Altered eye movements during reading under degraded viewing conditions: Background luminance, text blur, and text contrast

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Degraded viewing conditions caused by either natural environments or visual disorders lead to slow reading. Here, we systematically investigated how eye movement patterns during reading are affected by degraded viewing conditions in terms of spatial resolution, contrast, and background luminance. Using a high-speed eye tracker, binocular eye movements were obtained from 14 young normally sighted adults. Images of text passages were manipulated with varying degrees of background luminance (1.3–265 cd/m^2), text blur (severe blur to no blur), or text contrast (2.6%–100%). We analyzed changes in key eye movement features, such as saccades, microsaccades, regressive saccades, fixations, and return-sweeps across different viewing conditions. No significant changes were observed for the range of tested background luminance values. However, with increasing text blur and decreasing text contrast, we observed a significant decrease in saccade amplitude and velocity, as well as a significant increase in fixation duration, number of fixations, proportion of regressive saccades, microsaccade rate, and duration of return-sweeps. Among all, saccade amplitude, fixation duration, and proportion of regressive saccades turned out to be the most significant contributors to reading speed, together accounting for 90% of variance in reading speed. Our results together showed that, when presented with degraded viewing conditions, the patterns of eye movements during reading were altered accordingly. These findings may suggest that the seemingly deviated eye movements observed in individuals with visual impairments may be in part resulting from active and optimal information acquisition strategies operated when visual sensory input becomes substantially deprived.

Introduction

Reading is a highly complex process that involves cognitive, linguistic, visual sensory, and oculomotor components. Thus, reading performance can be hampered not only by any abnormalities in higher-level cognitive/linguistic processing (Shaywitz & Shaywitz, 2008) but also by any deficits in bottom-up visual sensory processing (Legge, Rubin, Pelli, & Schleske, 1985). In our daily living, we encounter various degraded viewing conditions due to either variation in the natural environment or visual disorders, which often leads to difficulties in reading. Even for individuals with normal vision, reading can be challenging under degraded viewing conditions such as under dim light or when text appears faint or blurry. The visual requirements for reading in people with normal vision have been well documented in the seminal work by Legge and his research team (Kwon & Legge, 2011; Legge, Pelli, Rubin, & Schleske, 1985; Legge, Rubin, & Luebker, 1987). Legge, Pelli et al. (1985) showed that people's reading speed decreased with increasing text blur; particularly when the spatial frequency component of a letter is less than 2 cycles per character, the reading speed drops sharply. Similarly, Legge et al. (1987) showed that the reading speed decreased rapidly when the text contrast dropped below 10%, and it continued to decrease by 90% when the contrast was reduced down to 2%. In light of such visual sensory requirements for reading, it is not surprising that reading difficulty is one of the main complaints among patients with visual impairments (Brown et al., 2014; Margrain, 1999; Stelmack, 2001). Consistent with subjective reports, a number of studies have shown a significant deficit

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in reading speed in visually impaired individuals such as age-related macular degeneration (Calabrèse et al., 2010; Cheong, Legge, Lawrence, Cheung, & Ruff, 2007; Cheong, Legge, Lawrence, Cheung, & Ruff, 2008; Chung, 2020; Crossland, Culham, & Rubin, 2004; Sunness, Applegate, Haselwood, & Rubin, 1996; Tarita-Nistor, Brent, Steinbach, Markowitz, & González, 2014; Timberlake et al., 1986), glaucoma (Burton, Crabb, Smith, Glen, & Garway-Heath, 2012; Kwon, Liu, Patel, & Girkin, 2017; Ramulu, Swenor, Jefferys, Friedman, & Rubin, 2013; Smith, Glen, Mönter, & Crabb, 2014), or amblyopia (Kelly, Jost, De La Cruz, & Birch, 2015; Kelly et al., 2017; Levi, Song, & Pelli, 2007). Importantly, a decrease in reading speed was shown to be significantly correlated with a reduction in contrast sensitivity (Brown, 1981), visual acuity (Legge, Rubin et al., 1985), or the extent of the visual field defects (Calabrése, Bernard, Faure, Hoffart, & Castet, 2014; Cheong et al., 2008; Kwon et al., 2017). For this reason, patients with visual impairment are more vulnerable to suboptimal viewing conditions compared to healthy cohorts (Blumberg, Liebmann, Hirji, & Hood, 2019; Burton et al., 2012; Seiple et al., 2018). For example, Blumberg et al. (2019), using the Low Luminance Questionnaire, found that patients with glaucoma often report difficulty in seeing or depth perception at night or in a poorly lit room. According to the study done by Seiple et al. (2018), the reading speed of patients with age-related macular degeneration (AMD) is further slowed down by small fonts under low luminance (3.5–30 cd/m^2).

Reading involves coordinated movements of the two eyes over the print. When we read, our eyes make a series of short rapid eye movements called saccades interleaved with short fixations that usually take about 250 ms (Rayner, 1998). Through such coordinated eye movements, the visual system brings the target of interest into the fovea and extracts relevant visual information. Previous clinical studies showed that low-vision patients often exhibited abnormal eye movements such as longer fixation duration, shorter saccade amplitude, more frequent saccades, or more regressive (backward) saccades (Pijnacker, Verstraten, Van Damme, Vandermeulen, & Steenbergen, 2011; Shanidze, Heinen, & Verghese, 2017; Tarita-Nistor, González, Markowitz, & Steinbach, 2009; Wiecek, Pasquale, Fiser, Dakin, & Bex, 2012) correlated with slower reading speed (Calabrése et al., 2014; McMahon, Hansen, Stelmack, Oliver, & Viana, 1993; McMahon, Hansen, & Viana, 1991). For example, McMahon et al. (1991) found that, when presented with a five-letter sequencing task, patients with macular degeneration showed an increase in both forward and regressive saccades and a decrease in the reading rate compared with normal controls. The role of microsaccades during reading has also been reported in previous work (Bowers & Poletti, 2017). Microsaccades (i.e., small involuntary eye movements produced during fixation) are known to prevent visual fading (Collewijn & Kowler, 2008; McCamy, Macknik, & Martinez-Conde, 2014; Rayner, 1998) and to sample high spatial frequency information, thereby enhancing the processing of fine spatial detail (Rucci, Iovin, Poletti, & Santini, 2007). These eye movements vary based on the type of task and stimulus in terms of its rate, direction, and amplitude (Rucci & Poletti, 2015). In particular, this fine oculomotor behavior appears to be beneficial in reading by optimally relocating the stimuli within the foveola and enhancing the visibility of nearby words (Bowers & Poletti, 2017). Finally, reading long text passages often involves a large amount of line-changing saccades, also referred to as return-sweeps; thus, they are an important component of real-life reading (Parker, Slattery, & Kirkby, 2019). Previous studies have also shown that both patients with visual impairment and individuals with simulated vision loss exhibit more saccades during return-sweeps, a slow transition to new lines of text, and increased page navigation time (Bowers & Reid, 1997; Mathews, Rubin, McCloskey, Salek, & Ramulu, 2015; Passamonti, Bertini, & Ladavas, 2009).

It is perhaps possible that these apparently deviated eye movements may, to some degree, reflect adaptive behaviors to maximize information acquisition given degraded visual sensory input. Alternatively, it may simply represent abnormalities in oculomotor control due to pathological conditions; however, little is known about how degraded sensory input alters the way our eyes move from word to word during reading. Here, we investigated how the pattern of such eye movements changes under degraded viewing conditions and how it is related to reading performance. To this end, we examined the effects of background luminance, text blur, and text contrast on patterns of eye movements during reading and reading speed. The levels of text blur (from severe blur to no blur; Snellen acuity equivalent ranging from normal vision [20/20] to severe low vision [20/200–20/400]), text contrast (2.6%–100%), and background luminance (1.3–265 cd/m^2) were chosen based on previous findings (see the Method section for details).

Using normally sighted individuals, we systematically manipulated the three degraded viewing conditions with varying levels of severity and recorded both their reading speed and scanpaths. We first examined how reading speed and eye movement strategies vary across different levels by calculating a similarity index between the scanpaths. We then probed the key eye movement parameters, including saccade amplitude, saccade velocity, fixation duration, number of fixations per line, proportion of regressive saccades, microsaccade rate, microsaccade amplitude, and line-changing (return-sweeps) time under different degraded viewing conditions. It should be noted that, by simulating degraded viewing conditions in normally sighed young adults, we aimed at focusing solely on how degraded visual sensory information influences the patterns of eye movements during reading while minimizing the effects of potential confounders such as deficits in oculomotor control in older or clinical populations.

The outcomes of the current study are expected to bring valuable insights to our understanding of how changes in low-level sensory information contribute to abnormal eye movement patterns. Furthermore, these findings may help us understand the quantitative relationship between reading and eye movement parameters under varying viewing conditions.

Methods

Participants

Study participants included 14 young normally sighted subjects (age range, 18–28 years; mean age, 23.07 ± 3.15 years; 10 males). All participants were recruited from the Birmingham, AL, metropolitan area. They were native English speakers without known cognitive or neurological impairments. They had normal or corrected-to-normal vision. Normal vision was defined as having better than or equal to 0.1 logMAR (equivalent to 20/25 Snellen acuity) corrected visual acuity, normal contrast sensitivity (better than 1.9 log units), normal stereoacuity (40–45 arcsec), and no known visual disorder. Proper refractive correction for the viewing distance was used. Mean visual acuity (Early Treatment Diabetic Retinopathy Study Chart) was −0.16 ± 0.07 logMAR (i.e., better than 20/15). Mean contrast sensitivity (Pelli–Robson Contrast Sensitivity Chart) was 2.01 ± 0.10 log units. Mean stereoacuity (Titmus Fly SO-001 StereoTest) was 42.14 ± 5.58 arcsec. All the measurements including main experiments were performed binocularly. The experimental protocols followed the tenets of the Declaration of Helsinki and were approved by the Internal Review Board at the University of Alabama at Birmingham. Written informed consent was obtained from all participants before the experiment and after an explanation of the nature of the study.

