The Impact of Glaucomatous Visual Field Defects on Speed and Eye Movements during Reading

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ABSTRACT

Objective: To investigate the link between glaucomatous visual field defects and reading performance by assessing reading speed and eye movements in reading.

Methods: Eight glaucoma patients and 8 normal-sighted participants were recruited using convenience sampling in this cross-sectional study. The visual field was evaluated using the Humphrey Matrix 24-2. Reading speed was assessed in words per minute using Buari-Chen Malay Reading Chart and the SAH reading passages compendium. Eye movements in reading were recorded using 3D video-oculography.

Results: Glaucoma and control groups displayed significant differences in reading speed ($t=3.12$; $p<0.05$) and fixation ($t=-2.59$; $p<0.05$). Reading speed was significantly correlated with the total defect areas ($r=+0.62$, $p<0.05$) and the types of glaucomatous field defects (Analysis of Variance, ANOVA: $F=4.65$, $p<0.05$). No correlation was apparent in eye movements ($p>0.05$).

Conclusion: The association of defect areas and types with reading speed but not with eye movements might suggest a different coping strategy between eye movement adjustment and reading adaptation in response to visual field defects. Significant association with fixation but not with saccades might indicate that the disengaged and engaged mechanisms of visual attention are affected differently by visual field defects.

Keywords: Glaucoma; visual field defect; reading speed; eye movements (Siriraj Med J 2021; 73: 17-25)

INTRODUCTION

Reading involves the integration of visual information, encompassing visual-spatial skills in locating information, visual recognition of text, and visual encoding of letters, words, and sentences.[1,2] Intact visual field facilitates visual navigation to locate the text and lines during reading. Visual field defect has been reported to contribute to daily living difficulties among glaucoma patients.[3,4] Reading ability is generally found to deteriorate in glaucomatous eyes with increasing severity.[5]

The link between glaucomatous visual field loss and reading problems had been established using either a questionnaire approach or experimental design.[6-11] Some studies reported more reading difficulties among glaucoma patients; while other studies found glaucoma patients displayed similar reading performance or better than normal subjects.[8,12] The discrepancy might denote that the complex mechanism of the relationship. Reading speed varies widely among patients with glaucomatous visual field loss, but does not appear to be predicted by

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standard measures of visual function such as contrast sensitivity, visual acuity, and visual field damage.[8,10,12-14] Certain regions of the binocular visual field impairment were associated with reading performance even in patients with preserved visual acuity.[14] The inferior left region of patient integrated visual fields was suggested as important for changing lines during reading.[14]

We aimed to further investigate this link between glaucomatous visual field loss and reading performance. In this study, we explored the practicality of examining the reading speed together with the defect types, total defect area, and eye movements simultaneously in patients with glaucomatous visual field loss. We hypothesized that patients with glaucomatous visual field loss would be affected differently by the types of visual field defects and the total defect areas. Different types of reading eye movements were probed to reveal how the eyes navigated during reading. Tracking words during reading is imperative to retrieve information.[11,15] Visual information is neatly integrated during reading by positioning the eyes to text location.[8,12] Discontinuities are hardly noticed by readers as the eye moves from one viewing location to the next.[16,17] The parafoveal information from one fixation is integrated with information from the fovea during the next fixation. Peripheral visual impairment has been reported to compromise reading performance even in readers with preserved central visual acuity.[8,12] A peripheral vision problem may functionally inhibit a person seeing both ends of the line during reading.[8,12] Information processing primarily controls when the eyes move, while the oculomotor system control where the eyes move.[13] Eye movements represent the interface between high-level cognition (language) and the perceptual-motor loop (visual-oculomotor). Reading skills are associated with spatial reading parameters, such as the number of fixations per word, the total number of saccades, and saccadic amplitudes.[17] The eyes are relatively stationary during fixation and all visual input occurs at this time. The reading eye fixates on most content words in a rapid series of fixations (range 50-500 millisecond, ms) and saccades (20-35 ms).[18] When fixated, the eye remains immobile for a brief period on a content word and takes in a span of about seven to nine letters to the right of the fixation and three to four letters to the left before it jumps to the next fixation point.[18] Saccades typically move the eyes forward 7-9-character spaces. More letters are processed to the right of the fixation if the eye is scanning from left to right.[18] Both the detection of words in the center field of vision and awareness of words in the periphery is essential for proficient reading.[19] Diminished function of certain patterns of peripheral visual field defects might induce more challenges to move from word to word across the line for fluent reading. Different configurations might hurl different levels of struggles to enable readers to process a whole word at once. Visual field defects very close to fixation inhibit reading to a greater extent than peripheral defects, and the central 5° is particularly important for reading.[11,15] Defects in the inferior left hemifield and peripheral superior hemifield regions of the binocular visual field are related to reading difficulty, with damage to the inferior visual field slowed reading rates more than abnormalities in the superior, nasal or temporal field.[7,20] Information about the role of eye movements in mediating the effect of the visual field defects on reading difficulty remains inconclusive.

