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The effects of simulated hemianopia on eye movements during text reading

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ABSTRACT

Vision loss is a common, devastating complication of cerebral strokes. In some cases the complete contra-lesional visual field is affected, leading to problems with routine tasks and, notably, the ability to read. Although visual information crucial for reading is imaged on the foveal region, readers often extract useful parafoveal information from the next word or two in the text. In hemianopic field loss, parafoveal processing is compromised, shrinking the visual span and resulting in slower reading speeds. Recent approaches to rehabilitation using perceptual training have been able to demonstrate some recovery of useful visual capacity. As gains in visual sensitivity were most pronounced at the border of the scotoma, it may be possible to use training to restore some of the lost visual span for reading. As restitutive approaches often involve prolonged training sessions, it would be beneficial to know how much recovery is required to restore reading ability. To address this issue, we employed a gaze-contingent paradigm using a low-pass filter to blur one side of the text, functionally simulating a visual field defect. The degree of blurring acts as a proxy for visual function recovery that could arise from restitutive strategies, and allows us to evaluate and quantify the degree of visual recovery required to support normal reading fluency in patients. Because reading ability changes with age, we recruited a group of younger participants, and another with older participants who are closer in age to risk groups for ischaemic strokes. Our results show that changes in patterns of eye movement observed in hemianopic loss can be captured using this simulated reading environment. This opens up the possibility of using participants with normal visual function to help identify the most promising strategies for ameliorating hemianopic loss, before translation to patient groups.

1. Introduction

A complete (or partial) loss of vision in the contralateral hemifield in both eyes – a homonymous visual field defect (HVFD) – is a common complication reported after stroke (Goodwin, 2014; Smith, 1962; Zhang et al., 2006). This type of vision loss has a dramatic impact on quality of life because it functionally impairs performance on many routine visual tasks (Papageorgiou et al., 2007). One of the most prominent visual problems is a significant loss in reading ability (*hemianopic dyslexia*, Zihl, 1995). Reading is a highly complex task with multiple levels of representation, ranging from low level orthographic, phonological and morphological processing to higher level lexical, semantic and syntactic representation (Schotter et al., 2012). Ultimately, however, it relies on the brain receiving the appropriate visual information through precise oculomotor control mechanisms that first bring the area of highest acuity (fovea) to fixate on a region of text and then serially reposition it as reading progresses (Rayner, 1998).

A key component that is disrupted by stroke is the perceptual span – defined as the window of useful vision available during fixation (McConkie & Rayner, 1975). It is asymmetrical in shape, typically extending 3–4 letter spaces left of fixation and 14–15 letter spaces to the right of fixation (McConkie & Rayner, 1976; Rayner, 1998; Rayner et al., 2010; Schotter et al., 2012). Although visual information crucial for reading is imaged on the foveal region (up to 2° from fixation), readers often extract useful parafoveal (2–5°) information from the next word or two in the sequence. This preview benefit has been shown to inform 'when' and 'where' the eyes should move, having a facilitatory effect on word processing during periods of stable fixation and regulating future eye movements to new areas of text (Drieghe et al., 2005; Kennedy, 2000; Morris et al., 1990; Paterson & Jordan, 2010; Pollatsek & Rayner, 1982; Rayner et al., 1982; Schotter et al., 2012; Williams et al., 2006). In hemianopic field loss, parafoveal processing is compromised, resulting in slower reading speeds (Schuett et al., 2008a; Schuett, 2009; Trauzettel-Klosinski & Brendler, 1998).

The side on which the HVFD occurs differentially impacts eye movements during reading. This has been linked to the idea that the

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vision loss affects different regions of the perceptual span in the right and left visual fields (Schuett et al., 2008a; Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995). For instance, individuals with left HVFD find it difficult to re-fixate to the new line of a paragraph during a return sweep, often making multiple saccades when attempting to find the start of the new line. In contrast, right HVFD affects eye movements in left-to-right reading more, leading to a larger number of smaller forward (rightwards) and regressive saccades (leftwards) and more fixations which are usually longer in duration; this ultimately results in much slower reading speeds.

In terms of rehabilitation for HVFD, compensatory strategies often involve repetitive training to develop adaptive oculomotor strategies to improve eye movement control during reading (for more in depth review see Schuett (2009)). These approaches have been shown to produce clinically stable and relevant improvements (Mannan et al., 2010; Nelles et al., 2001; Schuett et al., 2008b; Spitzyna et al., 2007) and as a result are favoured over other treatment options.

Although the effectiveness of restitutive or restorative strategies for treating HVFD has been hotly debated (Horton, 2005; Liu et al., 2019; Pollock et al., 2011; Reinhard et al., 2005), a growing body of work has explored the use of anatomical and functional measures of brain activity to assess the rehabilitation potential of the blind field by trying to identify areas of potential residual function (Beh et al., 2022; Das & Huxlin, 2010; Huxlin et al., 2009; Papanikolaou et al., 2014). The general idea of these more recent approaches is to identify residual cortical visual function in part of the visual field that has been deemed ‘blind’ by some clinical measure (e.g. perimetry), but may in fact still support some form of visual function (Beh et al., 2022; Papanikolaou et al., 2014). Such regions may then be amenable to perceptual training to attempt to recover some useful visual capacity. Recent work in post-stroke patients with chronic HVFD has shown that intensive training, using orientation and global direction tasks in perimetrically blind regions of the field, results in perilesional recovery of luminance detection thresholds (Barbot et al., 2021). Interestingly, in most patients tested, the gains in visual sensitivity are most pronounced at the border of the scotoma, suggesting that it may be possible to use training to restore some of the lost visual span for reading.

However, it is not clear if the extent of change in visual sensitivity in the ‘blind’ field would lead to any functional improvements in reading fluency. It is important to be able to evaluate the likelihood of improvements in reading ability before subjecting patients to particular rehabilitative strategies. This is especially important, considering the time commitment and intensity of the training usually required. There has been a large body of work that uses a gaze contingent paradigm to simulate HVFD in healthy controls to investigate how the hemianopic field loss affects daily visual functions such as visual search (Nowakowska et al., 2016, 2019; Simpson et al., 2011; Tant et al., 2002) and reading ability (Bao et al., 2015; Schuett et al., 2009b, 2009a; Sheldon et al., 2012).

A convention for simulating hemianopia is to blank out the hemianopic field (leaving only the color of the background). This removes any stimulus components that appear in the hemianopic field with respect to the current eye position. As we are trying to simulate circumstances with some degree of residual visual function, a stimulus manipulation that can parametrically alter the available visual information is required. A study by Nowaskowska et al., (2016) used a condition in which images were spatially filtered (low-pass, cut-off: 2 cycles per degree) to simulate residual visual capacity. This mirrors the approach we have taken in our study.

Here, we explore how simulated HVFD and recovery of visual sensitivity in the blind field might impact reading performance. To address this question, we employed a gaze contingent paradigm and manipulated the degree of spatial blurring in one hemifield to simulate hemianopic loss (and potential recovery). We then measured how these manipulations changed oculomotor behaviour during text reading. At high levels of blurring, visual information fundamental to text recognition and comprehension is no longer available (Kwon & Legge, 2012). We argue that this can be used to functionally simulate the effects of vision loss in each hemifield. By manipulating the degree of blurring, we systematically control access to spatial information in one hemifield and measure how this changes both the pattern of eye movements and reading speed. This parameter (degree of spatial filtering) acts as proxy for visual function recovery that could arise from restitutive strategies, and allows us to evaluate and quantify the degree of visual recovery required to support normal reading fluency in patients. This is an important first-step in being able to predict what levels of recovery in spatial vision might be needed to improve reading performance.

