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Eye movements and reading in glaucoma: observations on patients with advanced visual field loss

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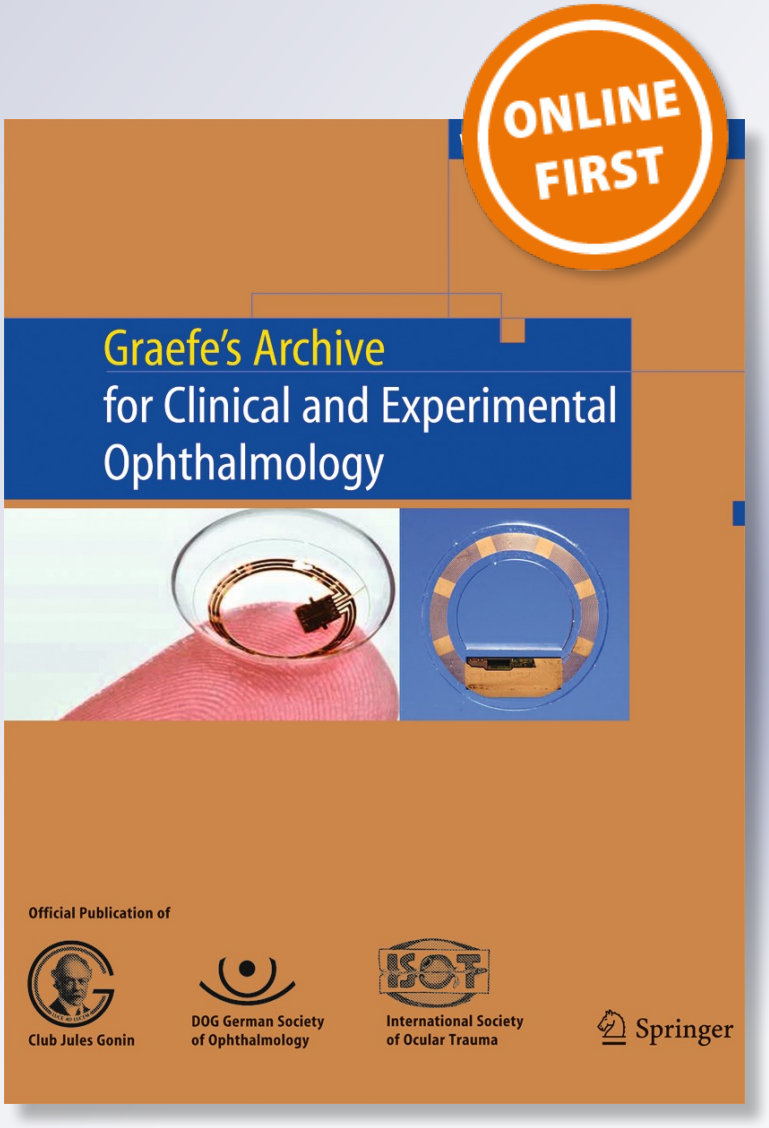

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GLAUCOMA

Eye movements and reading in glaucoma: observations on patients with advanced visual field loss

Robyn Burton · Nicholas D. Smith · David P. Crabb

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Abstract
Purpose To investigate the relationship between reading speed and eye movements in patients with advanced glaucomatous visual field (VF) defects and age-similar visually healthy people.
Methods Eighteen patients with advanced bilateral VF defects (mean age: 71, standard deviation [SD]: 7 years) and 39 controls (mean age: 67, SD: 8 years) had reading speed measured using short passages of text on a computer set-up incorporating eye tracking. Scanpaths were plotted and analysed from these experiments to derive measures of '*perceptual span*' (total number of letters read per number of saccades) and '*text saturation*' (the distance between the first and last fixation on lines of text). Another eye movement measure, termed '*saccadic frequency*' (total number of saccades made to read a single word), was derived from a separate lexical decision task, where words were presented in isolation.
Results Significant linear association was demonstrated between *perceptual span* and reading speed in patients (R^2=0.42) and controls (R^2=0.56). Linear association between *saccadic frequency* during the LDT and reading speed was also found in patients (R^2=0.42), but not in controls (R^2=0.02). Patients also exhibited greater average *text saturation* than controls (P=0.004).
Conclusion Some, but not all, patients with advanced VF defects read slower than controls using short text passages. Differences in eye movement behaviour may partly account for this variability in patients. These patients were shown to *saturate* lines of text more during reading, which may explain previously-reported difficulties with sustained reading.

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Keywords Glaucoma · Reading · Eye movements · Visual fields · Perimetry

Introduction

Difficulty with reading is a common complaint made by patients with glaucoma [1–5]. Studies measuring actual reading performance have revealed impaired reading speed in patients when reading small print [6] or passages of text presented at low contrast [7]. Other studies measuring reading performance indicate that patients are likely to read more slowly than normally sighted peers if they have visual field (VF) defects located within the central 3° of vision [8], or if they have advanced bilateral VF loss [9, 10]. Recent work has revealed that differences in average reading speeds between glaucoma patients and normally sighted peers are particularly pronounced during periods of sustained silent reading [11]. A common feature of these studies is that reading performance (reading speed) is subject to much between-person variability.