MATERIALS AND METHODS

Ethical approval was obtained from the Research Ethics Committee of University (IRB/IEC Certification 600-RMI (5/1/6) REC/108/15). Our study adhered to the declaration of Helsinki. Written informed consent was obtained. A sample size of 16 participants with an effect size of 1.38 was based on the actual power of study 84% and an α error of 0.05. Sixteen participants were divided into experimental and control groups in this cross-sectional study. The experimental group consisted of eight patients with a diagnosis of glaucoma from the ophthalmology clinic at a public university. The inclusion criteria for the experimental group was the best-corrected LogMAR (Logarithm of the Minimum Angle of Resolution) visual acuity of 0.8 or better; no known neuro-ophthalmic or other retinal or optic nerve conditions likely to affect the visual field. Eight normal sighted subjects with no known vision disorders, no known ocular diseases, and normal visual fields were assigned to the control group. The mean age of participants for experimental and control groups was 64 ± 8 years old and 56 ± 8 years old respectively. Any patients who were unable to read in the Malay language fluently were excluded.

Reading performance was evaluated using "Buari and Chen AH Reading Investigation Apparatus" (BaCA RIA with copyright registration code of CR001460). BaCA RIA consisted of the standardized Malay language reading materials, the Buari-Chen Malay Reading Chart (BCMRC), and the SAH reading passages compendium (SAHRPC).[21,22] Subjects were instructed to read the BCMRC aloud monocularly from the largest to the smallest print size. The critical print size was the smallest print size as reading speed constant across the larger print sizes from the plateau plot.[23] Critical print size was obtained from a graph plotted using reading speed to determine the print size for the SAHRPC assessment. Four reading passages from the SAHRPC were employed. The passages from the SAHRPC subtend 41° x 28° of the visual field. The passages contained upper- and lower-case letters and standard punctuation marks. Each had 50 words over 4-5 lines each, printed on A4 matte paper in landscape orientation at a size of 30 x 21 cm in 10-point Arial font, and subtending a visual angle of 0.28° in the lowercase letters. They were randomly selected and positioned at eye level on a reading stand inclined at 45° at a working distance of 40 cm. The total time used to read the whole text was measured. Reading errors (mispronunciations, substitutes, refusals, additions, omissions, and reversals) were recorded. The reading speed was quantified as correct words subtracting the total number of reading errors and divided by the total time taken to read the text in words per minute (wpm). Digital recordings were used for post-reading evaluation of reading time and reading errors.

Eye movements during reading were video recorded using a 3D Video-oculograph (3D-VOG, SensoMotoric Instruments GmbH version 5.0 SP8© 1991-2003, Berlin, Germany). A head-mounted eye tracking device with a built-in infrared light video camera was attached to a goggle and linked to a computer workstation. The computer workstation was integrated with MS Windows version 5.04.02 with stimulus software. The monitor screen resolution was set at 1024 x 768 pixels with a refresh rate of 60Hz and 32-bit color depth. The eye position was calibrated on a target positioned at eye level at the primary gaze. Eye movement data were extracted automatically from the 3D-VOG into the spreadsheet.

The visual field was assessed using a Humphrey Matrix visual field analyzer (Carl Zeiss Meditec, Dublin, Calif) with frequency doubling technology program 24-2 threshold protocol. All measurements were taken monocularly. Participants were instructed to press the response button when a stimulus appeared from any direction in the periphery while maintaining central fixation. Visual field result was considered reliable when fixation losses were <20%, false positives were <15% and false negatives were <25%. The field defects were determined from the pattern deviation plot. The 16 glaucoma eyes were categorized into one of five pre-determined field defect categories: nasal step, arcuate defect, centrocecal, pre-perimetric, or advanced.