Stimulus and apparatus

The 26 lowercase Courier New font letters of the English alphabet (a serif font with fixed width and normal spacing) were used for the reading task. The letters were black on a uniform gray background. Letter size was defined as the font x-height of 0.68° at the 57-cm viewing distance. As shown in Figure 1A, one paragraph of a text consisting of five sentences was presented on a display screen at a time (hereafter we call it text page). All of the sentences were 56 characters in length and formatted into one line. The horizontal end-to-end distance of each sentence spanned approximately 38 degrees of visual angle. For each subject, a total of 48 text pages were used for the reading task. The difficulty of the sentences was roughly second- to fourth-grade level. These simple and standardized sentences were chosen to minimize the influences of higher level cognitive and linguistic factors, thereby assessing the front-end visual aspects of reading (Kwon & Legge, 2012; Kwon et al., 2017; Legge, Ross, Luebker, & LaMay, 1989; Liu, Patel, & Kwon, 2017).

The current study design included three viewing conditions that differed in either the luminance of a uniform gray background, text contrast, or text blur. The text page with the uniform gray background luminance of 80 cd/m^2, a contrast of 100%, and no blur served as a baseline (normal viewing) condition (Figure 1A left panel). Whenever one aspect of the text was manipulated, the other two parameters were set as the baseline values. For example, when presenting text pages with varying levels of text blur, the background luminance of the text and the text contrast were set to 80 cd/m^2 and 100%, respectively. There were four background luminance levels (1.3, 2.7, 80, and 265 cd/m^2). There were five text contrast levels (2.6%, 4%, 6%, 9%, and 100%) and five blur levels (σ of 5, 4.5, 4, and 3.5 pixels, approximately corresponding to Snellen acuities of 20/420, 20/375, 20/335, and 20/295, respectively), including no blur (20/20). The text contrast was defined by Weber's contrast. The text was blurred by applying a Gaussian lowpass filter (i.e., $\sigma = 5$ pixels corresponding to 0.78 dva) to the entire text passage image. The Gaussian function is as follows:

$$G(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

where x and y represent the distance from the origin in the horizontal and vertical axis, respectively, and σ is the standard deviation of the Gaussian function in pixel units. Thus, a larger σ value induces more blur to the text.

For the blur and contrast conditions, our range of choice was largely based on that of previous studies on reading (Legge et al., 1987; Legge, Rubin et al., 1985) as we were interested in understanding how the pattern of eye movements is related to slower reading speed in impaired vision. Note that our blur viewing condition covered the Snellen acuity ranging from normal vision (20/20) to severe low vision (20/200–20/400). On the other hand, the luminance values (1.3, 2.7, 80, and 265 cd/m^2) were chosen to cover the range from the mesopic (0.01–3.0 cd/m^2) to photopic (10–10^8 cd/m^2) condition.

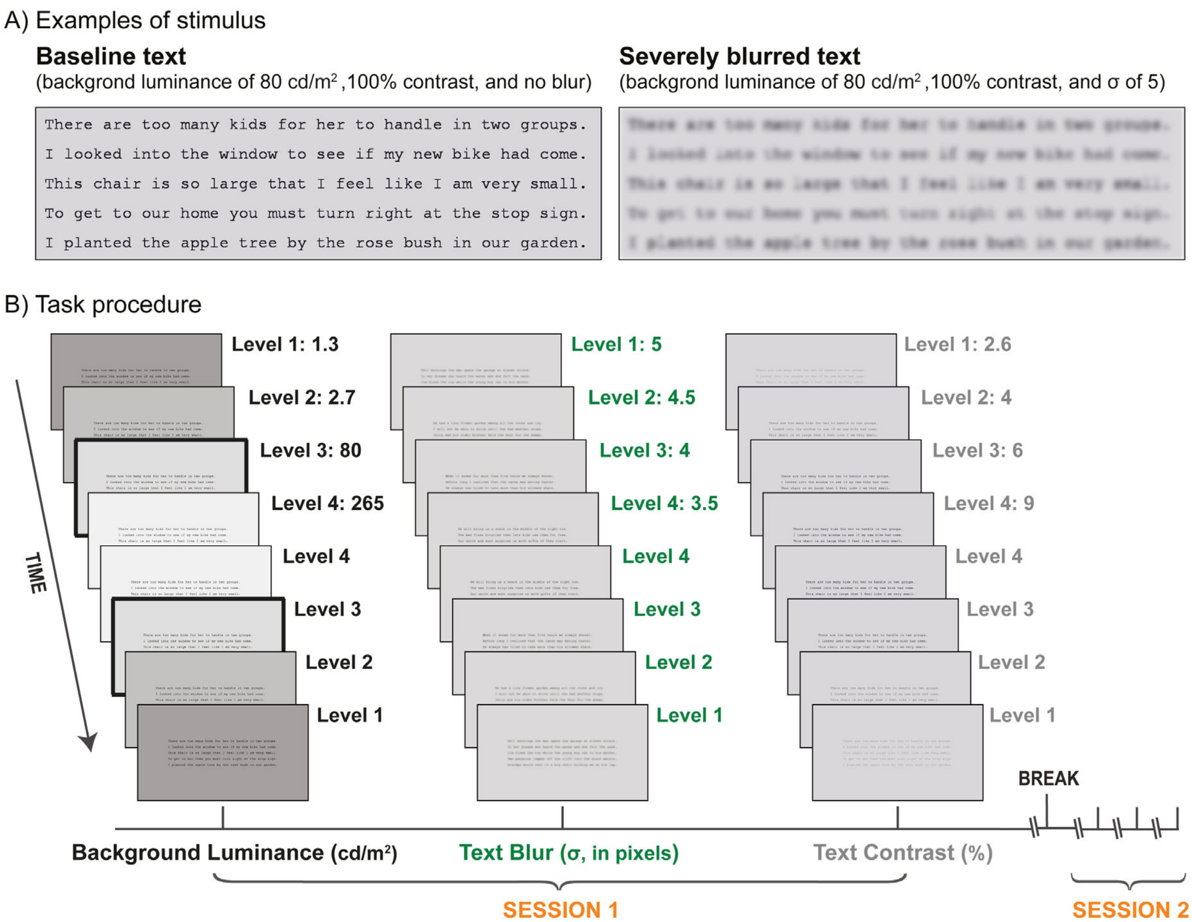

Figure 1. (A) Examples of stimulus. The left panel shows the five sentences within one text page under the baseline condition (normal viewing; level 3 of the background luminance condition, with background luminance of 80 cd/m^2, text contrast of 100%, and no blur), and the right panel depicts the text page under the blur condition (level 1). (B) Task procedure and viewing conditions. The order of the testing conditions (i.e., the background luminance, text blur, and text contrast) in the first and second sessions was randomized across subjects. The sequence of intensity levels (i.e., levels 1, 2, 3, 4, 4, 3, 2, and 1) for each testing condition remained identical for both sessions. Each intensity level was followed by a blank response interval and an interstimulus interval, which is not shown in the schematic diagram. The two bolded black frames in the background luminance condition at level 3 served as the baseline condition (background luminance of 80 cd/m^2, text contrast of 100%, and no blur).

All stimuli were generated and controlled using MATLAB 8.3 (MathWorks, Inc., Natick, MA) and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) for Windows 7, running on a PC desktop computer (Dell Precision Tower 5810; Dell, Inc., Round Rock, TX). Stimuli were presented on a liquid crystal display monitor (VS278H-E; ASUS Computer International, Fremont, CA) with a refresh rate of 144 Hz and resolution of 1920 × 1080, subtending 60 × 34 dva at a viewing distance of 57 cm. Stimuli were rendered with 10.8-bit grayscale levels using the bit-stealing method (Tyler, 1997). Luminance of the display monitor was made linear using an 8-bit look-up table in conjunction with photometric readings from a luminance meter (Minolta LS-110 Luminance Meter; Konica Minolta, Inc., Tokyo, Japan).

Task procedure

A subject's oral reading speed was measured with static text consisting of five sentences with the same length on one page (see Figure 1A) while the subject's gaze position over the text was continuously recorded by a high-speed eye tracker (see the section below for details on the eye movement recordings). Subjects were instructed to read the sentences aloud as quickly and accurately as possible whenever a text page appeared on a display screen. Whenever participants finished reading, the experimenter pressed a key on the keyboard to indicate the end of reading time and entered the number of words read incorrectly. Thus, for each text page, reading time and reading accuracy (i.e., number of words read correctly) were recorded and the corresponding reading speed (i.e., number of words read correctly per minute [wpm]) was computed.

The study design consisted of two testing sessions with one short break in between. Within each session, subjects went through three different viewing conditions: background luminance, text blur, and text contrast. The order in which the viewing conditions were presented was randomly assigned across subjects. Within each viewing condition, the intensity levels were presented from level 1 to 4. To counterbalance any potential confounding factors (if any) such as practice or fatigue, we adopted the mirror image sequence of level 4 to 1 immediately after. Therefore, in each session, two text pages were used for each intensity level. After a break from the first session, we conducted a second session for each participant. The order of the intensity levels within each viewing condition was identical to the first session. Therefore, for each subject, a total of 48 (3 viewing conditions × 4 intensity levels × 2 text pages × 2 sessions) unique text pages (48 reading speed measurements) were used. No subject saw the same text twice.