Eye movements are inherently linked to the process of reading [12]. So, one potential explanation why some, but not all, glaucoma patients experience difficulties with reading, may relate to differences in eye movement behaviour. Therefore, this study focuses on observations on eye movement measures in glaucoma patients who have advanced VF defects in both eyes whilst performing reading tasks. As an example, the size of the window of characters in a word that are attended to at each fixation, known as the perceptual span [13], is associated with reading speed. People with a reduced perceptual span saccade more frequently [14] have smaller forward saccade amplitudes and show slower reading speeds [15]. One indirect measure of the size of the perceptual span is the number of letters read divided by the number of forward

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saccades made to read these letters in a short passage of text [16]. The perceptual span as a mechanism for slower reading in glaucoma patients has not yet been explored; for example, advanced central VF defects may limit the patient's ability to assimilate information during any given fixation.

This study primarily aimed to explore associations between perceptual span and reading speed in patients with advanced glaucoma and in age-similar visually healthy controls. We also examine the relationship between reading speed and the number of saccades made during the presentation of a single word in a lexical decision task (LDT). Put simply, this is the number of saccades made to read a set of words presented in isolation. We assume that the occurrence of multiple eye movements indicates that a word cannot be read during a single fixation; a feature that may reflect the restricting presence of scotoma, especially those found in patients with advanced VF loss. We hypothesise that larger numbers of saccades made during the LDT may be related to slower reading speeds in patients. We also investigate a third eye movement and reading measure, that we name *text saturation*: defined as the distance covered by the point of regard between the first and final fixation on a line of text. It is expressed simply as the percentage of a line covered; thus, 100 % would be a fixation from the beginning of the very first letter of a line of text to the end of the final letter on that line. We hypothesise that patients with advanced VF defects need to 'cover' a greater amount of text on a line and, therefore, may exhibit more *text saturation* than their normally sighted peers.

Methods

Participants, inclusion criteria, and vision testing

Patients were recruited from Moorfields Eye Hospital NHS Foundation Trust, London, UK. All patients were recruited to have a clinical diagnosis of glaucoma and be between 50 and 80 years of age. All patients had advanced glaucomatous VF defects as defined by the Hodapp, Parrish, and Anderson classification [17] in both eyes using the Humphrey Field Analyzer (HFA; Carl Zeiss Meditec, Dublin, CA, USA). In short, to be classified as having an 'advanced' VF defect, an eye has to either have a HFA Mean Deviation (MD) of worse than −12 dB, or have more than 50 % of their VF test point sensitivity values depressed below the 5 % normative level, or have more than 20 points depressed below the 1 % normative level on the HFA pattern deviation plot, or have at least one point in the central 5° with a sensitivity of 0 dB. Participants were not recruited if they had any ocular disease other than glaucoma (except for an uncomplicated lens replacement cataract surgery). Patients had slit-lamp biomicroscopy performed by an ophthalmologist to exclude ocular disease, especially any concomitant macular pathology. Patients were not recruited if they had ocular surface disease or any significant problems with dry eye. Visually healthy controls, of a similar age to the patients, were recruited from the City University London Optometry Clinic, which is located close to the hospital. Therefore, cases and controls were drawn from an identical geodemographic area.

Recruitment, for patients and controls, was restricted to those with corrected binocular visual acuity (BVA) of at least 0.18 logMAR (Snellen equivalent of 6/9) as measured using an Early Treatment Diabetic Retinopathy Study (ETDRS) chart. We chose to restrict the study to patients with preserved VA to allow for the contribution of VF loss on reading to be better isolated, since previous research has suggested that differences in reading speed in patients with glaucoma may be mediated through the loss of VA and not VF defects [9]. Astigmatic error was less than ±2.5 Dioptres in all those recruited, and no eyes were amblyopic. All participants had English as a first language, or had spoken it for 15 years or more (one patient and two controls), and were not recruited if they reported reading difficulty such as dyslexia. Participants were not enrolled if they were on any significant medication other than that for their glaucoma; 'significant medication' included anti-depressants, or treatment for diabetes, or significant use of β-blocker medication.

All participants underwent vision testing on the day of the study. Contrast sensitivity was measured in log units with a Pelli–Robson chart (PRlogCS). VFs were measured using the HFA 24–2 SITA standard and 10–2 SITA standard algorithms in both eyes. The latter were then used to compute a central binocular measure of the VF known as the Integrated Visual Field (IVF). The IVF is a method of quantifying the binocular VF by merging results from monocular fields, whereby each individual's best point-by-point monocular sensitivity is used [18, 19]. In this study, IVF and IVF MD was calculated for each patient's 10–2 SITA standard VF using purpose-written software (freely available from the authors). To confirm that control participants had no VF defects which would compromise their role as a control in the study, 24–2 SITA fast VFs were conducted in both eyes satisfying Glaucoma Hemifield Test classification 'within normal limits'. To eliminate significant media opacity (cataract) and other lens type artefacts as confounding ocular conditions, all participants were required to be within 'normal limits' for abnormal light scattering in the eye media using the Oculus C-Quant straylight meter (Oculus GmbH, Wetzlar, Germany).

The study was approved by 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 participation. All data from the study, with patient identifiers removed, were transferred to a secure computer at the University.

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Experimental procedures

Reading experiment

The reading material consisted of eight paragraphs of text (68–79 words per text), adapted from an English fiction book. The texts were presented at 100 % contrast on a 560 mm CRT computer monitor displaying at a resolution of 1,600 × 1,200, with a refresh rate of 100Hz (Iiyama Vision Master PRO 514; Iiyama Corporation, Iiyama, Japan). All texts were fixed and non-scrolling, and matched for readability according to the Flesch–Kincaid measure [20]. Text was displayed in Arial font size 48 subtending 34 pixels on the screen and equating to 0.84° (height) for the largest character. This size approximately corresponds to a medium/large size newspaper heading, and was chosen at the outset to improve the accuracy of the eye movement data. Line length subtended 20° width. All participants wore standard trial frames with a refractive correction suitable for the viewing distance of 60 cm. Testing was performed in a dark room, and a table-mounted chin rest was used to maintain this viewing distance. The letters of the text were 'black on white', with a background screen luminance of 33.4 cd/m^2. The mean luminance of the screen was 0.05 cd/m^2. Participants viewed one passage at a time in random order. Participants were given the same verbal instructions: to "read the text silently, as quickly and accurately as possible" and to "…confirm when they had reached the end of the passage". Participants were also asked questions about the content of the text to check for reading comprehension.