The statistical analysis was conducted using SPSS comparing normal and glaucoma using independent t-test depending on the test of normality Shapiro-Wilk. Further analysis of the types of glaucomatous visual field defects was performed using Analysis of Variance (ANOVA). The relationship of total defect area with eye movements and reading speed was examined using Pearson correlation analysis. A p-value ≤0.05 was used as the criterion of statistical significance.

RESULTS

A comparison between experimental and control groups was summarized in Table 1. Fixation in reading is a point where the eyes come to rest during reading. In this study, the total number of eye fixations during the reading of the entire text was recorded to indicate the efficiency of reading performance. Readers with fewer eye fixations were assumed to take in more words with each fixation. Fixation counts showed a significant increase in glaucoma eyes. Therefore, glaucoma eyes were less efficient in reading than normal eyes due to higher fixation count. Meanwhile saccadic and regression showed no significant difference between glaucoma and normal eyes. Reading speed was significantly lower in glaucoma eyes.

The contributing factors for the difference found between control and glaucoma eyes were dissected from the perspectives of total defect area in percentages (Table 2) and the types of visual field defects (Table 3). The main feature of glaucoma pathogenesis is the progressive degeneration of retinal ganglion cells that leads to irreversible optic nerve damage and eventually vision field loss. The progression of visual field loss can be captured in terms of threshold sensitivity changes and total field defect areas. Hypothetically, those with more field defect areas should have experienced the defect for a longer period. In contrast, those at the early stage of glaucoma (early arcuate and pre-perimetric) supposedly had experienced the defect for a shorter period. The faster reading speed might connect to the duration of adaptation concerning the progressive degeneration of retina ganglion cells. The advanced glaucoma eye displayed the least fixation counts and the fastest reading speed seemed to support further the adaptive reading ability to longer duration of adaptation.

The arcuate defect was the most common (10/16=62.5%), followed by pre-perimetric and nasal step (2/16=12.5% each). The reading speed differed significantly for the various types of glaucomatous field defects (ANOVA: $F_{(2,1985)} = 4.90$, $p<0.05$). Post-hoc analysis showed slower reading speed in pre-perimetric and early arcuate defects; while advanced defects displayed the fastest reading speed. Fixation counts also differed significantly in different field defects (ANOVA: Welch's $F_{(3,5.965)} = 5.32$, $p<0.05$). Post-hoc analysis revealed higher fixation counts in nasal steps, followed by pre-perimetric, centrocecal, and

TABLE 1. Comparison of reading speed and eye movements between normal and glaucomatous eyes.

Parameters of investigation		Control Mean ± SD	Glaucoma Mean ± SD	t-test
Reading speed (wpm)		101.0±29.8	71.9±22.7	t=3.12; p<0.05
Eye movement	Fixation	46.3±14.2	61.3±18.2	t=-2.59; p<0.05
[counts (n)]	Saccadic	28.9±8.82	24.4±9.62	t=1.39; p>0.05
	Regression	14.1±6.13	12.2±7.16	t=0.82; p>0.05

Abbreviations: *SD* - standard deviation; *wpm* - words per minute

TABLE 2. Comparison of total defect area and the relationship with eye movement counts and reading speed measurements for 16 glaucomatous eyes.

Eye Code	Total defect area* (%)	Eye movements (counts, n)			Reading speed (wpm)
		Fixations	Saccades	Regressions	
G01	44	37	16	4	114
G02	39	65	24	24	84.0
G03	33	77	26	10	105
G04	19	73	36	11	93.0
G05	44	81	34	24	77.4
G06	43	88	26	18	44.9
G07	35	69	27	2	99.9
G08	28	69	15	8	57.2
G09	22	36	17	13	70.9
G10	35	49	21	7	76.2
G11	22	55	11	10	76.1
G12	13	28	16	6	44.9
G13	6	62	41	21	49.1
G14	11	62	41	21	49.1
G15	24	85	12	7	48.5
G16	69	45	25	9	114

*Calculated as the number of depressed points in the field/54 x 100%

Abbreviation: *wpm* - words per minute

TABLE 3. Comparison of the types of glaucomatous field defects and the relationship with eye movement counts and reading speed measurements for 16 glaucomatous eyes.

