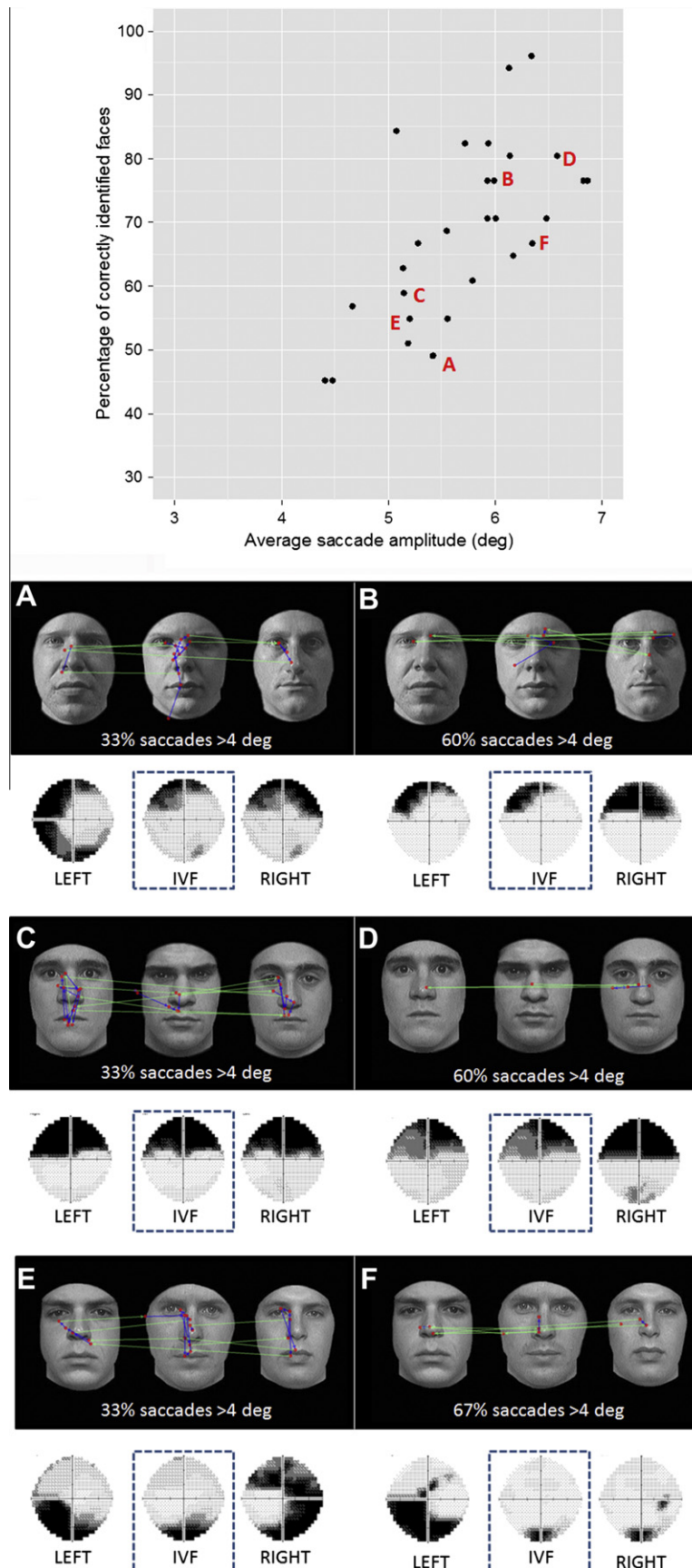


Fig. 5. Saccadic eye movements made during selected face recognition trials and corresponding 10-2 VFs for six example patients (greyscales of integrated visual field displayed in centre). The average saccade amplitude and performance of each patient is displayed within the graph. For illustrative purposes, 'large saccades' [>4 deg] are coloured green, whilst 'small' saccades [<4 deg] are blue. Each fixation is coloured red. An increased proportion of saccades made by patients B, D and F are large: these patients also performed better in the task than patients A, C and E. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4

Mean (SD) relative proportion of fixations allocated to regions of interest (ROI) in the viewing and recognition stages of the task for the three study groups.