For each subject, the final reading speed for a given viewing condition and intensity level was the average across the four measurements (i.e., four text pages from the two sessions). Thus, a total of 12 (3 viewing conditions × 4 intensity levels) final reading speed measurements were obtained for each subject. Subjects performed all tasks in a dimly lit room while they were seated in a comfortable position with a forehead rest. A forehead rest (not chin rest) was used to maintain the desirable viewing distance and to minimize head motion while allowing subjects to read out loud freely without compromising eye tracking accuracy.

Eye movement recording

Each subject's eye movements were monitored (binocular tracking) using an infrared video-based eye tracker with a sampling rate of 500 Hz (EyeLink 1000 Plus/Desktop Mount; SR Research Ltd., Kanata, Ontario, Canada) and a maximum spatial resolution of 0.01°. A nine-point calibration/validation sequence was performed at the beginning of every experimental session that relied on the eye tracker. Calibration and/or validation were repeated until the validation errors for all points were smaller than 1°. The gaze position error (i.e., the difference between the target position and the computed gaze position) was estimated during the nine-point validation process. The average gaze position error was 0.25°. A forehead rest was used throughout the experiment to minimize head movements and trial-to-trial variability in the estimation of gaze position.

Data analysis of eye movement measurements

Gaze data were analyzed using the EyeLink parsing algorithm, which robustly classified fixations and saccades, excluding blinks. The saccadic velocity threshold of 30°/s, saccadic acceleration threshold of 8000°/s^2, and saccadic motion threshold of 0.1° were used to distinguish saccades from fixations (Bethlehem et al., 2014; Lingnau, Schwarzbach, & Vorberg, 2008; Smith et al., 2014; Van der Stigchel et al., 2013). Microsaccades were defined as saccades with an amplitude of less than 1° and velocity exceeding 30°/s. Additionally, we extracted the scanpaths (i.e., sequences of fixation positions) for each line of the text pages as follows: First, using the saccade data, the saccades corresponding to changing the lines were extracted. The line-changing saccades were characterized as the backward saccades with large amplitudes (>15°) considering the horizontal end-to-end distance of each sentence (~38°) used for the study.

The time points corresponding to the line-changing saccades, T_l, $l = 1, 2, \ldots, 5$, were used to determine the starting and ending fixation points of the line. Note that T_l for the last line ($l = 5$) was considered as the last recording point of the text page, as there was no line changing for the last line. For line l, we considered the leftmost fixation point after the T_{l-1} (line-changing time of the previous line) as the starting point (except for the first line for which the starting point was the first recording point of the text page), and the last fixation point before the T_l as the last fixation point. After determining the starting and ending fixation points of each line, we built the temporal sequence (time series) of fixation points corresponding to that line by using the horizontal location and the duration of fixations that occurred between the starting and ending fixations. It is worth mentioning that the reason we constructed the sequence of fixation points instead of using the raw gaze position data was that the number of data points in the raw gaze positions was high due to the high sampling rate (500 Hz), which was redundant for our analysis. Thus, we downsampled the raw data for our analysis. However, because the typical downsampling of the raw data could potentially omit some fixation points (depending on the downsampling rate), we instead downsampled the raw data by interpolating the data points between consecutive fixation points. Note that we used only the horizontal gaze positions because the vertical positions did not vary much within each line. The data were also visually inspected to ensure that the lines were extracted correctly. For each subject, a total number of 240 lines (48 pages × 5 lines) were obtained. The highly noise-contaminated eye movement data (lines) were identified through visual inspections and removed from the data prior to the analysis. Overall, around 5% of the lines were excluded from the analysis.

Data analysis

To examine the effect of different intensity levels of each viewing condition (i.e., the background luminance, text blur, text contrast) on reading speed and eye movement parameters (i.e., saccade amplitude and velocity, fixation duration, number of fixations, microsaccade rate and amplitude, proportion of regressive saccades, and return-sweeps), we performed a separate one-way, repeated-measures analysis of variance (ANOVA) for each eye movement parameter under different levels for each viewing condition. To evaluate the relative importance of the eye movement factors affecting the reading speed, we also performed simple and multiple regression analyses in which saccade amplitude, saccade velocity, fixation duration, proportion of regressive saccades, microsaccade rate, microsaccade amplitude, and line-changing duration were entered into the model as independent variables; reading speed was considered to be a dependent variable. Statistical analyses were performed using SPSS Statistics 28.0.0.0 (IBM, Chicago, IL).

To study the similarity between scanpaths (i.e., sequences of horizontal fixation positions) during reading across different viewing conditions, we utilized the dynamic time warping (DTW) algorithm (Berndt & Clifford, 1994). DTW measures the alignments (similarity) between two time series that might vary in length or speed, and it has been commonly used for measuring time series similarities (Han, Han, & Gao, 2021; Kumar, Timmermans, Burch, & Mueller, 2019; Le Meur & Liu, 2015). A smaller DTW distance between a pair of time series suggests more similarity between them, whereas a greater distance indicates more dissimilarity. The scanpaths extracted for different lines of the text pages (see the previous section) were compared using the DTW algorithm. Specifically, for each subject and each viewing condition, we calculated the DTW distance between all pairs of scanpaths corresponding to the lines from different intensity levels. As a result, we obtained 100 × 100 distance matrices for the blur and low-contrast conditions (each had 100 lines; 5 conditions × 20 lines) and 80 × 80 matrices for the background luminance condition (4 conditions × 20 lines). Note that there were four levels of background luminance, one of which served as the baseline condition (i.e., background luminance of 80 cd/m^2, 100% contrast, and no blur). When analyzing the blur and contrast conditions, this baseline condition was added, resulting in five conditions in total for the blur and contrast conditions. Then, for each condition, we averaged the distance matrices across all subjects and normalized all values between 0 and 1 by using the maximum distance value across all conditions. Because the greater distance values in these matrices indicate more pronounced dissimilarity between a pair of scanpaths, we refer to these matrices as the *dissimilarity* matrices throughout this paper.

Additionally, we calculated the ratio of saccade landing positions for each letter position within words and the spacing between the words as follows: For each saccade landing position location following a forward saccade, we calculated a 5 × 56 distance matrix (5 lines × 56 characters), quantifying the Euclidean distance between the forward saccade landing position and all characters in the text page. The character position corresponding to the minimum distance in this matrix was considered as the closest character to the saccade landing position. This character could be a letter within a word or spacing between the words. We then assigned this information about the closest character to the corresponding saccade landing position. For example, the forward saccade landing position is on the first letter position within a word or it is on a space between words. Then, by finding this information about the landing position of all saccade landing positions following forward saccades, we calculated the ratios of saccade landing positions for different letter positions within words, as well as spacings between the words (for a given subject, viewing condition, and intensity level).

Probability density maps of microsaccades and saccades during reading were derived via density estimation with a bivariate Gaussian kernel (Botev, Grotowski, & Kroese, 2010) using the data from all subjects for each viewing condition and intensity level. The same method was also used in our previous work (Kwon, Nandy, & Tjan, 2013; Liu & Kwon, 2016).

Results

Changes in reading speed under degraded viewing conditions

Figure 2 summarizes how reading speed (wpm) is modulated by degraded viewing conditions. For the background luminance condition, all data were best fitted with the following linear model or the constant model:

$$y = ax + b \quad (1)$$

where y is log reading speed, a is the slope, x is log luminance level, and b is the intercept.

For all text blur and text contrast conditions, data were best fitted with an exponential decay function as follows:

$$y = ae^{-bx} + c \quad (2)$$

where y is log reading speed, a is the scaling factor, b is the decay rate, x is the log blur (σ)/contrast (%) level,

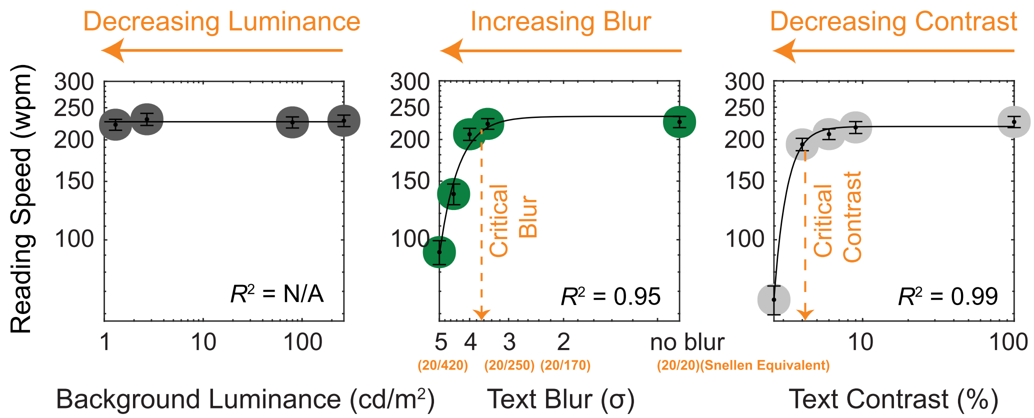

Figure 2. Reading speed as a function of degraded viewing conditions. The left, middle, and right panels plot reading speed (wpm) as a function of the background luminance (1.3, 2.7, 80, and 265 cd/m^2), text blur (σ of 5, 4.5, 4, and 3.5 pixels and no blur; the numbers in parentheses, such as 20/20, below the *x*-axis of the middle panels denote the approximate Snellen acuity corresponding to each blur level at σ of 5, 3, and 2 pixels and no blur), and text contrast (2.6%, 4%, 6%, 9%, and 100%) in log–log coordinates, respectively. Each data point is the average value across all subjects ($n = 14$). Note that the fifth level (i.e., the rightmost datapoint on the *x*-axis) in the text blur and text contrast plots (middle and right panel) represents the baseline (normal viewing) condition (80 cd/m^2 background luminance with a contrast of 100% and no blur). The critical intensity levels determined by estimating the *x*-value at which the *y*-value had a 10% decrease or increase from the asymptote of the fitted exponential function are indicated by orange dashed arrows.

and c is the constant. Solid lines indicate the best-fitted model. The R^2 values of the best-fitted models are reported in the corresponding plots. The lack-of-fit test (Cook & Weisberg, 2009) uses F statistics to pit the magnitude of the residual error resulting from model fitting against the magnitude of the intrinsic error (or pure error) of a dependent variable resulting from measurements and/or responses. Its null hypothesis ($p > 0.05$) states that the proposed model fits the data well. Therefore, p values > 0.05 observed in the current study support that our models offer satisfactory descriptions of the data. We also obtained the critical intensity levels, denoted by orange dashed arrows, by estimating the x-value at which the y-value had a 10% decrease or increase from the asymptote of the fitted exponential function.