Eye movements and reading duration (number of words read per minute [WPM]) were measured using an EyeLink 1,000 (SR Research Ltd., Mississauga, ON, Canada). The EyeLink samples pupil position monocularly at 500 Hz, with an average accuracy of better than 0.5°, and uses velocity and acceleration thresholds of 30°/s and 8,000°/s^2 respectively to identify saccades. The EyeLink proprietary algorithm was used to calibrate and verify the subject's point of regard in relation to the correct location on the display. A specified calibration accuracy of at least a "good" level was a prerequisite before each trial. Between each trial, a drift correction was performed and in the case where a large drift was detected, the system was recalibrated as necessary.

Lexical decision task

This computer-based test was performed on the same experimental setup as previously described. Participants were required to fixate on a centrally located target that was then replaced with a stimulus. This stimulus was either a real word such as '*spoon*' or a false word such as '*sploon*'. Participants identified the target word as either real or false by verbally expressing 'true' and 'false' respectively (forced choice). Words were presented at 100 % contrast in Times New Roman with a font size of 14, subtending a height of 1.14°. The width of the words presented ranged from 1.10 to 3.20°. All stimuli remained on screen until a response was given. A practice session of five stimuli words was used before a total of 30 stimuli words (15 real words and 15 false words) were presented to participants in a random order. All words were matched for frequency in the English language, and false words were matched to the real words with regard to word length.

Non-vision measures

Participants also completed two non-vision tasks. The Middlesex Elderly Assessment of Mental State (MEAMS, Pearson, London, UK) is a psychometric screening test designed to detect impairment of cognitive skills in an elderly population [21, 22]. Participants also completed a modified form of the Burt Word Reading Test, a standardised reading test designed to measure reading abilities [23]. Participants read the words out loud in a quiet, brightly lit room, starting at the top of a list and reading down to progressively more difficult words. The Burt test score was the number of words read incorrectly.

Eye movements and analysis

Scanpaths of eye movements were plotted for each and every passage of text (trial). The reading speed in words per minute (wpm) for each trial was calculated by simply dividing the number of words read by the patients' reading duration. The median value from the eight trials was used as an estimate of each participant's overall average reading speed. The perceptual span was computed as the number of letters read, divided by the number of forward saccades (from left to right) [16]. The median value from the eight trials was used to estimate a participant's average perceptual span.

Scanpaths of eye movements were plotted for every LDT trial. A measure of *saccadic frequency* was calculated as the total number (sum) of saccades made during the first 1,000 ms of the LDT across each of all 30 trials. This measure differs from the measure of perceptual span in that it is based on the eye movements made during the presentation of a single word, rather than a paragraph of text. Any saccade exceeding the length of the word presented was assumed to be noise and was excluded.

Text saturation was calculated as the average percentage of a line of text covered by the point of regard during reading of the passages of text. As with the other analyses, this was done by retrospectively considering every plotted scanpath for each trial, identifying the fixations on a line and computing the distance covered in the horizontal values as recorded by the eye tracker. The difference in horizontal distance between the first and last fixation, calculated as a percentage of the

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Table 1 measured characteristic of participants

	Patients n=18: mean (standard deviation)	Controls n=39: mean (standard deviation)	P value for between-group difference
Age	71 (7)	67 (8)	0.07
Percentage female	54	67	0.36
logMAR BVA	0.05 (0.08)	−0.05 (0.09)	<0.001
PRlogCS	1.79 (0.20)	1.95 (0.00)	<0.001
Left eye 24–2 VF MD (dB)	−11.0 (5.9)	–	–
Right eye 24–2 VF MD (dB)	−13.9 (8.1)	–	–
Average reading speed (wpm)	273 (51)	293 (63)	0.30
MEAMS score*	34.1 (1.9)	34.4 (1.8)	0.49
Burt test score**	0.9 (0.7)	1.3 (1.6)	0.36
Lexical decision task (LDT) score***	0.8 (1.0)	0.8 (0.8)	0.91

* scored out of 35, ** number of words read incorrectly, *** number of incorrectly identified words

horizontal distance between the first and last letter in each line of the text, was computed for each trial. The median of the different values from each line of text (excluding the first and last lines) was used as an estimate of the participant's *text saturation* per trial, and the median of these was used to estimate average *text saturation* per person.

Average differences between the patient and control group for reading speed, size of perceptual span, *saccadic frequency*, and other experimental variables were calculated and compared using two-sample *t*-tests. Univariate correlation coefficients for perceptual span and *saccadic frequency* against reading speed (wpm) were calculated for patients and the controls separately. Additional variables considered as potential correlates of reading speed in patients were the IVF 10–2 MD, PRlogCS, and LogMAR BVA. 'Statistical significance' was represented by a value of at least 1 % (alpha=0.01), in order to accommodate modest multiple testing of univariate correlations. Average difference in *text saturation* between the patient and control group was compared using a Mann–Whitney test. Scanpaths were analysed throughout using the EyeLink Data Viewer software (SR Research Ltd., Mississauga, ON, Canada) and also plotted using IGOR Pro (Wavemetrics, Lake Oswego, OR, USA). All statistical analysis was conducted using SPSS 18 (IBM Corporation, Somers, NY, USA).