	Significant 10° defect	Non- significant 10° defect	Controls	p-Value
<i>Viewing stage</i>				
Eyes	0.26 (0.21)	0.18 (0.19)	0.25 (0.17)	0.29
Nose	0.44 (0.21)	0.55 (0.21)	0.46 (0.19)	0.13
Mouth	0.12 (0.11)	0.10 (0.09)	0.15 (0.18)	0.27
Other regions	0.18 (0.15)	0.17 (0.15)	0.15 (0.15)	0.64
<i>Recognition stage</i>				
Eyes	0.17 (0.16)	0.16 (0.18)	0.19 (0.18)	0.80
Nose	0.46 (0.17)	0.48 (0.21)	0.45 (0.20)	0.75
Mouth	0.14 (0.16)	0.11 (0.14)	0.14 (0.16)	0.64
Other regions	0.23 (0.12)	0.25 (0.15)	0.22 (0.17)	0.82

restricted to those aged between 50 and 80 with preserved VA (equal to or better than Snellen 6/9) but there were still differences between groups in terms of age, VA and CS (Table 1). However, the reported effects between eye movements and task performance did not substantially change when these variables were accounted for within the correlations. Furthermore, the results of the multiple regression analysis revealed that there did not appear to be any strong relationship between eye movements and the severity of VF defect (as measured by best eye MD for the 24-2 and 10-2 HFA VFs). Therefore, it seems unlikely that the saccadic behaviour differences observed in the face recognition task were strongly related to the severity of damage in the VF. This point is illustrated in Fig. 5 which shows how patients with very similar binocular defects in their central 10° of vision produced very different saccade patterns and also performed differently to each other in the task. For example, patient A, despite having a very similar binocular defect in the central 10°, performed better than patient B and also appeared to make a higher proportion of larger eye movements. They also appeared to display a more systematic strategy than patient B as they looked for the face they recognised. Perhaps the strategy is related to other factors more specific to the individual's relationship with their VF defect, such as how aware they are of it; a topic which may benefit from future research. It is also possible that more intricate aspects of the defect, such as specific locations within the central 10°, were of influence, but there was not enough data here to be able to quantify the effects of different VF defect locations. Furthermore, some studies have suggested that glaucoma is linked to processing deficits, such as difficulty with the detection of global forms (Loffler, 2008; McKendrick, Badcock, & Morgan, 2005). The ability to detect contrast has also been shown to be linked to face recognition ability in other low vision populations (Barnes, De L'Aune, & Schuchard, 2011; Dinon & Boucart, 2005). Suprathreshold contrast discrimination also appears to be affected by glaucoma, and may provide a more accurate depiction of real world function than other visual measures (McKendrick et al., 2010). Future studies may therefore also wish to investigate in more detail whether such underlying processing difficulties translate to behavioural changes in a face recognition task.

The idea that the eye movement strategy becomes more influential for task performance once damage has occurred within the central 10° of VF was supported by multiple regression analyses of the data. When all measured variables were entered into the model, the most influential variable when predicting task performance, for patients with significant 10° defects, was average saccade amplitude when recognising a face. However, interestingly, this variable was less important in explaining variance in task performance within the group of patients who did not have significant 10° defects, and in the control group. The apparent importance of the central VF is not all that surprising given the nature of the

current task: for instance, the average size of the faces presented to the participants roughly subtended to the region covered by the 10-2 VF. Therefore, making larger saccades may be more beneficial for a person with VF defects in this region. It is also worth noting that some of the patients classed as not having significant 10° defects had a MD $p < 1\%$ in their worst eye 10-2 VF. Unfortunately, there was not enough data here to determine whether there were any statistically significant differences in performance for those who had more advanced vision loss in one eye versus those with truly intact 10-2 VFs. Further research involving patients with monocular defects may therefore reveal additional information regarding the nature of any compensatory processes occurring during tasks such as face recognition.