Types of Glaucomatous Field Defect	n	Percentages from a total of 16 eyes	Eye movements (counts, n)			Reading Speed (words/min)
			Fixation	Saccade	Regression	
Nasal step	2	12.5%	81	19	8.5	77.0
Arcuate defect*	10	62.5%	64	25	14	76.7
• *Early arcuate*	*(1)*	*6.25%*	*62*	*41*	*21*	*49.1*
• *Partial arcuate*	*(6)*	*37.5%*	*59*	*22*	*13*	*80.5*
• *Full Arcuate*	*(3)*	*18.8%*	*73*	*25*	*11*	*78.2*
Centrocecal	1	6.25%	49	21	7	76.2
Pre-perimetric	2	12.5%	45	29	14	47.0
Advanced	1	6.25%	45	25	9	114

**Arcuate defect was subcategorized to early arcuate, partial arcuate, and full arcuate according to progression stages*
Abbreviation: Min- minutes

advanced glaucomatous visual field defects (Games-Howell test=31.8, 95% CI [3.74, 59.85], $p<0.05$). However, the saccadic and regression counts showed no significant difference (ANOVA: Saccadic, $F_{(3, 61.55)}=0.598$, $p>0.05$; and regression, $F_{(3,17.05)}=0.284$, $p>0.05$).

Further analysis was conducted to examine the directional element of glaucomatous defects and their impact on reading speed and eye movements. Two eyes [early arcuate (G14) and pre-perimetric (G13)] were excluded due to the nature of the defect that was unable to be categorized. For horizontal defect impact analysis, 7 eyes suffered defect in the right region, and 7 eyes displayed in the left region. For vertical defect impact analysis, 6 eyes were categorized as visual field defect at the superior region, 5 eyes were categorized as visual field defect at the inferior region and 3 eyes were categorized as mixed. Neither reading speed (t = -0.97, $p>0.05$) nor eye movements differed significantly by horizontal locality of visual field defect [Fixation (t=-0.66, $p>0.05$); Saccadic (t =-0.40, $p>0.05$); Regression (t=0.99, $p>0.05$)]. Vertical defect impact analysis concluded similarly [ANOVA: Fixation (F=0.07, $p>0.05$); Saccadic (F=1.14, $p>0.05$); Regression (F=0.41, $p>0.05$); Reading speed (F=1.09, $p>0.05$)].

The correlation of the total percentages of the defect areas with eye movements and reading speed was shown in Fig 1. The total defect area caused a significant positive correlation with reading speed (r=+0.62, $p<0.05$). Reading speed was found to be faster with an increment of the total defect area. Meanwhile, none of eye movements was found to correlate with total defect area [fixation (r=+0.05, $p>0.05$); saccadic (r= -0.16, $p>0.05$); regression (r= -0.11, $p>0.05$)].

DISCUSSION

Difficulties with reading in glaucoma affect quality of life.[24] Glaucomatous VFD has been associated with more fixations, longer search time, more errors, shorter fixation durations, and longer reading duration.[8,16] Our finding is in agreement with previous studies that reported slower reading speed in glaucoma than normal.[8,9] Normal eyes in our study read 30 words more per minute than glaucoma eyes using SAHRPC. Decrement of reading speed in glaucoma eyes might due to the restricted visual span (field of view) during reading. Glaucoma eyes with peripheral visual field defects have a smaller field of view than normal eyes, which might cast difficulty to read from one word to another word efficiently.