Because reading ability changes with age (for a detailed summary see Laubrock et al., (2006)) and the effects of spatially blurring text may differentially impact eye movement characteristics in younger and older subjects, we recruited two groups of observers – one with younger participants, another with older participants. The second group was chosen to be closer in age to the risk group for ischaemic strokes (Public Health England, 2018). Our results show that changes in patterns of eye movement and most notably reading performance observed in HVFD can be captured (and recreated) using this simulated reading environment. This opens up the possibility of using participants with normal visual function to help identify key parameters required to achieve the desired outcome measures, before translation to patient groups.

2. Materials and methods

2.1. Participants

We recruited 15 young adult participants (mean age is 20.9 yrs) and 15 participants for an older control group (mean age is 54.7 yrs). For the control group, we recruited between ages 40 and 70. This age bracket was informed by stroke incidence rates, indicating that 97% of estimated stroke incidence occurs above the age of 40 (Public Health England, 2018). Data from 1 participant in the young adult group was excluded, as it was incomplete. The young adults were recruited from the student population at the University of Nottingham, while the older group were recruited through local communities in Nottingham. The inclusion criteria for participation in the study were: 1) normal or corrected to normal vision; 2) no history of a stroke. 3) formally educated in the English language. Experiments were approved by the School of Psychology Ethics committee and all participants provided informed, written consent.

3. Reading stimuli

The text stimuli used in our reading task were based on paragraphs from the *International Reading Speed Test* (iRest, Trauzettel-Klosinski et al., 2012). The paragraphs are standardised in terms of length, difficulty, and linguistic complexity and have previously been used to assess reading performance in individuals with low vision (Kortuem et al., 2021; Mathews et al., 2017; Ramulu et al., 2013).

The text stimuli were displayed on a gamma-correct CRT monitor (resolution: 1024x768, screen width = 40.6 cm, refresh rate: 85 Hz) using custom software written in Python/PsychoPy (Peirce, 2007). Text was displayed using the Arial font and the individual letters were sized such that the vertical size of the letter ‘x’ (x-height) was at 0.4 logMAR (0.21°). Initial pilot testing showed this to be a comfortable text size for reading paragraphs. The viewing distance was set to 114 cm and text was rendered in white on a grey background (root mean square contrast: 0.2, Weber contrast: 1.0).

In total, we used 10 different paragraphs, one of which was randomly selected for an initial practice trial and excluded from the final analysis. The total number of words in the paragraphs ranged from 136 to 166 (mean number, 154). The average number of words in a single line was 9.7 and the vertical spacing between lines was 0.25°. All but one of the text stimuli contained 16 lines in one paragraph (one having 15 lines).

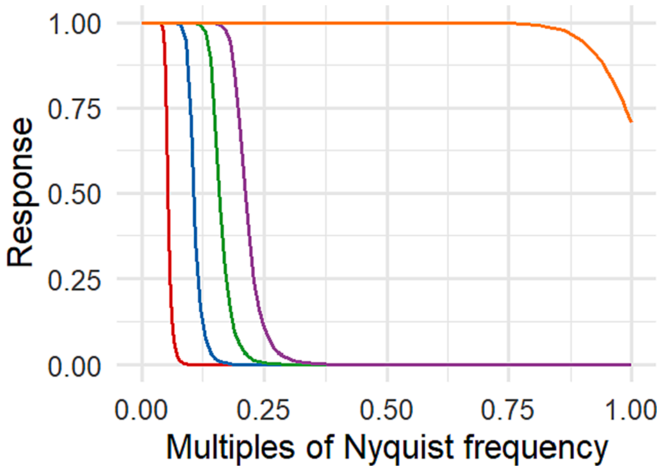


Fig. 1. Response function of the 10th order Butterworth filter at various frequencies (1, 0.2, 0.15, 0.1, and 0.05). These cutoff frequencies translate to 5.5, 1.1, 0.825, 0.55, 0.275 cycles per letter at 0.22° letter size.

To avoid order effects, the sequence of text displayed was randomised across individuals. Participants were instructed to read the text silently and to signal when they had finished reading by pressing the ‘space‘ key.

4. Eye tracking and gaze contingent viewing

Eye positions and movements were recorded monocularly (right eye) with an Eyelink 1000 infrared eye tracker (SR Research Ltd., Ottawa) at a sample rate of 500 Hz. A 9-point fixation grid was used to calibrate the eye tracker at the start of every trial. Calibration was repeated if fixation to any point had an error of 1° or higher. The eye level of participants was set to the centre of the screen with their chin firmly resting on a chin rest.

To simulate visual field loss in one of the hemifields (left or right), the text image was blurred towards the left or right side of the screen with respect to the current eye position. To achieve this gaze-contingent display, we combined the original (unblurred) text image with a blurred version which was revealed with a moving “aperture” through alpha-blending. This aperture was constructed to reveal a particular side of the screen with respect to fixation, as seen in Fig. 2b. The screen position of the aperture was only updated every 100 ms to reduce the effect of high temporal frequency noise in the eye position measurements.

To blur the text stimuli used in this display, we applied a 10th order Butterworth low-pass filter (Kwon & Legge, 2012). The filter is described by the following function:

$$f = \frac{1}{\left(1 + \left(\frac{r}{c}\right)^{2n}\right)}$$

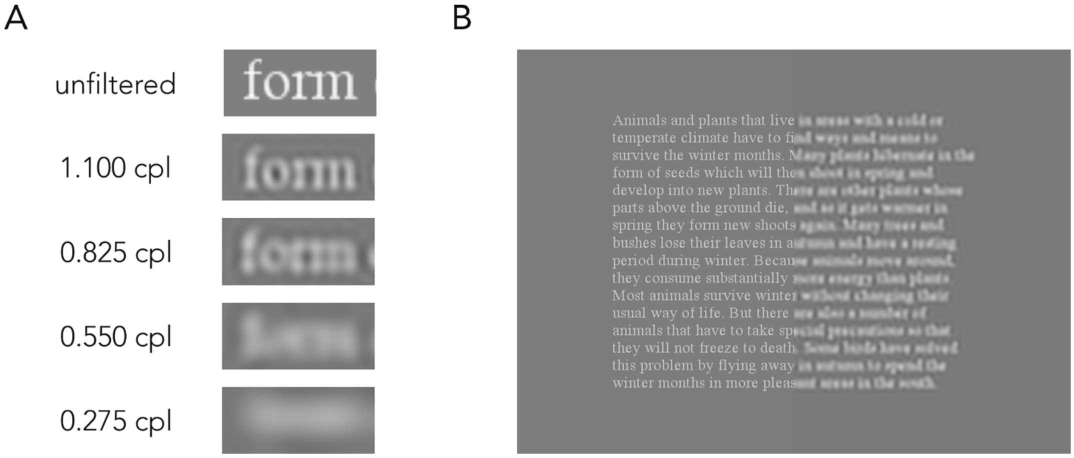
where r is the spatial frequency, c is the low-pass cutoff spatial frequency, and n is the filter order.

The cutoff frequency of the filter was set at different multiples of the Nyquist frequencies: 1, 0.2, 0.15, 0.1, and 0.05 (see Fig. 1). The lower the cutoff frequency of the pass band, the more blurred the text appeared. Using the pixel width of the letter ‘x’ as a baseline (11 pixels / 0.22° wide, in our display), the cutoff frequencies can also be translated into units of *cycles per letter*. The values corresponded to 5.5 (unfiltered), 1.1, 0.825, 0.55, 0.275 cycles per letter (cpl). Examples of the blurred stimuli are shown in Fig. 2a. The selection of this particular set of blurring values was based on pilot measurements to establish a suitable range of reading performances, while keeping the number of testing conditions manageable.