Results

Participant characteristics

Eighteen patients with glaucoma and 40 visually healthy controls took part in this study. One control was removed from the analysis due to problems with lost data. Fifty-eight

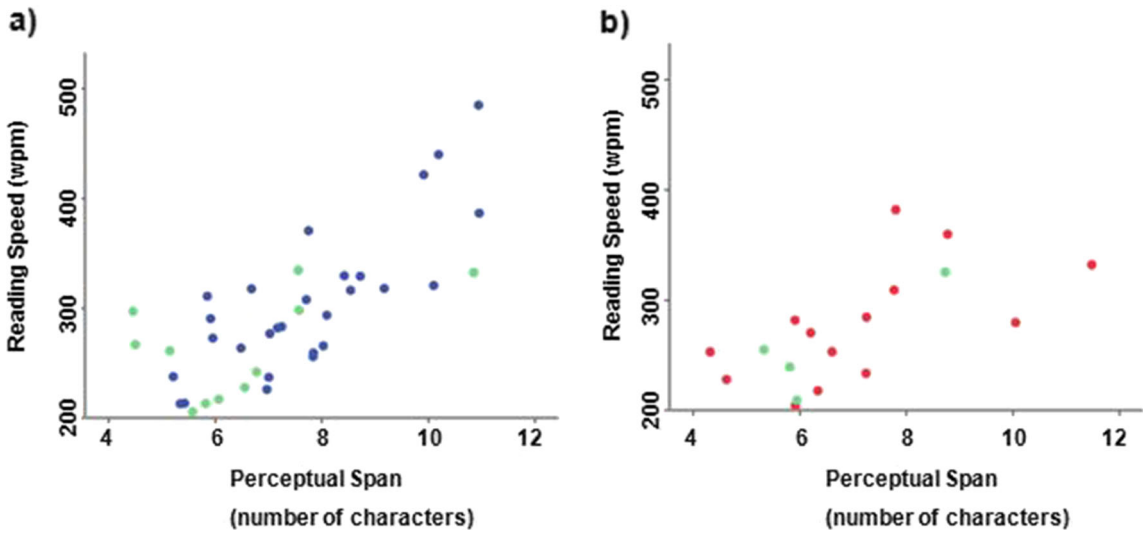

Fig. 1 The relationship between perceptual span and reading speed (*wpm*) across (**a**) the control subjects and (**b**) the patients with glaucoma. Each data point refers to a single tested individual. The *green data points* are participants who made two or more errors in the Burt Test

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trials out of the total 456 reading trials (8 %) were excluded due to calibration issues with the eye tracker (no person had more than 50 % of trials removed). The average number of excluded trials was 1.0 (standard deviation [SD]: 0.8) and 1.0 (SD: 1.1) for the patient and control group respectively. Measured characteristics of the study groups are shown in Table 1.

In summary, average values from the patients were statistically significant from controls on measures of visual function, but not on age, sex, MEAMS, the number of errors in the Burt Word Reading Test, the number of incorrectly identified words in the LDT. No statistically significant difference in average reading speed (wpm) between patients and controls was found (P=0.30).

Perceptual span and reading speed

The correlation between perceptual span and reading speed was moderate and statistically significant for control subjects (R^2=0.56, P<0.001) and for patients (R^2=0.42, P=0.004) (Fig. 1). No statistically significant difference in the average size of the perceptual span between control subjects (mean=8, SD=2.2 characters) and patients with glaucoma (mean = 7, SD=1.9 characters) was observed (P=0.34).

Saccadic frequency and reading speed

Correlation between *saccadic frequency* from the LDT and reading speed was moderate and statistically significant for patients (R^2=0.42, P=0.004). In contrast, there was no evidence of correlation between *saccadic frequency* from the LDT and reading speed in the controls (R^2=0.02, P=0.50) (Fig. 2). Control subjects made fewer total number of saccades (mean=60.5, SD=12.3) during the LDT than patients (mean=68, SD=12.9), and this difference was statistically significant (P=0.04).

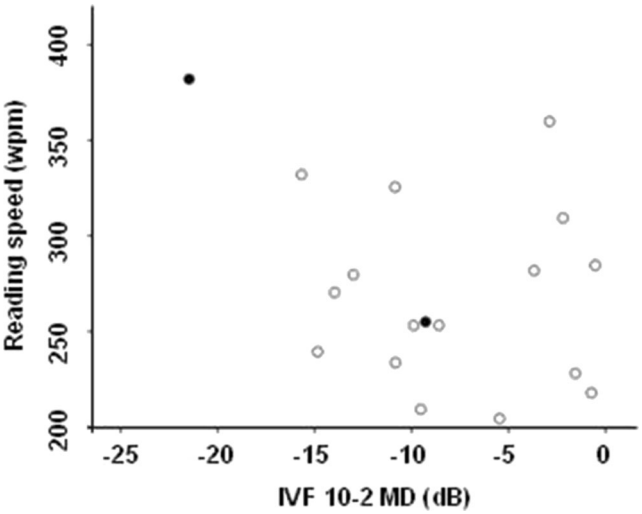

Fig. 3 The relationship between 10–2 IVF MD (*dB*) and reading speed (*wpm*) in the patient group. Each data point refers to a single tested individual. The data points indicated by *closed symbols* are discussed in Figs. 4 and 5

Visual function and reading speed

No statistically significant correlation was found between logMAR BVA and reading speed (R^2=0.03, P=0.46) or PRlogCS and reading speed (R^2=0.11, P=0.11) in the patient group. Moreover, there was no statistically significant correlation between IVF 10–2 MD and reading speed (R^2=0.10, P=0.20) in the patient group.