We first confirmed that reading speed is significantly impaired under degraded viewing conditions. This finding is well aligned with previous findings (Kwon & Legge, 2012; Legge, Pelli et al., 1985; Legge et al., 1987). The left, middle, and right panels of Figure 2 depict reading speed (wpm) as a function of background luminance, text blur, and text contrast, respectively.

Our one-way, repeated-measures ANOVA (hereafter referred to as ANOVA for simplicity) on reading speed with the background luminance as a within-subject factor showed no significant effect of the background luminance on reading speed, $F(3, 39) = 1.93$, $p = 0.14$. For text blur, our ANOVA results showed a significant effect of the text blur ($p < 0.001$) on reading speed. Post hoc analysis with a Bonferroni correction further showed that reading speed under blur levels of $\sigma = 5$ and $\sigma = 4.5$ were significantly different from the other three levels, as well as each other ($p < 0.001$). The critical blur level for reading speed was $\sigma = 3.66$ (Figure 2, middle panel). Overall, reading speed decreased by 59% from no blur to the most severe blur ($\sigma = 5$; 225.82 ± 8.69 wpm vs. 91.80 ± 7.58 wpm; $p < 0.001$). For text contrast, our ANOVA results showed a significant effect of text contrast ($p < 0.001$) on reading speed. The post hoc analysis further confirmed that the reading speed of the lowest contrast level (2.6%) was significantly different from the rest ($p < 0.001$). This relation between the reading speed and the text contrast was also well captured by the best-fitted exponential model with the critical contrast of 4.18% (Figure 2, right panel). Overall, reading speed decreased by 71% when text contrast was reduced from 100% to 2.6% (225.82 ± 8.69 wpm vs. 66.06 ± 6.56 wpm; $p < 0.001$).

Changes in patterns of eye movements under degraded viewing conditions

Figure 3A visualizes the eye movement patterns during the reading of three randomly selected pages under the baseline (background luminance of 80 cd/m^2, contrast of 100%, and no blur), severely blurred (background luminance of 80 cd/m^2, contrast of 100%, and $\sigma = 5$), and very low contrast (background luminance of 80 cd/m^2, contrast of 2.6%, and no blur) viewing conditions for an exemplary subject. The green circles are centered at the fixation locations, and their radii denote the fixation duration (the bigger circles correspond to the longer fixation durations). It

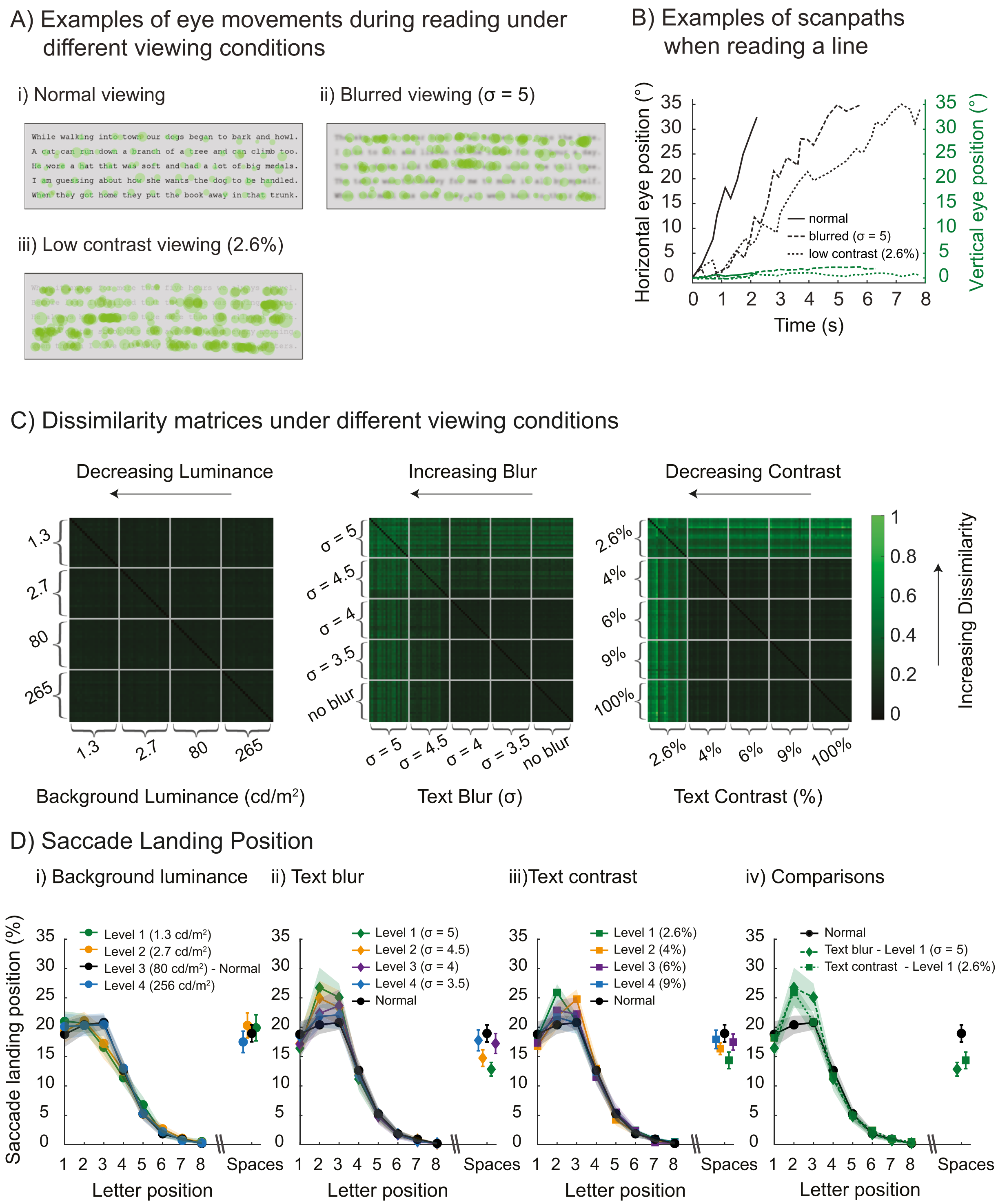

Figure 3. (A) Examples of eye movements during reading under (i) normal viewing, (ii) blurred viewing, and (iii) low-contrast viewing. Green circles represent the fixation locations. The radius of the circles indicates the fixation durations, with bigger circles corresponding to longer fixations. (B) Examples of horizontal (black) and vertical (green) scanpaths when reading a line under normal (solid line), blurred (dashed line), and low contrast (dotted line) viewing. Note that the scanpaths plotted here are the downsampled scanpaths (see Methods). (C) Dissimilarity matrices of scanpaths for different levels of each viewing condition. The lighter green colors are associated with greater dissimilarities between the eye movement patterns. (D) Saccade landing position, showing the ratios of saccade landing positions on different letter positions in words and spacing between the words for (i) background luminance, (ii) text blur, and (iii) text contrast conditions; the shaded areas show the 95% confidence intervals. (iv) Comparison of the normal versus severely blurred ($\sigma = 5$) and very low contrast (2.6%) texts.

is evident that the number and duration of fixations vary under different viewing conditions, and degraded viewing conditions were associated with more and longer fixations. This pattern can also be observed in the horizontal eye movement trajectories as shown in Figure 3B (black lines). However, the vertical positions did not vary much within each line (green lines).

Motivated by these observations, we looked into whether the patterns of eye movements change under different viewing conditions. To this end, we performed the DTW analysis to examine how the eye movements patterns from each level of different viewing conditions are clustered together and separated from other levels. The DTW can measure the similarity between two time series with different lengths, which makes it a proper choice to study the problem at hand.