4.1. Procedure

The day before the experiment, participants were told that the task involved reading and were asked to wear any corrective lenses they would normally use when reading at home. Participants were briefed to wear prescription contact lenses if available to correct for any myopia. However, across both groups of participants, only 5 wore corrective spectacle lenses and the other 25 did not require any vision correction. All participants had normal, or corrected to normal, distance visual acuity (Bailey-Lovie chart) and could comfortably read the text at the presented size (equivalent to 0.4 logMAR). For those wearing glasses, we did not find any detrimental effects on eye tracking.

At the start of the experiment, participants were instructed to position themselves comfortably using the chin and forehead rest. The eye tracker was then adjusted to provide an optimum view of the right eye. Participants were instructed to silently read through the entire paragraph at their normal reading pace. They were also told to move on to the next word if they were struggling to read any particular words. When they finished reading, they terminated the trial by pressing the ‘space‘ key. As participants reported the simulated vision loss to be quite unusual when first applied, we made sure to include several training blocks using the sample text (at the highest blurring level) until they were comfortable finishing the paragraph.



Animals and plants that live in areas with a cold or
temperate climate have to find ways and means to
survive the winter months. Many plants hibernate in the
form of seeds which will then shoot in spring and
develop into new plants. There are other plants whose
parts above the ground die, and as it gets warmer in
spring they form new shoots again. Many trees and
bushes lose their leaves in autumn and have a resting
period during winter. Because animals move around,
they consume substantially more energy than plants.
Most animals survive winter without changing their
usual way of life. But there are also a number of
animals that have to take special precautions so that
they will not freeze to death. Some birds have solved
this problem by flying away in autumn to spend the
winter months in more pleasant areas in the south.

Fig. 2. Example of gaze contingent blurring on the text stimuli. (A) Example of the word ‘form’ at different blurring levels using the cutoff frequency thresholds indicated (cpl, cycles per letter). (B) Visualisation of the partially blurred paragraph of text (here, blurred on the right side with respect to the current eye position, approximately in the centre of the display).

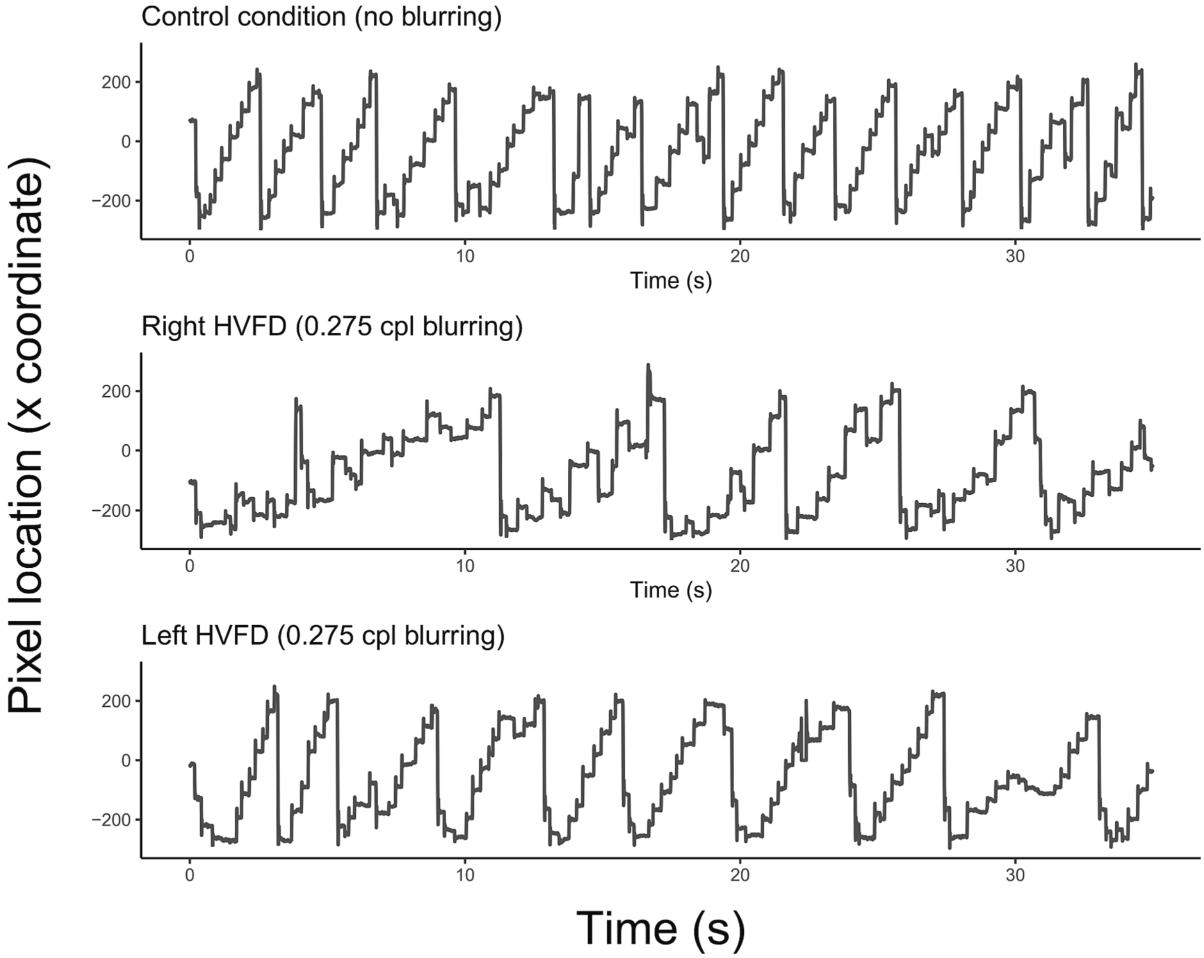


Fig. 3. Samples of raw eye traces along the x coordinate domain (pixels) in an experiment trial for control (top), right simulated HVFD – 0.275 cpl blurring (middle) and left simulated HVFD – 0.275 cpl blurring (bottom). Note that the time scale is specific to each condition to show the overall pattern of the trial. Lateral eye movement patterns resemble a staircase-like pattern when reading a paragraph, where each step is a fixation and a forward saccade would move the staircase upwards and a regressive saccade would move the staircase downwards. The staircase would then 'reset' when the line is complete and the reader is moving on to the next line. In some conditions there is a jitter before resetting as readers struggle to fixate on the first word of the next line.