No statistically significant correlation between the measures of non-vision function (MEAMS, errors on Burt Word Reading Test, and LDT score) and reading speed was found in either the patient or control group (all P>0.05).

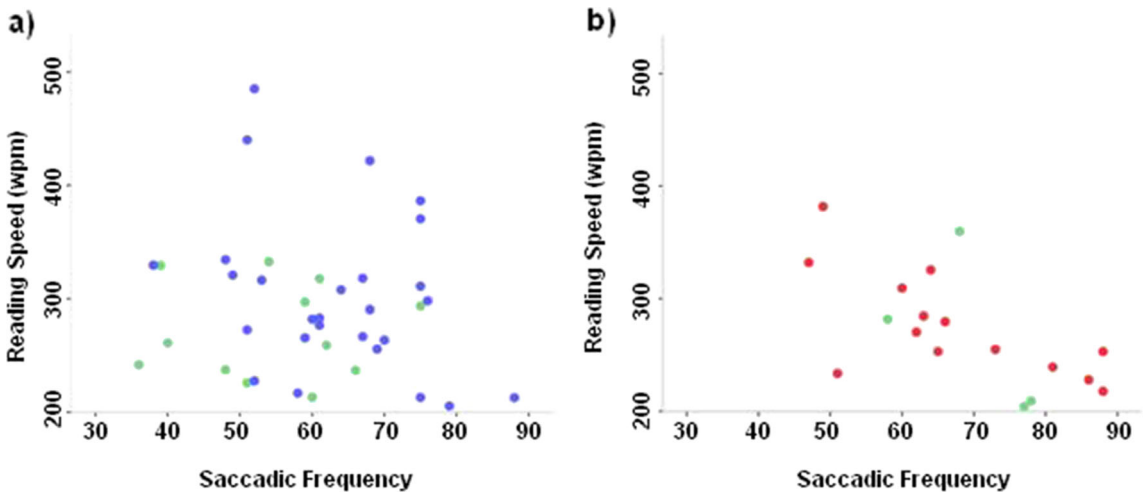

Fig. 2 The relationship between saccadic frequency in the LDT and reading speed (*wpm*) across (**a**) control subjects and (**b**) patients with glaucoma. Each data point refers to a single tested individual. The *green data points* are participants who made two or more errors in the Burt Test

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Observations of eye movement patterns in patient cases

The patient labelled in the upper left region of the plot shown in Fig. 3 had a proficient average reading speed of 382 wpm despite having an advanced binocular central VF defect (IVF MD=−21.5 dB). Scanpaths superimposed on one of the reading trials, and some of the LDT words for this patient (Fig. 4), illustrate how this patient exhibits an idiosyncratic tendency to fixate diagonally to the upper right of a presented word, or the line of text. When considering the status of this patient's central VF, it is tempting to observe that this patient is adjusting their point of regard in such a way to efficiently bring the text of interest into their area of preserved vision.

Another patient with an advanced central binocular defect (IVF MD=−9.9 dB), shown towards the bottom of the graph (Fig. 3), had an average reading speed of 253 wpm. Scanpaths superimposed on one of the reading trials, and some of the LDT words for this patient, are shown in Fig. 5.

Text saturation

Control subjects had a median *text saturation* of 84.1 % (interquartile range: 81.1–86.3 %), and this was significantly less than patients who had median *text saturation* of 86.7 % (interquartile range: 85.6–89.3) (Mann–Whitney test; P=0.004). The tendency for patients to *saturate* more of a line of text is illustrated in Fig. 6.