We calculated the dissimilarity values between all pairs of scanpaths corresponding to single lines (20 lines per level of each viewing condition; see the Method section for more details). The left, middle, and right panels of Figure 3C show the dissimilarity matrices for the background luminance, text blur, and text contrast conditions, respectively. Different levels of each condition are demarcated with light gray lines. The darker colors correspond to fewer dissimilarities (or more similarities), whereas the lighter green colors denote more dissimilarities between the scanpaths. From Figure 3C, it is apparent that the scanpaths from different levels of the background luminance condition have very low dissimilarity values. In other words, the patterns of scanpaths do not vary across different levels. For the text blur and text contrast conditions, on the other hand, scanpaths under the highest level of the text blur and the lowest level of text contrast have the highest dissimilarities with scanpaths under less degraded viewing conditions. Specifically, for the text blur condition, the scanpaths corresponding to the blur levels of $\sigma = 5$ and $\sigma = 4.5$ have high dissimilarity with the scanpaths under lower levels of blur and no blur, and this dissimilarity is higher for reading under the more blurred text ($\sigma = 5$). For the text contrast condition, the highest dissimilarity was observed between the lowest contrast level (2.6%) and all other levels. Interestingly, scanpaths under other levels of contrast (4%, 6%, and 9%) were more similar to the normal viewing (a contrast of 100%) than the 2.6% contrast level. Considering these results, one can see that scanpaths do not differ much from the scanpaths under normal viewing unless the viewing condition is highly degraded (e.g., highly blurred or very low contrast text), which suggests some level of robustness in the eye movement pattern with respect to the degraded viewing condition. It is worth mentioning that, because we only used the scanpaths during reading of the single lines for the dissimilarity analysis, the line-changing parts of the scanpaths were not included in the analysis.

Furthermore, to explore whether there was a preference for making saccades toward specific letter positions within words and how this varied across different viewing conditions, for each viewing condition and intensity level we calculated the average saccade landing position ratio for each letter position and the spacing between the words across subjects. Figures 3D(i) to 3D(iii) show these results for the background luminance, text blur, and text contrast conditions, respectively. It is apparent that the second and third letters had the highest ratio of saccade landing positions. This finding is in line with the results of previous work on the ideal observer model of reading which showed similar curves for the ratio of landing position as a function of letter position within words (Legge, Klitz, & Tjan, 1997). Notably, this pattern is quite similar across different conditions and intensity levels. However, there seems to be a trend toward making more saccades on the second letter position compared with the third one as the viewing condition becomes more degraded. To see this more clearly, we plotted the results for normal versus severely blurred ($\sigma = 5$) and very low contrast (2.6%) texts in Figure 3D(iv). Note that, due to very low ratios of saccade landing positions on letter positions greater than eight (which could be due to the limited number of longer words in the texts used in this study), we only show the ratio for positions up to the eighth letters. Another observation from these results suggests that the ratio of saccade landing positions on spacing between the words decreases in more degraded viewing conditions as compared with the normal viewing condition (average of 18.95% ± 2.90%, 12.84% ± 2.31%, and 14.36% ± 2.80%, for normal, severely blurred, and very low contrast texts, respectively).

The left, middle, and right panels of Figures 4A to 4H plot saccade amplitude (degree), saccade velocity (°/s), fixation duration (ms), number of fixations per line, proportion of regressive saccades (%), microsaccade rate (#/sec), microsaccade amplitude (degree), and the time to change lines (ms) as a function of the background luminance (1.3, 2.7, 80, and 265 cd/m^2), text blur (σ of 5, 4.5, 4, 3.5 pixels, and no blur), and text contrast (2.6%, 4%, 6%, 9%, and 100%) in log–log coordinates, respectively. Each data point is the average value across all subjects ($n = 14$). Note that the fifth level (i.e., the rightmost datapoint on the x-axis) in the text blur and text contrast plots (Figures 4A–4H) represents the baseline (normal viewing) condition (80 cd/m^2 background luminance with a contrast of 100% and no blur). In each panel, solid lines are the best-fitted model (see more details in first section of result regarding reading speed). R^2 values of the best-fitted models are reported in each panel. We obtained the critical intensity level denoted by orange dashed arrows by

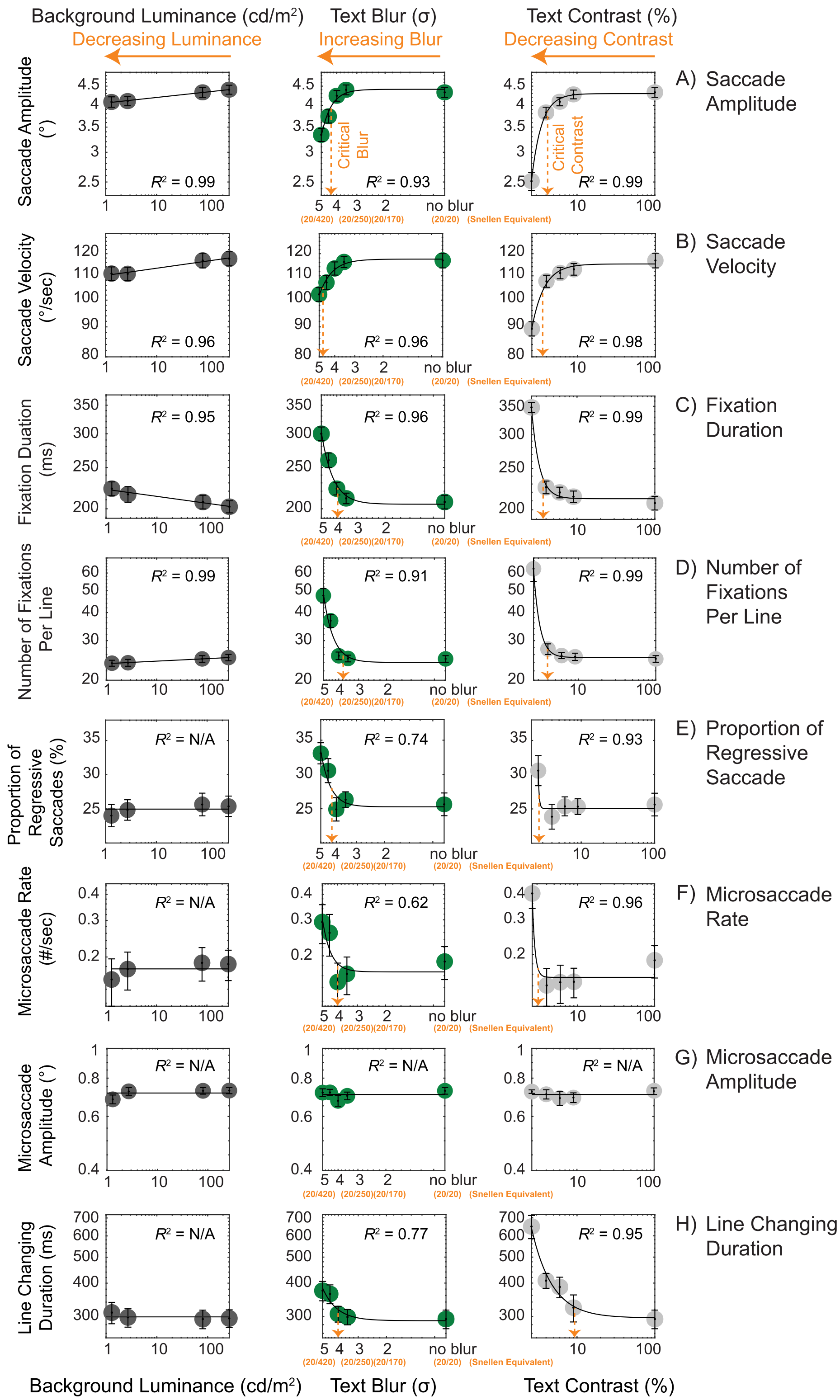

Figure 4. Eye movement parameters as a function of degraded viewing conditions. The left, middle, and right panels plot each eye movement parameter as a function of the background luminance (1.3, 2.7, 80, and 265 cd/m^2), text blur (σ of 5, 4.5, 4, and 3.5 pixels and no blur; the numbers in parentheses, such as 20/20, below the *x*-axis of the middle panels denote the approximate Snellen acuity corresponding to each blur level at σ of 5, 3, and 2 pixels and no blur), and text contrast (2.6%, 4%, 6%, 9%, and 100%) in log–log coordinates, respectively (except for the panels for proportion of regressive saccade, of which only *x*-axes are in log coordinates). Each data point is the average value across all subjects ($n = 14$). Note that the fifth level (i.e., the rightmost datapoint on the *x*-axis) in the text blur and text contrast plots (middle and right panels) represents the baseline (normal viewing) condition (80 cd/m^2 background luminance with a contrast of 100% and no blur). The critical intensity levels determined by estimating the *x*-value at

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←
which the *y*-value had a 10% decrease or increase from the asymptote of the fitted exponential function are indicated by orange dashed arrows. (A) Saccade amplitude (degree). (B) Saccade velocity (°/s). (C) Fixation duration (ms). (D) Number of fixations per line. (E) Proportion of regressive saccades (%). (F) Microsaccade rate (#/sec). (G) Microsaccade amplitude (degree). (H) Line-changing duration (ms), which refers to the time to change a line of text during reading.

estimating the *x*-value at which the *y*-value had a 10% decrease or increase from the asymptote of the fitted exponential function. Table 1 summarizes the ANOVA statistics and estimated critical intensity levels.

Saccade amplitude and velocity

As shown in the left panel of Figure 4A, for background luminance we observed a significant yet marginal increase in saccade amplitude with increasing background luminance (i.e., a 4% reduction from 265 to 1.3 cd/m^2; $p < 0.001$). For text blur (middle panel), the saccade amplitude dropped by 23% when text blur increased from no blur to the most severe blur level, $\sigma = 5$ ($p < 0.001$). A similar dependency of saccade amplitude was also observed for text contrast. Overall, saccade amplitude decreased by 41% from 100% to the lowest contrast of 2.6% (4.42° ± 0.05° to 2.62° ± 0.08°; $p < 0.001$) (Figure 4A, right panel). Furthermore, when we expressed the average saccade amplitude (degree) for the baseline (normal viewing) condition in terms of the number of letters per forward saccade, we found that the average saccade amplitude (letters per saccade) amounted to approximately seven letters per forward saccade. This value was comparable to the size of the visual span (i.e., the number of letters recognizable at one glance) reported in the previous studies on normal vision (Legge, Ahn, Klitz, & Luebker, 1997; Legge, Mansfield, & Chung, 2001).