5. Results

5.1. Eye movement traces

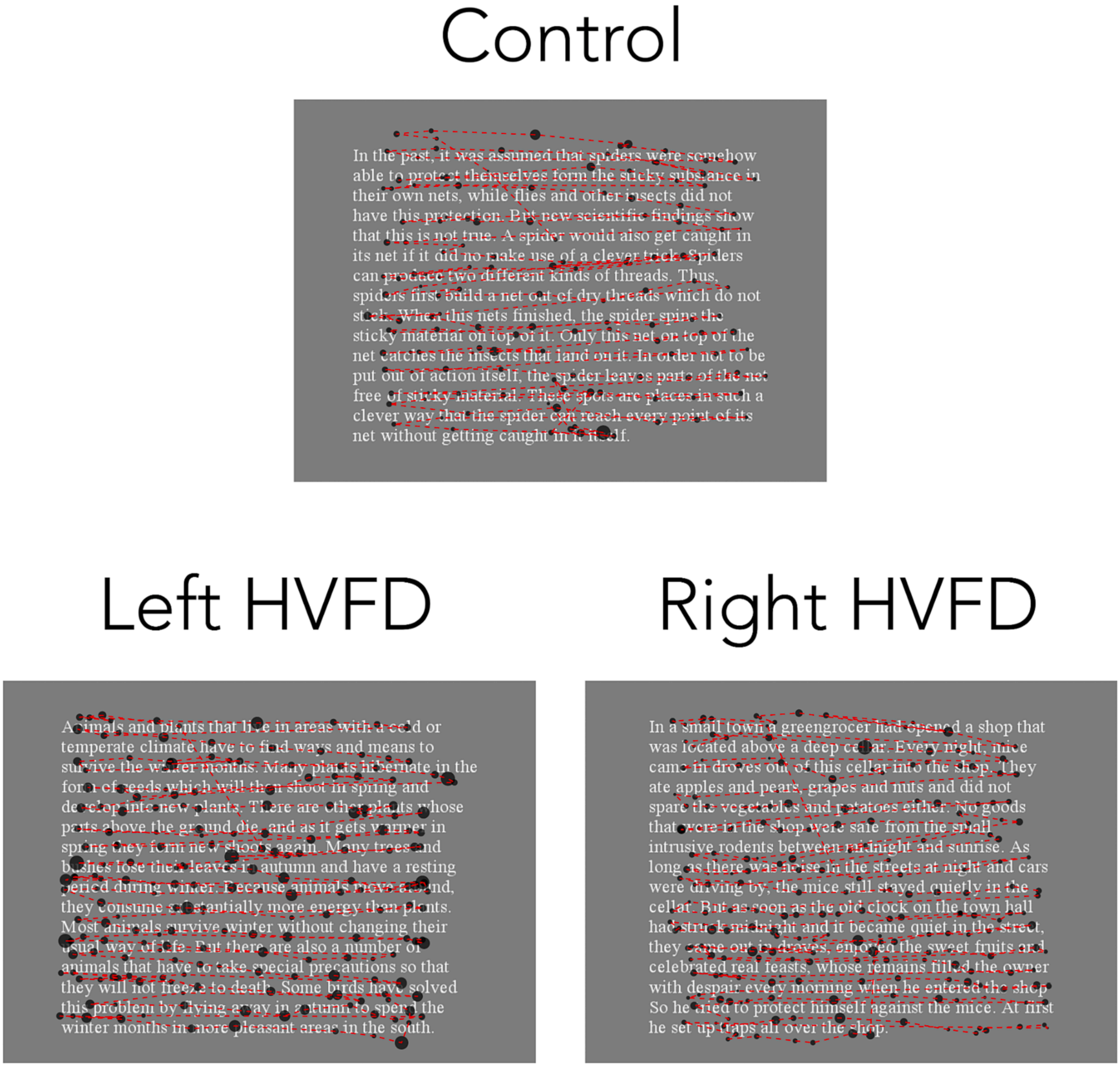
To illustrate the patterns of eye movement we observed across the different conditions, samples of raw eye traces are shown in Fig. 3. The plots show the horizontal component of the eye movements (x-coordinate) as a function of time for the beginning of example trials. The three panels show traces for a control trial (no blurring, top), one for simulated right homonymous visual field defect (HVFD, midde), and a third for the corresponding left HVFD condition (bottom). Pixel coordinates [0, 0] refer to the centre of the screen, positive x-coordinates refer to the right side of the screen (negative values to the left); positive y coordinates refer to the top part of the screen (negative values to the bottom).

Normal reading behaviour, as seen for the control condition, results in a typical, repeating staircase pattern of the x-coordinates: the participant fixates on a word for a short period, then promptly moves to the next, until the end of the line is reached. The search for the start of the new line is indicated by the large displacement, eye position changes from ~ −200 to +200 in pixel coordinates along the x-axis. Note that the duration of a single staircase pattern can be used to quantify the time taken for a participant to read one line of text. The data from a simulated *left* HVFD condition looks similar to the control condition, however, the corresponding simulated *right* HVFD produces a much more variable pattern of eye movements. It is also apparent that a higher number of saccades are being made as the reader progresses through the text. As a result, the participants took longer to complete each line. In the example shown here, the time to complete a line in the slowest condition is about four times that of the control condition.

6. Classifying eye events

Some algorithms for classifying fixations and saccades only use a single velocity threshold. Because we were actively impairing normal reading behaviour and we had a large age range in our participants, we anticipated larger variance in the eye movement patterns and higher levels of variability across participants and trial conditions. To accommodate this, we employed an adaptive velocity-based algorithm (Nyström & Holmqvist, 2010). Eye movements were filtered using the Savitzky Golay Filter (Savitzky & Golay, 1964) to derive velocity and acceleration estimates and velocity thresholds were adapted to the varying noise levels across trials and participants. This data-driven approach has been shown to be less sensitive to the effects of noise and better suited than other commonly used algorithms for detecting both fixations and saccades (Nyström & Holmqvist, 2010). We also performed a visual quality check of the eye traces for each trial to ensure data quality. Samples of these traces, visualised on to the text stimuli, can be seen in Fig. 4.

The following variables were derived from this pre-processed data



In the past, it was assumed that spiders were somehow able to protect themselves form the sticky substance in their own nets, while flies and other insects did not have this protection. But new scientific findings show that this is not true. A spider would also get caught in its net if it did no make use of a clever trick. Spiders can produce two different kinds of threads. Thus, spiders first build a net out of dry threads which do not stick. When this nets finished, the spider spins the sticky material on top of it. Only this net on top of the net catches the insects that land on it. In order not to be put out of action itself, the spider leaves parts of the net free of sticky material. These spots are places in such a clever way that the spider can reach every point of its net without getting caught in it itself.

Animals and plants that live in areas with a cold or temperate climate have to find ways and means to survive the winter months. Many plants hibernate in the form of seeds which will then shoot in spring and develop into new plants. There are other plants whose parts above the ground die, and as it gets warmer in spring they form new shoots again. Many trees and bushes lose their leaves in autumn and have a resting period during winter. Because animals move around, they consume substantially more energy than plants. Most animals survive winter without changing their usual way of life. But there are also a number of animals that have to take special precautions so that they will not freeze to death. Some birds have solved this problem by flying away in autumn to spend the winter months in more pleasant areas in the south.

In a small town a greengrocer had opened a shop that was located above a deep cellar. Every night, mice came in droves out of this cellar into the shop. They ate apples and pears, grapes and nuts and did not spare the vegetables and potatoes either. No goods that were in the shop were safe from the small intrusive rodents between midnight and sunrise. As long as there was noise in the streets at night and cars were driving by, the mice still stayed quietly in the cellar. But as soon as the old clock on the town hall had struck midnight and it became quiet in the street, they came out in droves, enjoyed the sweet fruits and celebrated real feasts, whose remains filled the owner with despair every morning when he entered the shop So he tried to protect himself against the mice. At first he set up traps all over the shop.

Fig. 4. Sample of eye traces for the control - unfiltered condition (top), simulated left HVFD condition – 0.275 cpl blurring (bottom left) and simulated right HVFD condition – 0.275 cpl blurring (bottom right). The black circles are plotted on fixation positions and larger sizes indicate longer fixation durations, the red dashes between the black circles are the saccade direction. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and used in further analysis:

- *number of fixation per line,*
- *number of forward saccades per line,*
- *number of regressive saccades per line* (saccades that were in the opposite direction to the reading direction),
- *number of saccades made during return sweep* (any additional saccades from the final fixation to the new line),
- *average median fixation duration* and
- *average median forward saccade amplitude*.