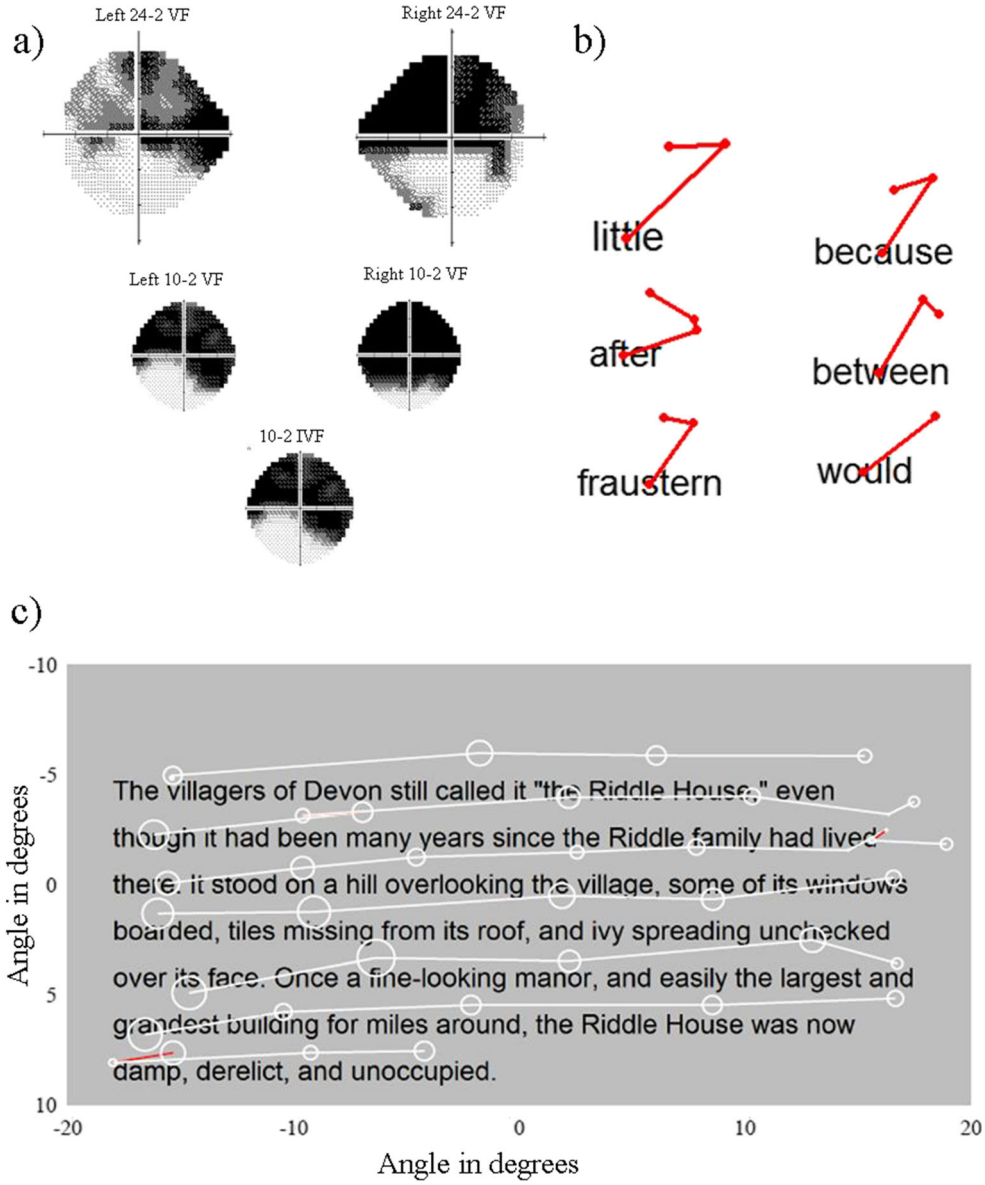

Fig. 4 **a** HFA Grayscales of patient VFs. **b** The scanpath of the eye movements made during the presentation of some of the words during the LDT within the 1,000-ms censored time window. Each *dot* shows the fixation and the *red connecting lines* refer to the saccades made between these fixations. **c** The scanpath of this patient during one trial of the reading experiment. Each *white circle* corresponds to a fixation location. The *size of the circle* is related to the fixation duration. The *white lines* represent the left to right saccades, and the *red lines* indicate regressive saccades (right to left). Saccades made between lines have been removed for visual clarity. The patient's logMAR BVA was 0.18, and the number of errors made on the Burt test was 1. This patient is identified by the *closed symbol in the upper left of the plot* shown in Fig. 3

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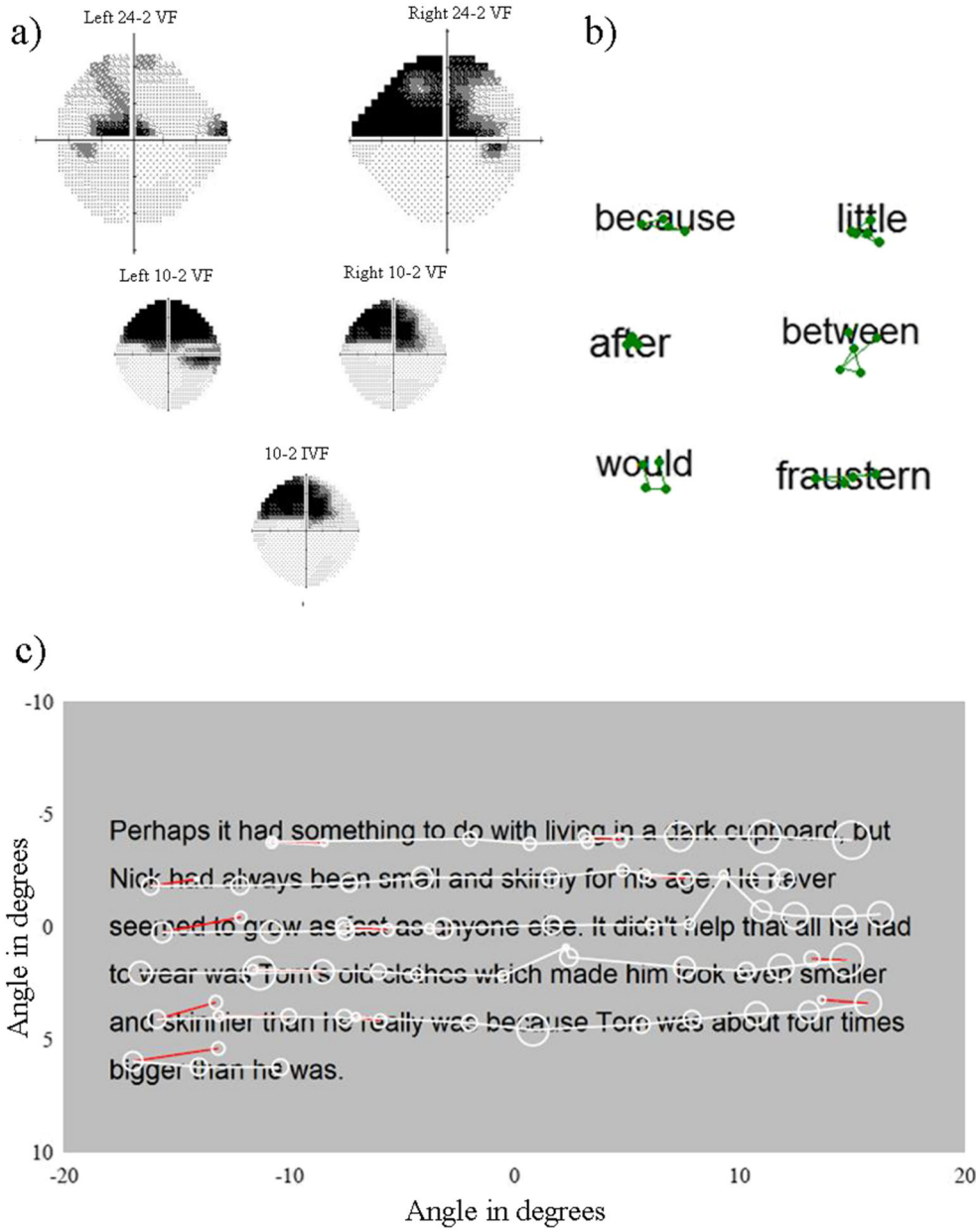