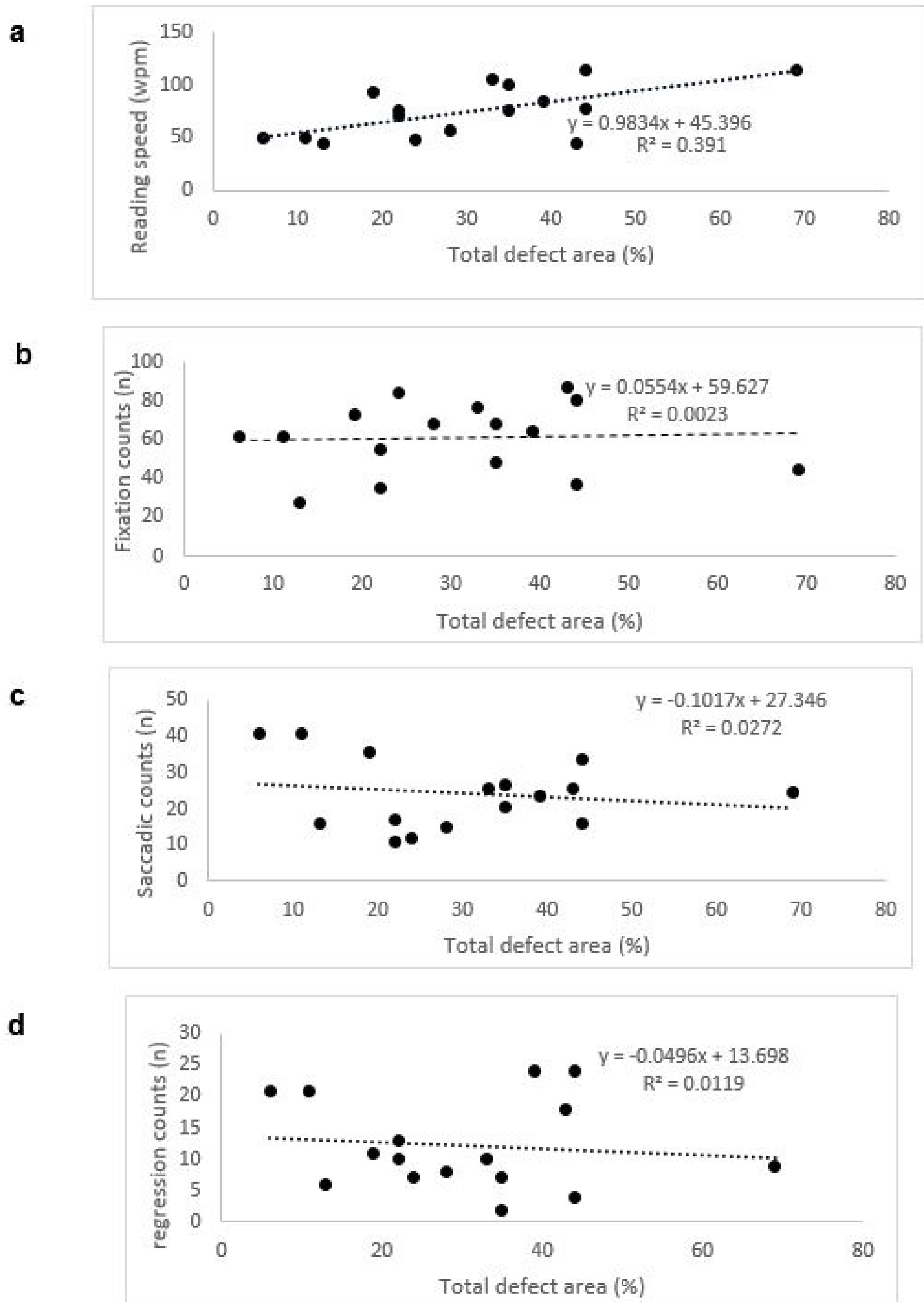

Fig 1. Correlation of total defect area with eye movements and reading speed. **(a)** reading speed, **(b)** fixation, **(c)** saccade, and **(d)** regression

Undeniably that some readers with glaucomatous visual field defects experienced more difficulties with reading; while others remained the same or better than readers with normal vision.[3,8,9,12] This ambiguity probed us to further examine the eye movements and reading speeds concerning different types of glaucomatous visual field defects and different sizes of defect areas in comparison to normally sighted subjects. Our findings seem not to align fully with previous studies because eye movements remained the same as the increment of the total defect area. We expect otherwise because the peripheral visual defect was reported to compromise reading performance despite preserved fovea acuity.[16] The slower reading speed in glaucoma was reported to correlate with the reduction of the visual field.[9] Greater visual field defects had been associated with greater self-reported difficulty finding the next line of text while reading.[5,9] This dissimilarity of our findings with previous studies might indicate the potential of visual adaptation. The key feature of glaucoma pathogenesis is the progressive degeneration of retinal ganglion cells.[25] Understandably, visual defect worsens over time. The progression of visual field loss is usually reported as threshold sensitivity changes and total field defect areas.[26] Those with more field defect areas logically has experienced the defect for a longer period. The faster reading speed might connect to the duration of adaptation concerning the progressive degeneration of retina ganglion cells. Adaptation might happen to cope with the visual challenges in daily activities. Our findings might denote the possibility of visual adaptation in glaucoma. Glaucoma was associated with a reduction in contrast detection and discrimination adaptation in the early stages.[27] Reduction of visual acuity or contrast sensitivity caused slower reading speed in glaucoma.[28] Our findings might suggest that reading speed reduction in the early stages of glaucoma might be just transient evidence of coping mechanisms being established. The brain can be rehabilitated.[29-30] Neuroplasticity research reveals the ability of the brain to adapt continuously throughout life.[31-32] The brain exhibited enormous capacities to adapt to damage. The repetitive visual training in daily activities might give an impact on visual learning in glaucoma.[33]