To quantify the number of oculometric events per line, we developed a new method that can reliably mark the first and last fixation made on a line. While the raw eye trace and the labelled trace for fixations itself provides some indication of where refixation to the new line occurs, simple manual segmentation of the events is prone to error. Furthermore, using the y-coordinate to determine a line change is unreliable in noisier datasets. Here, we used *dynamic time warping* – an algorithm which non-linearly matches two signals in time (Sakoe & Chiba, 1978). Although reading speed varies across people (depending on reading skill levels and strategies), the overall pattern of eye movements (large eye movement shifts from right to left to refixate to the start of a new line) will inevitably be similar given the fixed number of lines in a paragraph, as seen in Fig. 3. Therefore, we could construct a prediction of the expected eye movement patterns, particularly for the x-coordinates. By warping this signal to match each individual trial, we could efficiently identify the *start* and the *end* of the line across different reading speeds. First, we created a simplified 'design' matrix of the expected eye movement pattern over time and warped it onto the original dataset to find the first and last fixations for each line in the paragraphs. This process was then automated across each trial, adapting to different patterns of eye movements for each of the blurring conditions. The choice of using *dynamic time warping* to identify key time points in the data is motivated by the pursuit of reducing observer bias and achieving more reproducible methods using robust algorithmic methods as seen in eye event detection (Nyström & Holmqvist, 2010; Stuart et al., 2019). It is important to note, however, that we used information only from the raw data for the relevant oculometric measures, e.g., the number of forward saccades, regressive saccades, and so on.

A sample of the dynamic time warping process can be seen in Fig. 5.

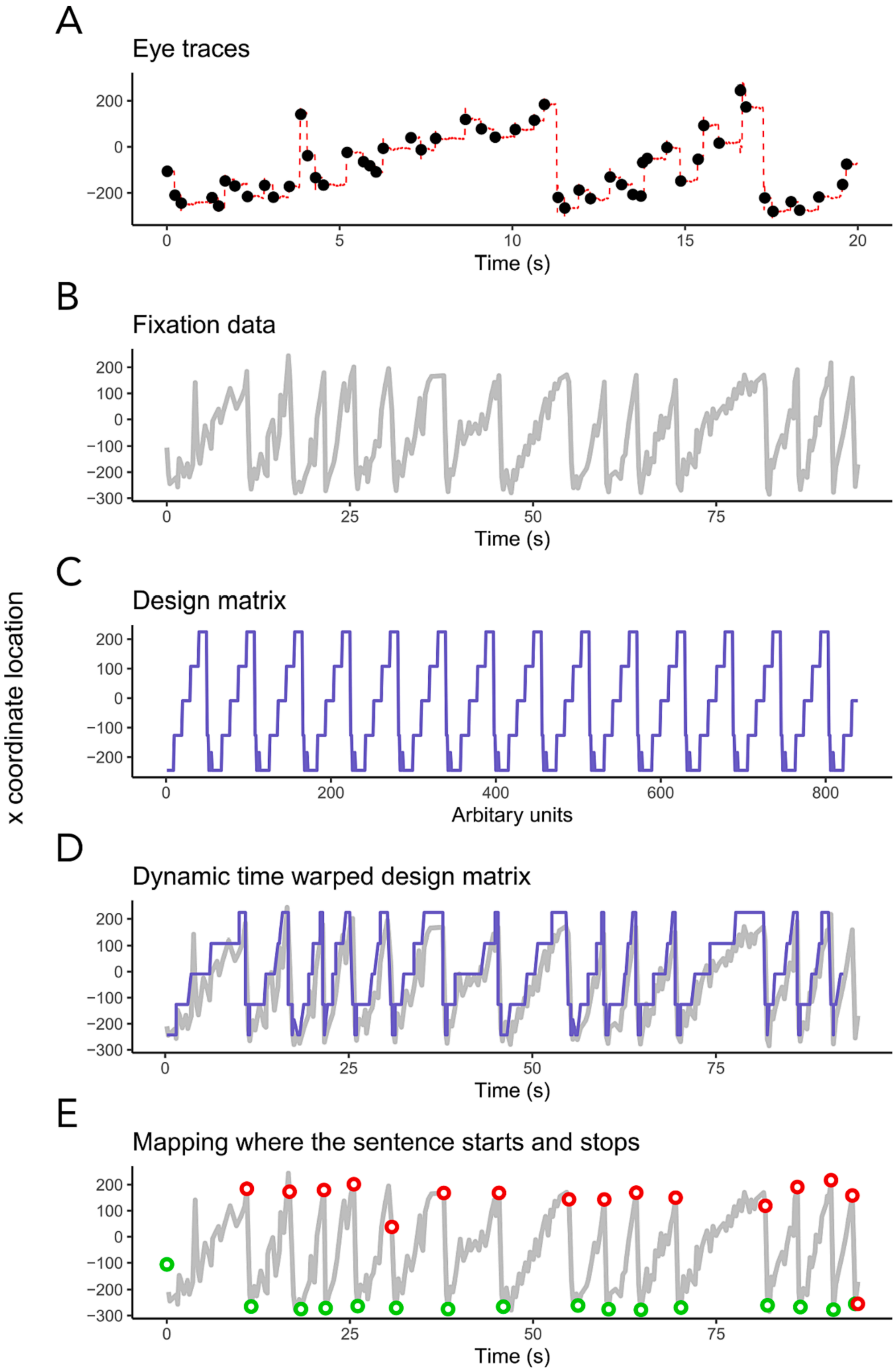


Fig. 5. Using dynamic time warping to mark first and final fixation on a line. Fig. 5a, A segment of the raw eye traces from a single trial from the right HVFD condition with cutoff frequency of 0.275 cpl (red dashes) with fixation points (black circles) plotted over them. Fig. 5b, fixation points plotted as a line plot across the entire trial. Fig. 5c, The design matrix of the expected eye movement patterns. Fig. 5d, The time warped design matrix plotted along the original fixation line plot. Fig. 5e, mapping of the first (green circle) and final (red circle) fixation points for each line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