Fig. 5 **a** Grayscales of patient VFs. **b** The scanpath of the eye movements made during the presentation of some of the words during the LDT during the 1,000-ms censored time window. Each *dot* shows the fixation and the *green connecting lines* refer to the saccades made between these fixations. **c** The scanpath of this patient during the reading experiment. Each *white circle* corresponds to a fixation location. The *size of the circle* is related to the fixation duration. The *white lines* represent the left to right saccades, and the *red lines* indicate regressive saccades (right to left). Saccades made between lines have been removed for visual clarity. The patient's logMAR BVA was 0.18, and the number of errors made on the Burt test was 1. This patient is identified by the *closed symbol towards the bottom of the plot* shown in Fig. 3

Discussion

Patients with glaucoma commonly report problems with reading [1–5], and studies of actual reading performance have confirmed that glaucoma, especially when in an advanced stage, impacts on reading performance [9–11]. The patients in our study had advanced VF defects and were, therefore, similar to those previously characterized to have poorer reading performance when compared to age-similar controls [9]. Whilst perimetry can obviously identify patients with advanced VF loss, it seems from our results to offer little value in further separating that patient group into those that have more or less efficient reading speeds (Fig. 3). The results from our study have principally shown that eye movement behaviour could explain some of the variability in reading speed in those patients with advanced glaucomatous VF loss.

This study adds new knowledge because it is the first to consider eye movements in patients with glaucoma during a reading task. For example, a significant association between size of perceptual span and reading speed was observed. This was unsurprising, because measurements of the perceptual span impacting on reading have been well-documented [16, 24], but it has not been demonstrated in patients with glaucoma before. No significant group difference in the average size of the perceptual span was observed between patients and controls. However, the patient group made more saccades during the LDT than the controls. Moreover, a statistically significant association was also observed in the patient group

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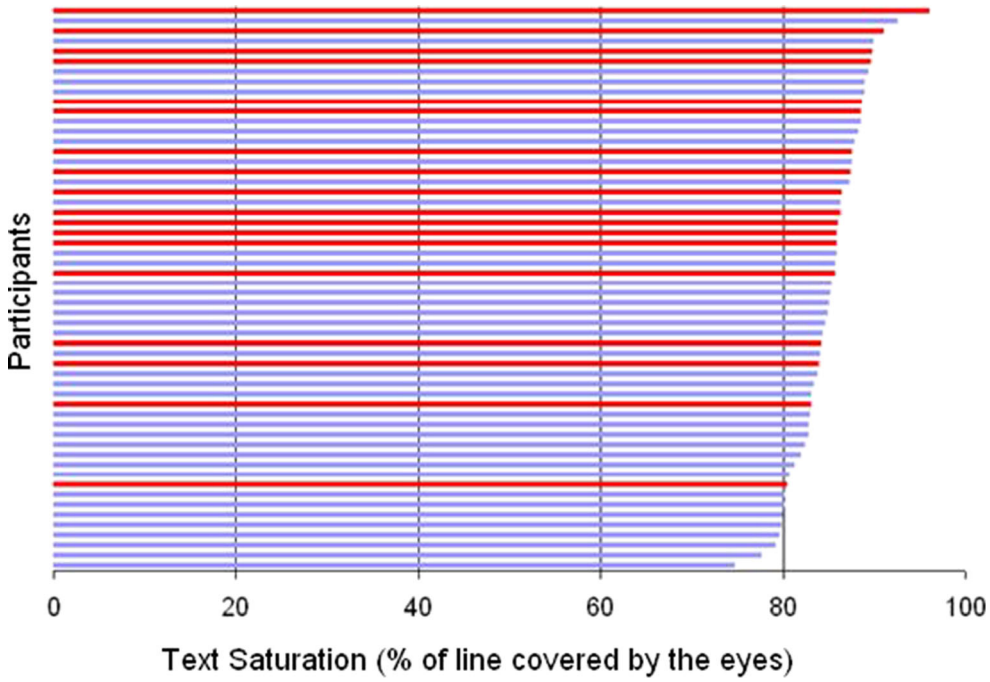