It is very important to note that the results reported here were based on associations, and therefore it cannot be said that the relationship is a causative one or that the results are definitely a sign of some adaptive strategy in glaucoma. There are other limitations about our experiment too: for example, the results may have been linked to the memory and cognitive skills of the participant beyond what was estimated by the MEAMS test. Since there was no time limit for recognition (the trial progressed until the participant made their response) it is possible that certain psychological factors may have contributed to the results; for instance some participants may have felt less motivated or confident in their decision than others and this may have influenced their behaviour. Future studies may therefore wish to consider information regarding the participant's perceived level of confidence in their response or whether restricting the length of time for recognition to occur has any bearing on the results. Whilst all participants underwent a short practice session prior to taking part in the study, this involved cartoon faces as opposed to faces similar to those used within the task. Practice effects may have influenced the results as participants gained more experience with the faces used in the actual task but this is unlikely to have had an effect on the average between group differences in eye movements reported in this study. Moreover, the CFMT, whilst previously shown to be a valid face recognition measure, is removed from real world contexts; for instance, the images are black and white and all were displayed at only one, fairly small, size.

Nevertheless, overall these data highlight the potential of examining eye movements for furthering understanding into visual functioning in glaucoma. It would also be interesting to know, for example, via a more controlled experiment whether any change in eye movements seen in a patient is a conscious strategy, or whether it may be more related to an underlying biological component of the disorder (Lamirel et al., 2012). More support for this idea could suggest a method for vision rehabilitation, a concept that has already been explored in other eye disorders. For instance, 'eccentric viewing training' for patients with AMD involves the encouragement of patients to make use of their peripheral vision by relocating fixation to a functioning area of the retina adjacent to the macular scotoma (commonly termed the 'preferred retinal locus'; PRL; for a review see Schuchard, 2005). It has been reported that training some participants to use eccentric viewing techniques improved patients' abilities to carry out Activities of Daily Living (as measured by the Melbourne Low Vision ADL Index (Haymes, Johnston, & Heyes, 2001)) compared with those who did not take part in the intervention (Vukicevic & Fitzmaurice, 2009). Another study found that gradually training participants to make larger eye movements lead to improvements on a reading task (Seiple et al., 2005). Similarly, "explorative saccade training" in patients with hemianopia appeared to lead patients to make more eye movements into their blind field. These patients also later reported subjective improvements in their performance in daily activities (Roth et al., 2009). Once a causative link is established it might be useful to encourage patients with glaucoma to utilise more

Table A1Spearman's rho correlations (*p*-value) between percentage of correctly identified faces and the proportion of fixations allocated to ROIs within each of the groups.

	Eyes	Nose	Mouth	Other regions
Viewing stage				
Percentage of correctly identified faces				
Sig. 10° defect	−0.14 (<i>p</i> = 0.50)	−0.21 (<i>p</i> = 0.30)	0.16 (<i>p</i> = 0.43)	0.32 (<i>p</i> = 0.11)
Non-sig. 10° defect	0.11 (<i>p</i> = 0.61)	0.35 (<i>p</i> = 0.09)	−0.37 (<i>p</i> = 0.08)	−0.39 (<i>p</i> = 0.07)
Control	−0.06 (<i>p</i> = 0.71)	−0.14 (<i>p</i> = 0.39)	−0.28 (<i>p</i> = 0.09)	−0.16 (<i>p</i> = 0.34)
Recognition stage				
Percentage of correctly identified faces				
Sig. 10° defect	0.02 (0.92)	−0.19 (0.32)	−0.21 (<i>p</i> = 0.27)	0.27 (<i>p</i> = 0.16)
Non sig. 10° defect	−0.03 (<i>p</i> = 0.91)	0.33 (<i>p</i> = 0.12)	−0.18 (<i>p</i> = 0.40)	−0.39 (<i>p</i> = 0.07)
Control	−0.09 (<i>p</i> = 0.58)	0.21 (<i>p</i> = 0.20)	−0.29 (<i>p</i> = 0.07)	−0.20 (<i>p</i> = 0.20)

deliberate eye movements during specific visual tasks in everyday situations. In turn this could help alleviate some of the functional difficulties experienced by patients as a result of glaucoma, thus improving their perceptions of quality of life.

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Appendix A.

See Table A1.

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