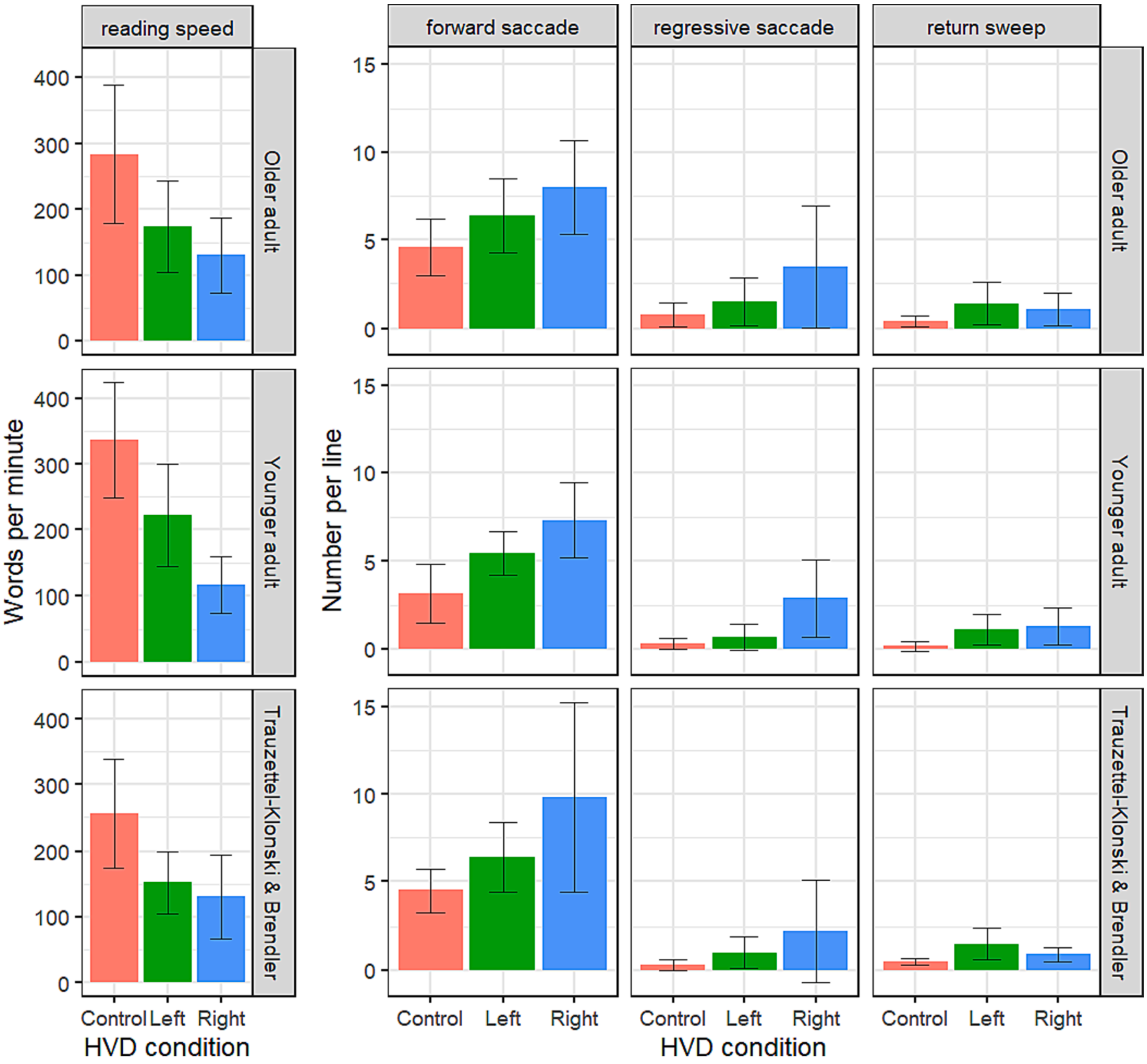


Fig. 6. Oculometric measures across simulated HVFD sides for both old and young adult groups, along with corresponding measurements from patients with HVFD replotted from Trauzettel-Klosinski and Brendler (1998) for comparison. To represent both left and right HVFD conditions, the trials of the highest simulated blurring condition (0.25 cpl) across both left and right were used. Number of eye event measures were calculated by the number of occurrences within a single line from the paragraph. (A) *Number of forward saccades per line (left), number of regressive saccades per line (middle) and number of saccades during return sweep (right)* are measured by the mean number observed across a line, with standard deviation as error bars. (B) Reading speed is measured using mean words per minute. Error bars, ± 1 standard deviation.

In Fig. 5a, we have classified fixation points (*black circle*) using the adaptive velocity-based algorithm and plotted it over the eye traces (*red dashes*). Plotting only the fixation starting points over the entire trial provides a simplified view of the data (Fig. 5b), which clearly shows some segments of the eye movement recordings with an increased number of saccades. The 'design' matrix for the expected eye movement pattern for our text stimuli can be seen in Fig. 5c: increasing values for the screen x-coordinates from left to right in a number ($n = 5$) steps in a regular staircase pattern, ending with a reset to the left which includes a short jitter to account for any additional saccade to find the new line. To reduce the number of local mismatches, we chose 5 equally spaced steps to reflect the average number of saccades per line in a typical trial.

The result of the dynamic time warping (the design matrix matched onto the original time series) captured the timing of the overall pattern of eye movements accurately as seen in Fig. 5d. In turn, this allowed us to accurately estimate the start (*green circle*) and end (*red circle*) of a line as seen in Fig. 5e. Using these markers, we can calculate (per line) the the number and amplitude of (1) forward saccades (2) regressive saccades, (3) saccades made during the return sweep. For further analysis, the median value of fixation durations and forward saccade amplitudes were estimated across each line and averaged for each subject.

7. Simulated loss in the right visual field affects reading more

To establish that our visual field manipulations produced the effects that we intended, we compared the control condition (normal reading behaviour) with the simulated hemianopia (left and right side) at the highest blurring level (cutoff frequency, 0.275 cpl). We plotted oculometric measures (*number of forward saccades per line, number of regressive saccades per line, number of saccades made during return sweep, and reading speed*) for both, simulated right and left HVFD and for both age groups (Fig. 6). Measurements from Trauzettel-Klosinski and Brendler (1998), who recorded similar oculometric measures in patients with pathological HVFD were also included for visual comparison.

Simulated blurring on both left and right hemifields led to significant changes in the oculometric measures compared to the control condition.

Table 1
Oculometric measures for control, right HVFD and left HVFD. The mean (and standard deviation) were derived after collapsing across age groups. Statistical comparisons were made across all conditions using pairwise *t*-test (using Bonferroni correction), ns $p > .05$, * $p < .05$, ** $p < .01$ *** $p < .001$.

	Control (normal reading)	Right HVFD	Left HVFD	Control - Right HVFD	Control - Left HVFD	Right HVFD - Left HVFD
Reading speed (words per minute)	309 (98.7)	124 (50.2)	197 (76)	***	***	***
Number of forward saccade per line	3.91 (1.77)	7.68 (2.39)	5.95 (1.79)	***	***	***
Number of regressive saccade per line	0.55 (0.59)	3.19 (2,88)	1.11 (1.17)	***	*	**
Number of saccades made during return sweep	0.28 (0.32)	1.18 (0.96)	1.27 (1.05)	***	***	n.s.
Median forward saccade amplitude (°)	2.23 (0.92)	1.32 (0.39)	1.70 (0.36)	***	**	***
Median fixation duration (ms)	339(217)	330 (55.5)	263 (33.7)	Main effect n. s.	Main effect n. s.	Main effect n.s.

Overall, *reading speeds* were slower and there was a higher *number of forward* as well as *regressive saccades per line.* In line with this, we found smaller *forward saccade amplitudes* and an increase in the number of *saccades made during the return sweep.* To assess statistical significance of these effects, we performed the following analysis. The *median forward saccade amplitude* and *median fixation duration* were calculated for each line and then aggregated for the analysis (see Appendix A). A multiple 3 × 2 mixed design repeated measures analysis of variance (ANOVA) was used to investigate differences between simulated HVFD location (within subjects factor) and age group (between subjects factor) across our oculometric measures. To correct for multiple comparisons, we adjusted the critical p-value to 0.05/6, using a Bonferroni correction.

For all measures, apart from *median fixation duration*, there was a significant main effect of the HVFD side (smallest $F(1.42, 38.37) = 11.30$, $p < .001$, with *Greenhouse-Geisser sphericity correction).* The simulated right HVFD condition led to smaller and more *forward saccades*, more *regressive saccades* along with slower *reading speeds* compared to the simulated left HVFD condition and control. The simulated left HVFD condition resulted in higher *number of saccades during the return sweep* compared to control, but no statistical difference with the simulated right HVFD condition was found for this measure. Although no significant differences were observed for *median fixation duration* at the aggregated level, we performed a more detailed analysis looking for patterns across lines (see Appendix B). Table 1 shows average values and results of pairwise comparisons. Note that across all measures with a significant main effect of HVFD, we found significant differences over all combinations of pairwise comparisons (control-right, control-left and right-left) with the exception of the *number of saccades made during return sweep*. Lastly, we did not observe any significant difference between age groups nor any other interaction effects.

8. The effect of spatial filtering on hemianopic reading

To test the relationship between spatial blurring (cut-off spatial frequency), simulated HVFD side and participant age, we used multiple mixed design repeated measures ANOVAs. The data were *reading speed, number of forward saccade per line, number of regressive saccade per line, number of saccades made during return sweep, average median forward saccade amplitude* and *median fixation duration* and we corrected for multiple comparisons using a Bonferroni corrected p-value of $0.05/6 = 0.0083$. The main effect of cut-off frequency was observed across all measures except *median fixation duration*, (smallest *$F(2.49, 67.26) = 16.23$, $p <. 001$), indicating that as the level of blurring increased (cut-off frequency decreased), we observed slower reading speed, a higher number of forward and regressive saccades, a higher number of saccades made during the return sweep and shorter average median forward saccade amplitudes. However, we did not find any influence of blurring on *average median fixation duration* (further explored in a later analysis).