Our analysis of reading speed and eye movements concerning glaucomatous field defects also revealed something interesting about the relationship. Besides reading speed, only fixation but not saccades or regressions were found to vary significantly with different types of glaucomatous field defects. Fixation in reading is a point where the eyes come to rest during reading. Reading is not just fixating on one word after another, but rather requires a complex series of fixations to see complete texts.[34] Readers who make fewer eye fixations read faster because they take in more words with each fixation. The visualization of a complete text during reading can benefit from an intact visual field and efficient eye movements. Peripheral visual field defect has been reported to obstruct readers to see both ends of the line during reading.[16] Before the reader begins to fixate at the first word in the text, the eyes scan across the reading materials to locate the first word of a text. Spatial reading parameters, such as the number of fixations per word, the total number of saccades have been tied to reading performance.[17] If visual search plays a role in reading performance, the left or superior defect areas would have reduced the reading speed more than right or inferior defect areas with the presumption that more efforts are required to locate the text situated at the left and superior region due to the defect. The inferior field has been regarded as an important positioning for reading.[7,11,14] The inferior left region has been indicated as important for changing lines during reading.[14] Reading speed had been reported to be faster in the inferior field compared to other areas in normal readers.[7] Hypothetically, the right-field defect or inferior field defect should have a more negative impact on reading speed.[7,35] Conversely, our findings were not in agreement with the previous report that reading was neither more affected with the presence of right than left field defects nor more affected in the inferior field defect.[35] Our horizontal and vertical field analyses revealed that the location of field defects did not seem to play a significant role in determining reading speed. Perhaps not the locality or sizes that determined the outcomes but the individual reading difficulty coping or adaptation mechanism that dictated the outcome. Parafoveal information from one fixation is connected to the information from the fovea in the next fixation during readings.[16] The integrated activities between the fovea and parafoveal during fixations are illustrated in Fig 2.[14,36,37] Parafoveal view gives readers partial information of what is to come next. If this reading assumption is correct, the right visual field defect would affect the reading performance too.

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Fig 2. Illustration of the integrated activities between fovea and parafovea during fixations. Bold letters denote fixations (what the eye is seeing directly in its foveal view). Underlined letters signify what is subconsciously processed during a fixation (not what readers see directly)

One possible explanation of our findings was visual adaptation through perceptual learning.[33] Different coping mechanism might be used to overcome the hindrances caused by visual field defect strategy. When the central vision was compromised, eccentric fixation might be used in the visual rehabilitation of the visual field defect. Scanning involving parafoveal and peripheral visual field is crucial to navigating reading. Patients with visual field defects might have adapted to the condition with adjusted eye and head movements or compensatory gaze strategies to improve reading performance.[33,38,39]

Fixations and saccades denote how readers acquire information. Visual attention can be in an engaged or disengaged state.[40] To move from one point to another, visual attention should be in the disengaged state. During engaged visual attention, saccades were inhibited to provide steady central fixation. The disengaged mechanism seemed to be intact (insignificant saccadic finding in our study) during visual search in reading despite visual field defects. A different coping inclination between eye movement adjustment and reading adaptation might occur in response to visual field defects. Future research with additional measurements on the time length of each eye movement is essential. Time length for saccade can estimate how fast the eye moves between fixations. Time length for regression predicts the effort required to reread a line of text.

In conclusion, reading speed and fixation were affected by different types of glaucomatous visual field defects patterns. The association of defect areas with faster reading speed but not significant in eye movements might suggest a possible different coping strategy between eye movement adjustment and reading adaptation in response to visual field defects.

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