Figure 4B shows saccade velocity across viewing conditions. The pattern of its dependency on viewing condition was very similar to that of saccade amplitude. The maximum saccade velocity in the normal viewing condition was 117°/s ± 3.38°/s. Compared to the normal viewing, saccade velocity decreased by 12% and 24% for severely blurred text and lowest contrast text, respectively ($p < 0.001$). Taken together, our results indicate that saccades become significantly shorter and slower with increasing text blur and decreasing text contrast.

Fixation duration and number of fixations per line

In Figure 4C, for background luminance, we observed a slight yet noticeable reduction in fixation duration with increasing background luminance ($p < 0.001$). Fixation duration increased by 9% when the luminance level decreased from 265 to 1.3 cd/m^2. For text blur (Figure 4C, middle panel), fixation duration increased by 42% as text blur increased from no blur to the most severe blur ($\sigma = 5$; $p < 0.001$). For text contrast, fixation duration increased by 68% from 100% to the lowest contrast 2.6% (205 ± 1.85 ms vs. 345 ± 4.32 ms; $p < 0.001$) (Figure 4C, right panel). Figure 4D plots the number of fixations per line across all viewing conditions. Each line (sentence) consisted of 56 characters with the *x*-height of 0.68°. Compared to the normal viewing condition (24.88 ± 0.84), the number of fixations per line increased by 91% and 150% for severely blurred text and lowest contrast text, respectively ($p < 0.001$). It is apparent that the number of fixations is inversely related to saccade amplitude.

Proportion of regressive saccades

The proportion of regressive saccades was calculated by dividing the number of regressive saccades per sentence by the total number of saccades (both forward and regressive) per sentence. As shown in the left panel of Figure 4E, the proportion of regressive saccades remained relatively robust to a change in background luminance, at least for the luminance level range (1.3–265 cd/m^2) used in the current study ($p = 0.42$). On the other hand, the proportion of regressive saccades increased exponentially ($p < 0.001$) as the blur level became more severe than $\sigma = 4.26$ (Figure 4E, middle panel). The proportion of regressive saccades increased by 29% when text blur increased from no blur to the most severe blur level ($\sigma = 5$; $p < 0.001$). The proportion of regressive saccades increased substantially ($p < 0.001$) when text contrast was less than 2.66% (Figure 4E, right panel).

Microsaccade: Its rate, amplitude, and distribution

As shown in the left panel of Figure 4F, the microsaccade rate remained relatively constant across different background luminance levels ($p = 0.39$). On the other hand, microsaccade rate increased exponentially as the blur level became more severe than $\sigma = 4$ (Figure 4F, middle panel). Overall, the microsaccade rate increased by 56% when text blur increased from no blur to the most severe blur level ($\sigma = 5$; $p < 0.01$). In the right panel of Figure 4F, the microsaccade rate increased substantially when text contrast was less than 3.11%. The microsaccade rate increased by 114% from 100% to the lowest contrast level of 2.6% (0.19 ± 0.03 #/sec vs. 0.40 ± 0.06 #/sec;

Parameter	Background luminance (cd/m^2)	Text blur (σ)	Text contrast (%)
Saccade amplitude			
Mean value under normal viewing*: 4.42 ± 0.05 (°)			
ANOVA	$F(3, 39) = 37.49$ ($p < 0.001$)	$F(4, 52) = 965.57$ ($p < 0.001$)	$F(4, 52) = 1201.21$ ($p < 0.001$)
Critical intensity	N/A	4.34	4.20
Saccade velocity			
Mean value under normal viewing*: 116.87 ± 3.38 (°/s)			
ANOVA	$F(3, 39) = 11.69$ ($p < 0.001$)	$F(4, 52) = 52.66$ ($p < 0.001$)	$F(4, 52) = 75.27$ ($p < 0.001$)
Critical intensity	N/A	4.73	3.58
Fixation duration			
Mean value under normal viewing*: 205.31 ± 1.85 (ms)			
ANOVA	$F(3, 39) = 134.31$ ($p < 0.001$)	$F(4, 52) = 1723.78$ ($p < 0.001$)	$F(4, 52) = 1786.63$ ($p < 0.001$)
Critical intensity	N/A	3.95	3.67
Number of fixations per line			
Mean value under normal viewing*: 24.88 ± 0.84			
ANOVA	$F(3, 39) = 4.82$ ($p < 0.05$)	$F(4, 52) = 46.65$ ($p < 0.001$)	$F(4, 52) = 26.35$ ($p < 0.001$)
Critical intensity	N/A	3.75	3.95
Proportion of regressive saccade			
Mean value under normal viewing*: 25.64 ± 1.66 (%)			
ANOVA	$F(3, 39) = 0.96$ ($p = 0.42$)	$F(4, 52) = 22.82$ ($p < 0.001$)	$F(4, 52) = 6.31$ ($p < 0.001$)
Critical intensity	N/A	4.26	2.66
Microsaccade rate			
Mean value under normal viewing*: 0.19 ± 0.03 (#/sec)			
ANOVA	$F(3, 39) = 1.02$ ($p = 0.39$)	$F(4, 52) = 6.01$ ($p < 0.01$)	$F(4, 52) = 19.74$ ($p < 0.01$)
Critical intensity	N/A	4.00	3.11
Microsaccade amplitude			
Mean value under normal viewing*: 0.73 ± 0.02 (°)			
ANOVA	$F(3, 39) = 1.42$ ($p = 0.25$)	$F(4, 52) = 0.97$ ($p = 0.43$)	$F(4, 52) = 0.63$ ($p = 0.64$)
Critical intensity	N/A	N/A	N/A
Line-changing duration			
Mean value under normal viewing*: 293.87 ± 23.44 (ms)			
ANOVA	$F(3, 39) = 0.40$ ($p = 0.75$)	$F(4, 52) = 8.54$ ($p < 0.001$)	$F(4, 52) = 33.32$ ($p < 0.001$)
Critical intensity	N/A	4.00	9.30

Table 1. ANOVA statistics, estimated critical intensity levels, and mean values for the key eye movement parameters. *Note:* N/A = Not applicable. *Normal viewing here refers to the baseline condition in which text passages were presented with a background luminance of 80 cd/m^2, a contrast of 100%, and no blur.

$p < 0.01$). We, however, found that microsaccade amplitude remained relatively stable across different viewing conditions with the average amplitude of 0.73° ± 0.02° under normal viewing conditions (Figure 4G).

Figures 5A and 5B show the distribution of microsaccades in comparison with all saccades (including microsaccades). In each row, from left to right, the four two-dimensional polar maps plot the probability density maps under low luminance (1.3 cd/m^2), severe blur ($\sigma = 5$), very low contrast (2.6%), and normal conditions for all subjects. The radii of the polar plots and the numbers in red indicate retinal eccentricity in degree units. Note that, because here we are interested in the relative probability densities rather than the absolute values, we normalized the probability densities for each plot. From these plots, one can see

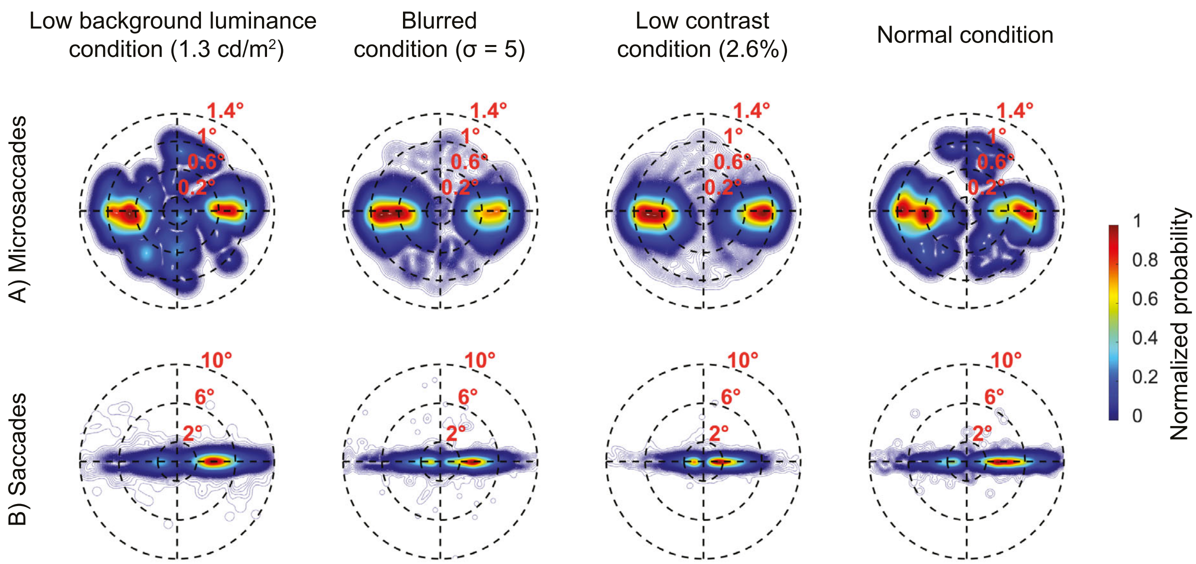

Figure 5. Distribution of microsaccades and saccades. Probability density maps of (A) microsaccades and (B) saccades are shown in two-dimensional polar maps representing the visual field. Each density map shows the data from all subjects. Note that saccade maps are based on the data from both regular saccades and microsaccades. Density maps are compared for low background luminance (1.3 cd/m^2), severe blur ($\sigma = 5$ pixels), very low contrast (2.6%), and normal conditions. The color bar indicates the colors corresponding to different probability density values. The radii of the polar plots and the numbers in red indicate retinal eccentricity in degree units.

that, under all conditions, saccades and microsaccades both exhibited a horizontal bias. However, compared with saccades exhibiting a predominant horizontal bias skewed rightward, microsaccades appeared to have a more balanced distribution horizontally with a noticeable number of vertical movements and a slight leftward bias. This pattern of the results was consistent with previous findings (Bowers & Poletti, 2017). Taken together, we found that, unlike microsaccade rate, the direction and amplitude of microsaccades remained relatively constant across different viewing conditions.