Fig. 6 A plot showing text saturation (expressed as the median percentage of a line covered) across controls and patients ranked in ascending order. *Blue lines* indicate controls, and *red lines* indicate patients

between this '*saccadic frequency*' and reading speed, but not in controls. It is tempting to explain these results by suggesting that the patients, with their restricted VFs, exhibit additional or compensatory saccades that impair reading speed, especially since this association was not seen in the control group during this task. The LDT required participants to read a single word as opposed to a string of sentences: syntactic (processes by which sentences are constructed) and semantic cues exist during the reading of sentences which do not exist during the presentation of an isolated word. These cues can be used to infer the meaning of the text at any given fixation, even when only part of a sentence is in view. Research has shown there are differences in the processing of words which are presented in context and in isolation [25, 26], and context aids word recognition. These contextual cues in the reading experiment may aid reading comprehension and reduce the effect of the visual function differences between groups, hence why no measured difference in perceptual span made during the passages of text was observed. Conversely, during the presentation of a single word, as in the LDT, these linguistic factors cannot aid comprehension. Therefore, patients may have to make additional eye movements to process a word, explaining the average difference in *saccadic frequency* between patients and controls. Postulating the significance of this result should be moderated by noting the limitations associated with our LDT experiment. It is possible that the reported relationship between *saccadic frequency* and reading speed observed in the patient group could arise if the measure of *saccadic frequency* is simply a surrogate measure for reaction time. Nevertheless, a 1,000 ms window was adopted to minimise the effect of slow processors. Furthermore, if this relationship was due to processing time, it should have also been observed in the control group, and it was not.

A new eye movement measure, termed *text saturation*, was considered to investigate if patient's reading difficulties were due to an increased requirement to fixate on all the words in a line of text. There was a small but statistically significant average difference between patients and controls with this measure in our experiment. On average, patients needed to saturate each line of the text more than controls when reading the passages of text. The effect would certainly not be noticeable when reading short passages of large text as in our experiment. Still, an experiment monitoring eye movements during sustained reading over a longer period of time might illuminate this effect. Certainly, recent research efforts have demonstrated an increased fatigue and difficulty with sustained silent reading [11, 27], and in this instance our measure of *text saturation* may provide a plausible mechanism as to why some, but not all, patients with glaucoma exhibit slower reading speeds.

Our sample of patients did not have statistically significant slower average reading speed when compared to the age-similar control group. This might be regarded as an unexpected finding, bearing in mind the nature of the advanced VF loss in the patient group, and previous research findings. Yet, one reason for this observation is that the reading tasks employed were of a short duration and text was presented on a computer screen, whereas previous studies used sustained periods of reading from a booklet [9, 11]. Another explanation is that the text size used in the present study was quite large, in order to facilitate more precise eye movement measurement. Moreover, all our glaucoma patients were deliberately chosen to

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have corrected binocular visual acuity of at least 0.18 logMAR (Snellen equivalent of 6/9) as measured using an ETDRS chart. These factors may have enabled patients and controls to read at comparable average rates. The rates are likely to diverge during the reading of smaller-sized text. Critically, our patient sample was small, and this study was not powered to detect differences in actual reading speed between groups.

There are several limitations associated with our study. First, it is difficult to be certain that visual and not cognitive factors are responsible for some of the results. Patients and controls did, however, perform similarly and well on the non-vision measures, with minimal between-person variability; noteworthy departures did not, for example, seem to impact on the associations as indicated on Figs. 1 and 2. But MEAMS and the Burt Word Reading Test may not have been sufficiently sensitive to measure subtle cognitive and reading level differences. After all, the former is really only a screening test to detect gross cognitive impairment, and the Burt Word Reading Test is only a simple gauge of reading ability. Future studies assessing reading in glaucoma ought to more carefully match cases and controls by cognitive ability. Perhaps the study would also have benefited from a more formal assessment of comprehension, in order to reduce some of the variability in our observed silent reading speeds [27]. Moreover, our sample of patients is unlikely to be representative of all patients with advanced VF loss in both eyes, since they have volunteered for a study where they knew reading performance would be assessed: poor readers may have been less likely to participate. This limitation to the study design might offer an explanation for the better or exceptional reading performance of some of the patients that took part. It is also worth noting that our univariable analyses did not adjust for level of education. Also, IVF measures, as used in this study, are disposed to bias in the absence of further binocular assessment; they can only be assumed to capture visual loss when looking straight ahead at a certain focal distance. Finally, we excluded patients with any ocular surface disease, but future studies ought to consider the influence of potential dry eye that might be induced by some glaucoma medication on reading performance.

Plots of eye movement scanpaths made during these experiments were revealing (Figs. 4 and 5). These examples hint at a possible mechanism whereby some patients with advanced glaucomatous VF defects read as efficiently as normally sighted peers. For example, eye tracking revealed idiosyncratic fixation behaviour in the patient depicted in Fig. 4, who had fast reading speeds despite advanced VF loss. Similar observations are well-reported in patients with macular disease [28, 29], where some patients develop a new preferred retinal locus over time, an eccentric retinal location which behaves as a pseudo fovea. The observation that some patients with advanced glaucomatous VF defects exhibit this adaptive shift has not been reported previously. For now this remains an observation, but it illustrates the utility of eye tracking in studies of reading in glaucoma, and hints at the design of future studies.

Only a handful of studies have directly measured reading performance in glaucoma, and the present study represents a contribution to the understanding in this important area. This study has revealed a relationship between eye movement measures and reading speed in a group of patients with advanced VF defects in both eyes. Evidence is presented that differences in eye movements might explain some of the large variability in reading rates exhibited by these patients, and may help provide a plausible mechanism as to why some, but not all, glaucoma patients have difficulties with reading. This study also adds to emerging evidence of eye movements being a useful way of understanding the functional consequence of glaucoma [30–33].

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