The side (left or right) of the simulated vision loss had a significant (main) effect across all measures except for *number of saccades made during return sweep* and *median fixation duration* (smallest $F(1, 27) = 13.43$, $p = .001$) indicating that these two measures showed similar performance metrics in both left and right simulated HVFD. The age of participants had no significant effect on any measure, indicating that younger and older participants performed similarly across conditions.

We found an interaction between cut-off frequency and HVFD side for *reading speed, number of forward saccade per line, number of regressive saccade per line*, (smallest *$F(2.39, 64.45) = 9.26$, $p < .001$), but no significant interaction effect for *number of saccades made during return sweep, median fixation duration* and *median saccade amplitude*. To provide a clear, parametric description of the relationship between cut-off frequency and HVFD side, we use a piecewise regression model to estimate the critical cut-off frequency and slope for each of these measures, similar to Kwon and Legge (2012). The descriptive model is captured by the following formula, starting either with a ascending or descending segment followed by a horizontal line:

$$f(x) = \begin{cases} a{\cdot}x + b - a{\cdot}c \text{ if } x < c \\ b \text{ if } x \geq c \end{cases}$$

where Y is the oculometric measure, X is the spatial frequency cutoff, a represents the slope of the ascending/descending line (depending on the sign of a), b represents the plateau of the oculometric measure in normal reading behaviour and c represents the critical cut-off frequency. We used an iterative, non-linear least-squares method (*optim()* in R version 4.1.0, R Core Team, 2021) to estimate the parameters (*a, b, c*) as well as standard errors (which are derived from the diagonal of the Hessian matrix).

Fig. 7 shows *reading speed, number of forward saccade per line* and *number of regressive saccade per line* plotted against different cut-off frequencies for each simulated HVFD side. The fitted model provided us with two key components that describe the relationship, the *critical cut-off frequency* and *slope of ascent/descent.* The *critical cut-off frequency* represents the estimated minimum frequency required to achieve normal reading behaviour, while the *slope* indicates the impact on reading performance with each additional filter step (beyond the critical cut-off point). These two measures allow us to quantify the interaction between HVFD side and age group, as cut-off frequency is reduced.

When looking at reading speed, we found that the *right* simulated HVFD had a lower critical cut-off (1.15 cpl, SE = 0.01) compared to *left* simulated HVFD (1.22 cpl, SE = 0.01). Beyond the critical frequency, reading speed was more affected in the right compared to the left simulated HVFD. A loss of 0.1 cpl in the right visual field resulted in a decrease of 22.0 wpm, SE = 0.12, compared to a decrease of 11.9 wpm, SE = 0.11 for left HVFD. Although the loss of visual information had a more severe impact in the *right* simulated HVFD condition, it only occurred at a lower cut-off frequency.

Although we did not find a main effect of age using the ANOVA, we

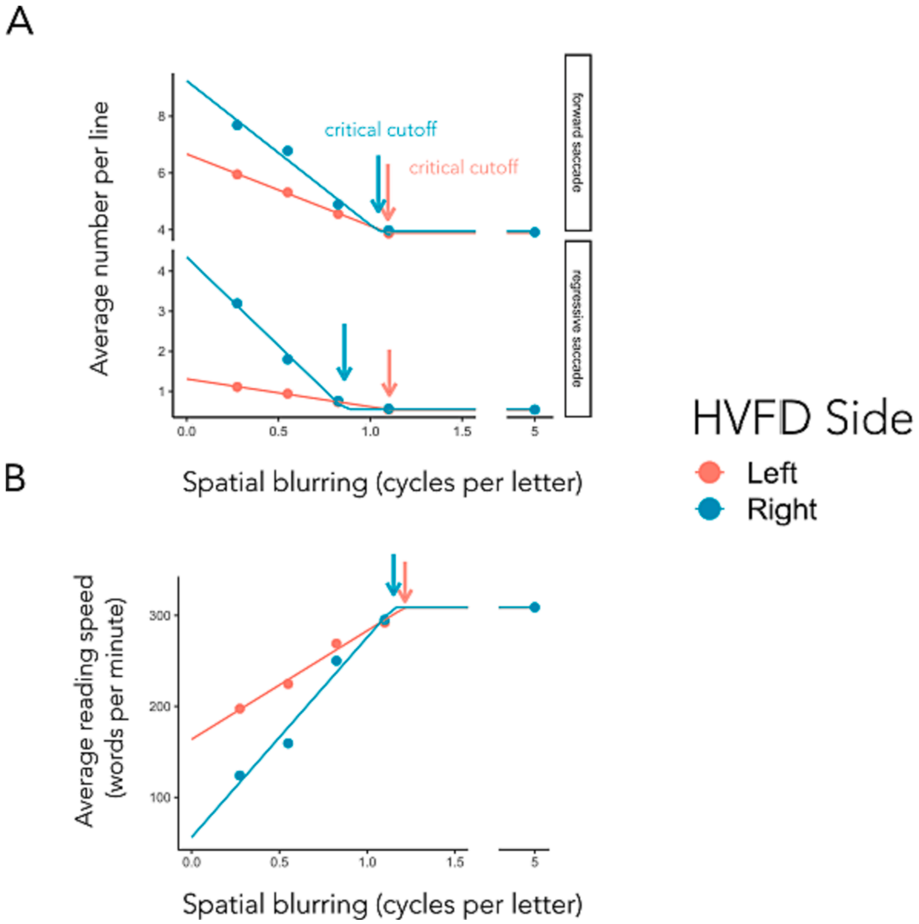


Fig. 7. Oculometric measures from simulated hemianopic reading at different levels of spatial blurring. The lower the cutoff frequency (cycles per letter) of the low-pass spatial filter, the larger the blur. Data is split between HVFD sides (colors). A piecewise linear model was fitted ti the group average data (collapsed across age groups), allowing the critical cutoff frequencies and slopes to be calculated. (A) Average number of forward and regressive saccades made per line. (B) Average reading speed - words per minute.

performed an analysis of reading speed as a function of cut-off frequency across both HVFD side and age groups, as we were interested in the detailed pattern of reading performance change which was not captured by an ANOVA. Fig. 8 shows that although the *older* age group shared similar critical cut-off frequencies in both *left* and *right* simulated HVFD (left: 1.23 cpl, SE = 0.01, right: 1.25, SE = 0.01 cpl), the *younger* age group showed that the *left* simulated HVFD had a higher critical cutoff (1.20 cpl, SE = 0.01) compared to *right* HVFD (1.06 cpl, SE = 0.01). This suggests that the difference in critical cut-off frequency found in our initial analysis could be largely driven by the *young* adult group.

Similarly, beyond the critical frequency, reading speed was more affected in the right compared to the left simulated HVFD for both age groups. However, the *younger* age group was more impacted by the loss of visual information: a loss of 0.1 cpl in the right-side results in a decrease in 29.1 wpm, SE = 0.02 (left HVFD: 12.5 wpm, SE = 0.02). In contrast, a loss of 0.1 cpl in the right visual field produces a more modest reduction in reading speed in the older age group (right HVFD: 16.5 wpm, SE = 0.01, left HVFD: 11.4 wpm, SE = 0.01).