Line-changing duration

We found that the time to return to the start of the next line of text (i.e., return-sweeps) is also affected by degraded viewing conditions. We considered such time to change a line as the time between the beginning of a line-changing saccade and the start point of the first fixation of the next line (see the Data analysis of eye movement measurements for more details). Also note that the horizontal end-to-end distance of each sentence spanned approximately 38 dva. In Figure 4H, for background luminance, there was no significant effect of background luminance ($p = 0.75$) on line-changing duration. As shown in the middle panel of Figure 4H, the time to change a line of text increased by 28% when text blur increased from no blur to the most severe blur level ($\sigma = 5$; $p < 0.001$). This increase became more pronounced when the blur level was worse than $\sigma = 4$. It is apparent that people have more difficulty with changing a line even with a moderate decrease in text contrast. As shown in the right panel of Figure 4H, the time to change a line increased rapidly as text contrast decreased to 9.30%. Overall, the time to change a line increased by 121% from 100% to the lowest contrast level of 2.6% (294 ± 23.44 ms vs. 650 ± 64.47 ms; $p < 0.001$).

Understanding the relative contribution of each eye movement factor to reading speed

In order to determine which eye movement factors could best predict reading speed, we performed a multiple regression analysis. In this model, saccade amplitude, saccade velocity, fixation duration, proportion of regressive saccades, microsaccade rate, microsaccade amplitude, and line-changing duration were entered as independent variables, with reading speed being the dependent variable. Specifically, we performed stepwise linear regression (Hocking, 1976) to determine the degree to which these independent variables contribute to prediction of reading speed. Independent variables were added to the model based on the degree to which they explained the dependent variable (all $p < 0.001$). Our results showed that fixation duration alone accounted for 78% of variance in reading speed ($R^2 = 0.78$; $p < 0.001$). Adding the proportion of

	β_0	β_1	β_2	β_3	ε
Coefficient value	295.70	−0.67	−2.76	31.54	402.33
p value	<0.001	<0.001	<0.001	<0.001	N/A

Table 2. Regression coefficient values. N/A = Not applicable.

regressive saccades and saccade amplitude to the model sequentially resulted in R^2 values of 0.83 and 0.90 ($p < 0.001$), indicating that these three variables together explained 90% of the variance in reading speed. The contributions of the other independent variables were negligible. The equation of the full regression model is given below:

$$\text{Reading speed} = \beta_0 + \beta_1 X_{\text{Fixation duration}} + \beta_2 X_{\text{Regressive saccades}} + \beta_3 X_{\text{Saccade amplitude}} + \varepsilon \quad (3)$$

where β_0 is the y-intercept, β_i is the regression coefficient for each predictor, X_i is an independent variable, and ε is the error term of the model. Table 2 summarizes the values of the regression coefficients.

Figure 6A plots reading speed as a function of fixation duration (left panel), proportion of regressive saccades (middle panel), and saccade amplitude (right panel). Each point shows the average data from one subject under one viewing condition and one intensity level. Dark gray, green, and light gray points are the data from the background luminance, text blur, and text contrast conditions, respectively. Solid black lines indicate the best-fitted regression lines to the data. As expected, there was a significant correlation between reading speed and fixation duration ($r = -0.88$; $p < 0.001$), proportion of regressive saccades ($r = -0.51$; $p < 0.001$), and saccade amplitude ($r = 0.76$; $p < 0.001$).

Discussion

In the current study, we investigated how deprived visual sensory information alters the patterns of eye movements during reading. Although many studies have examined the effects of degraded viewing conditions on reading speed (Bowers, Meek, & Stewart, 2001; Burton et al., 2012; Kwon & Legge, 2012; Legge, Pelli et al., 1985; Legge et al., 1987) or eye movements during reading (Bullimore & Bailey, 1995; Calabrése et al., 2014; Cerulli et al., 2014; McMahon et al., 1991; McMahon et al., 1993; Seiple, Szlyk, McMahon, Pulido, & Fishman, 2005; Timberlake et al., 1986), relatively little is known about the effects of degraded viewing conditions on eye movement patterns and their relationship with reading speed. Thus, the current study aimed to understand how changes in the most commonly occurring viewing conditions (i.e., background luminance, text blur, and text contrast) influence key eye movement features, such as saccades, microsaccades, regressive saccades, fixations, and return-sweeps, in normally sighted young adults. By employing simulated degraded viewing conditions in healthy young adults with normal vision, we hoped to pinpoint the effects of visual sensory degradation on eye movements during reading while controlling for any potential confounders such as deficits in oculomotor control that are often present in older or clinical populations.

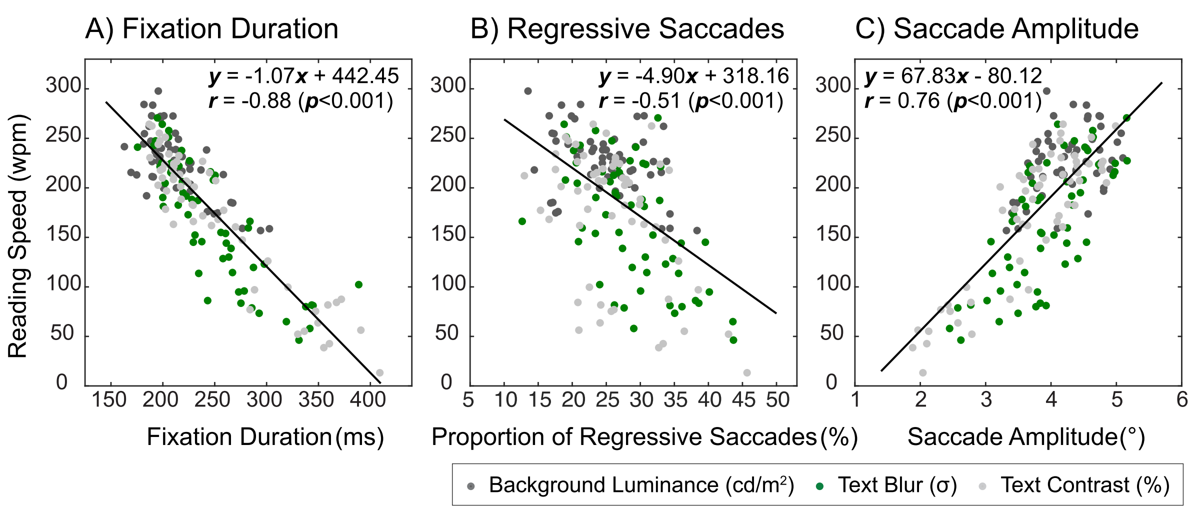

Figure 6. Correlations of reading speed with (A) fixation duration, (B) proportion regressive saccades, and (C) saccade amplitude. Each point represents the average data from one subject under one condition and one level. The data from background luminance, text blur, and text contrast conditions are denoted by dark gray, green, and light gray, respectively. The solid black line in each panel indicates the best-fitted regression lines to the data.

Reading difficulties under degraded viewing conditions

As expected from previous findings (Chung, 2020; Kwon & Legge, 2012; Legge et al., 1987; Rubin & Turano, 1994), we confirmed that reading speed significantly decreased under degraded viewing conditions (Figure 2A), particularly for increasing text blur and decreasing text contrast. Our results showed that the critical text blur level, where a person's reading speed starts to decrease sharply, was $\sigma =$ 3.66, equivalent to 1.34 cycles/letter. This value was comparable to what was reported in a study done by Kwon and Legge (2012). They showed that the average critical text blur level ranged from 1.27 to 1.34 cycles/letter across different types of reading speed measures (e.g., Flashcard, RSVP) and low-pass filters (e.g., Butterworth or Gaussian filters). Furthermore, the dependency of reading speed on text contrast was also reported in previous studies (Brown, 1981; Burton et al., 2012; Legge et al., 1987). For example, Legge et al. (1987) found that reading speed was tolerant when reading with character size between 0.2° to 1° under text contrast between 10% and 100%. However, reading speed declined rapidly when text contrast was below 10%, and reading speed decreased by 86% for the text contrast of 2%. These findings were consistent with our results showing that reading speed decreased substantially for text contrast below 4.18% and reading speed decreased by 71% when text contrast dropped down to 2.6%. Regarding the dependency of reading speed on luminance, previous studies have shown that reading performance, such as reading acuity, improved for patients with AMD with increased text luminance (Bowers et al., 2001; Ro-Mase, Ishiko, & Yoshida, 2020). For example, Bowers et al. (2001) found that, for the majority of AMD patients (i.e., 70%), their maximum reading speed improved by a factor of 1.4 when luminance was increased from 50 to 5000 lux (from 3.13 to 312.5 cd/m^2). On the other hand, our results showed that reading speed remained relatively constant when presented with a background luminance ranging from 1.3 cd/m^2 (i.e., mesopic condition) to 265 cd/m^2 (i.e., photopic condition). Although speculative, this may be due to our participant demographics including all young healthy participants whose vision might not be as vulnerable as elderly patient populations to changes in the range of luminance tested in the current study. For example, Fosse and Valberg (2004) reported that, although age-similar controls showed relatively stable reading speed for the range of luminance between 4 and 1200 cd/m^2, reading speed in AMD patients significantly improved up to 80 cd/m^2. Another possibility could be that our letter size (0.68°), equivalent to 0.9 logMAR, might have been too large for luminance to cause any effect on reading speed. Indeed, Seiple et al. (2018) showed that, although reading speed decreased with decreasing luminance in both normal control and AMD patients, such change became minimal when the letter size exceeded 0.5 logMAR. Thus, this apparent discrepancy calls for a future study.

Altered eye movements during reading under degraded viewing conditions

Next, we went on to see if there are any systematic changes in the patterns of eye movements under various levels of degraded viewing conditions. We first looked into whether the viewing condition alone can set the patterns of gaze positions apart from each other. To this end, we quantified pairwise dissimilarities between temporal sequences of horizontal fixation positions under different levels of each viewing condition using the DTW algorithm. As shown in Figure 3C, we observed a great deal of dissimilarity between the pattern of fixation positions under highly degraded viewing conditions (e.g., severely blurred or low contrast text), suggesting that subjects adopted noticeably different eye movement strategies when reading under such viewing conditions. This finding further suggests the potential to decode a person's viewing condition directly from the patterns of eye movements.

Consistent with the results of the dissimilarity analysis, there were significant differences in key eye movement features under different levels of each viewing condition. Our results showed that saccade amplitude and velocity decreased with increasing text blur and decreasing text contrast, whereas fixation duration, number of fixations, the proportion of regressive saccades, microsaccade rate, and duration of return-sweeps significantly increased. For the range of background luminance tested (1.3–265 cd/m^2), we found that saccade amplitude and fixation duration both showed small but significant changes from the highest to the lowest luminance (i.e., a decrease of 4% and an increase of 9%, respectively). Such findings were in line with previous findings indicating that, when reading under low ambient illumination (dim room), low screen luminance would lead to longer fixation duration and higher fixation rate compared to high luminance (Benedetto, Carbone, Drai-Zerbib, Pedrotti, & Baccino, 2014).

We also observed that saccade amplitude decreased by 23% (i.e., from 4.42° to 3.43°) from no blur to the most severe text blur and by 41% (i.e., 4.42° to 2.62°) from 100% text contrast to the lowest contrast (i.e., 2.6%). Saccade amplitude is known to be proportional to the size of the visual span—that is, the number of letters that can be recognized reliably in one fixation (Calabrése et al., 2014; Legge et al., 1997). Thus, when we converted our observed saccade amplitude into the visual span, we found that the size of the visual span for the baseline condition (i.e., normal viewing) was seven letters. However, the visual span shrank down to five letters for the most severe blur level and down to 3.9 letters for the lowest contrast level. These findings are consistent with the previous work by Kwon and Legge (2012) showing that the size of the visual span decreases significantly when text becomes severely blurred. The shrinkage of visual span is likely to lead to less information being transmitted within one fixation, thereby requiring smaller and more frequent saccades as observed in clinical populations (Calabrése et al., 2014; Cheong et al., 2008; Kwon et al., 2017).

We found that fixation duration increased by 42% (i.e., from 205 ms to 291 ms) from no blur to the most severe blur and by 68% (i.e., from 205 ms to 345 ms) from 100% contrast to the lowest contrast. This increase in fixation duration under severe blur or low contrast is likely to reflect an increase in information processing time. Indeed, previous studies have shown that a much longer viewing time is required for observers to recognize blurred letters or faces, supporting the suggestion that longer processing time is necessary for recognition when the bottom-up sensory information is severely degraded and/or unreliable (Cheong et al., 2007; Kwon, Liu, & Chien, 2016; Olds & Engel, 1998).

We also observed that the proportion of regressive saccades increased by 29% (i.e., from 26% to 33%) from no blur to severe blur and by 19% (i.e., from 26% to 31%) from 100% contrast to the lowest contrast. The increased regressive saccades are expected under degraded viewing conditions, as regressive saccades often occur when people experience comprehension failure and/or when they make incorrect saccades (Rayner, 1998). It has been reported that patients with amblyopia and macular degeneration exhibit more frequent regressive saccades during reading (Bullimore & Bailey, 1995; Kanonidou, Proudlock, & Gottlob, 2010; McMahon et al., 1991; Rubin & Feely, 2009).

Our microsaccade rate observed during reading under the normal viewing condition (0.19 ± 0.03 #/sec) was consistent with what was reported in previous work (0.30 ± 0.24 #/sec). Bowers and Poletti (2017) showed that microsaccade rate during reading is lower than what is observed during sustained fixation (0.30 ± 0.24 #/sec for reading vs. 1.2 ± 0.8 #/sec for fixation; $p < 0.01$). Interestingly, we found that the microsaccade rate increased by 56% (i.e., from 0.19 #/sec to 0.29 #/sec) from no blur to severe blur and by 114% (i.e., from 0.19 #/sec to 0.40 #/sec) from 100% contrast to the lowest contrast. The increase in microsaccade rate might have allowed for better visual exploration and calibration under degraded viewing conditions. For example, it has been shown that the images with low spatial frequencies (blur) can be recognized better when images are jittered (Watson et al., 2012). As demonstrated in previous studies (Bowers & Poletti, 2017; Rucci et al., 2007), the increased microsaccades under degraded viewing conditions might have enhanced text visibility.

Finally, we found that the time to change a line of text increased by 28% (i.e., from 294 ms to 374 ms) from no blur to severe blur and by 121% (i.e., from 294 ms to 650 ms) from 100% contrast to the lowest contrast. The time to change the line for the normal viewing condition (294 ± 23 ms) was substantially longer than the time taken for one saccade. This is because one line in our text spanned over 38 dva, which likely required more than one saccade to complete the successful transition into a new line (Parker et al., 2019). Particularly, it is noteworthy that the impact of low text contrast on the line-changing time is more pronounced compared to the blur condition. This substantial increase in line-changing time during reading appears to further slow down reading speed in people with low vision. Difficulties with changing a line of text during reading have indeed been reported in patients with visual impairment (Bowers & Reid, 1997; Mathews et al., 2015; Passamonti et al., 2009). Furthermore, our multiple regression analysis showed that three key eye movement features (saccade amplitude, fixation duration, and regressive saccades) together accounted for 90% of the variance in reading speed. The significant role of forward saccade amplitude and fixation duration in reading speed was also reported in a study on AMD patients (Calabrése et al., 2014).

We acknowledge the limitations of the current study. For example, reading speed and eye movements were studied using one reading method (i.e., oral reading with simple and standardized text on the computer screen). In addition, although a relatively wide range of text degradation was considered in terms of blur, contrast, and luminance, our findings pertain to the range of text degradation adopted in the current study. It should also be noted that the image-based low-vision simulation employed in the current study may not represent the exact perceptual deficits, such as optical defocus or reduced contrast sensitivity, that patients with low vision would experience in real life. Also, we adopted a text passage consisting of random sentences formatted into one paragraph. Such design was chosen to prevent participants from relying heavily on the sentential context from semantically related sentences. We believe that this design served our purpose to minimize the effect of potential higher level cognitive and linguistic factors, thus allowing us to focus on the visual aspect of reading. However, it would be worthy to examine the interactions between higher level contextual information and degraded viewing conditions on the patterns of eye movements during reading in a future study. Therefore, it still remains to be seen how much of our findings can be generalized to various real-world readings (e.g., silent newspaper, signage, long passage reading), thus calling for future studies. Although the scope of our current study is limited to the three major visual dimensions of spatial resolution, contrast, and background luminance, we also acknowledge the importance of investigating other types of visual impairments such as visual field loss and abnormal binocular interactions commonly occurring in AMD, glaucoma, or amblyopia. Finally, employing young normally sighted participants for the current study helped us minimize age or pathology related confounders, but it would be worth looking into the effect of background luminance on eye movements during reading in elderly populations with or without retinal diseases in future studies. Despite the aforementioned limitations, our study is a necessary step toward better characterizing the quantitative relationships between reading eye movements and impaired viewing conditions such as reduced spatial resolution or contrast sensitivity while controlling for potential confounders such as ocular motor abnormalities or age-related vision loss.

In summary, our findings showed that the patterns of key eye movements are significantly altered under degraded viewing conditions, particularly for severe text blur or reduced text contrast. With increasing text blur and decreasing text contrast, we observed a significant decrease in saccade amplitude and velocity, as well as a significant increase in fixation duration, number of fixations, proportion of regressive saccades, microsaccade rate, and duration of return-sweeps. We also found that, among all of these eye movements, saccade amplitude, fixation duration, and proportion of regressive saccades were the most significant contributors to reading speed, together accounting for 90% of variance in reading speed.

Our results together indicate that, when presented with degraded viewing conditions, the patterns of eye movements during reading are altered accordingly. These findings suggest that the seemingly deviated eye movements observed in individuals with visual impairments may be in part resulting from active and optimal information acquisition strategies operated when visual sensory inputs become substantially deprived.

Keywords: eye movements, reading, blur, contrast, background luminance, microsaccades, saccades, fixations, return-sweeps, eye tracking

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