Among all eye event measures, reading speed remains the most clinically relevant measure for any reading impairment. Although other eye movement measures may provide interesting insights into how they might play into overall reading performance, the experimental design of our study did not allow us to separate out those effects.

9. Discussion

We found similar eye movement patterns with simulated HVFD in healthy participants as those in patients with HVFD. Our first set of results, which compared the highest blurring level to simulate HVFD in each hemifield against the control (unfiltered) condition, showed directly comparable results to studies in patients with HVFD (Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995). This is an important first step in establishing that the stimulus manipulation we introduced mimics task-critical properties of HVFD.

Simulated right HVFD severely impairs reading speed (slowing reading speed to around half the rate of the control condition) with simulated left HVFD having a lesser impact. In our simulated left HVFD, both the younger and older group required more saccades to find the start of the new line during the return sweep. Surprisingly, an increase in the number of return sweep saccades was also observed in simulated right HVFD. Although this feature of impairment is more typically associated with left HVFD, our findings are again consistent with hemianopia patient data (Trauzettel-Klosinski & Brendler, 1998), where the increase in number of saccades during the return sweep was similar across both left and right HVFD (see Fig. 6, right column). In our simulated right HVFD conditions, we found higher numbers of smaller forward saccades and regressive saccades along with more fixations of longer duration in both younger and older adult populations (Note that the number of forward and regressive saccades are a proxy measure of number of fixations, as a saccade precedes a fixation).

Having established that our HVFD manipulation produces qualitatively similar effects on eye movement patterns for paragraph reading, we next examined how the degree of spatial filtering influenced reading speed. We estimated the critical filter cut-off frequency - the point where blurring a particular hemifield starts impacting reading speed. Importantly, the *slope* of the function quantifies the decline in reading performance with each filter step. Our findings suggest that the spatial requirements to maintain fluent reading is lower in the right HVFD side compared to the left HVFD side, as reflected in the lower critical cut-off frequency (right HVFD: 1.15 cpl, left HVFD 1.22 cpl).

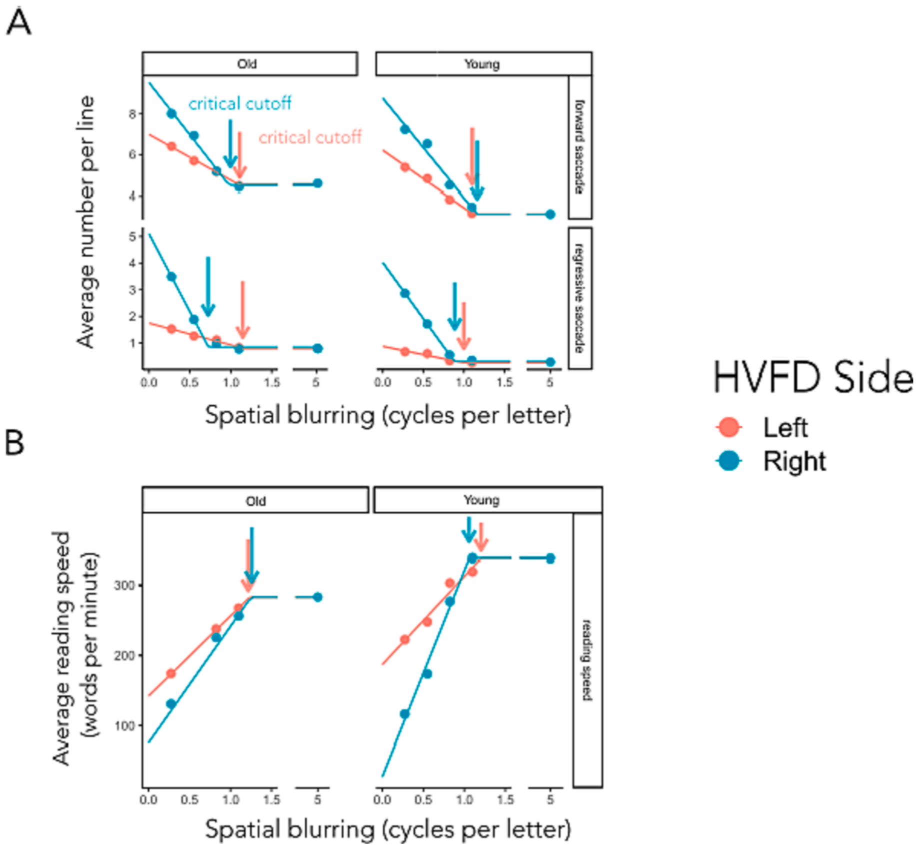


Fig. 8. Oculometric measures from simulated hemianopic reading at different levels of spatial blurring. The lower the cutoff frequency (cycles per letter) of the low-pass spatial filter, the larger the blur. Data is split up by age groups (left, right facets in plots) and HVFD sides (colors). A piecewise linear model was used to fit the the group average data, allowing the critical cutoff frequencies and slopes to be calculated. (A) Average number of forward and regressive saccades made per line. (B) Average reading speed - words per minute.

Beyond the critical cut-off, we observed a steeper decline in reading speed under the simulated right HVFD compared to simulated left HVFD, which is also consistent with patient data (Trauzettel-Klosinski & Brendler, 1998; Zihl, 1995). It seems that there is a resilience to the loss of spatial information in the right hemifield despite the steeper decline in reading speed past the critical cut-off, but why is this the case? In our analysis, it appears that this difference was largely driven by the younger adults, although we did not find any significant age-related differences in the ANOVA. The piecewise regression model provides a more detailed description of the age-related differences across different levels and a transition point -the *critical cut-off frequency*. In our experiments, the critical cut-off frequency for reading speed is approximately 1.20–1.25 cpl (across age groups and HVFD location). For the right simulated HVFD condition, the younger adult group showed a slightly lower critical cut-off of 1.06 cpl. Beyond the critical cut-off, young adults appear to be impacted more by systematic loss of spatial information in the right hemifield. Both age groups show a steeper decline in reading speed under the simulated right HVFD (compared to simulated left HVFD), but this difference is much more prominent in younger adults (29.5 wpm per 0.2 cpl in young adults against 16.5 wpm per 0.2 cpl in older adults). Overall, the difference in critical cut-off frequencies suggests that younger adults are less sensitive to the loss of spatial information in the right hemifield compared to older adults, however this relationship is reversed once we go beyond the critical cut-off.

One explanation for the lower critical cut-off in younger adults could be the decline in sensitivity to medium and high spatial frequencies as a function of increasing age (Ross et al., 1985). The difference between younger and older adults suggests that some higher spatial frequency content in the parafoveal region provides information to maintain reading fluency in younger adults. Previous studies have also shown that older adults are less efficient at using parafoveal information when reading (Rayner et al., 2009; Risse & Kliegl, 2011), possibly due to age-related decline of resilience in modulating fixation durations in response to processing opportunities in the perceptual span. We speculate that a combination of higher sensitivity to a larger range of spatial frequencies *and* more efficient parafoveal processing, is contributing to the lower critical cut-off frequency in younger adults.

Paterson et al., (2013) has shown that younger adults display better comprehension and faster reading speeds, compared to older adults, in conditions where text outside a moving-window contains only medium and high spatial frequencies. In this study they used a gaze-contingent moving-window paradigm, where text outside the moving window was spatially filtered to leave low, medium and high bands of spatial frequencies (2.6–5.2, 5.0–10.0, and 8.3–16.6 cycles per degree (cpd) respectively, with 4 letters subtending 1.2° so one letter subtending ~ 0.3°). They also found that reading performance in older adults was less affected when the filtered text contained only low (2.6–5.2 cpd) or medium spatial frequencies, compared to younger adults. Their findings suggested that younger adults are more attuned to fine scale information when reading (medium–high spatial frequencies) whereas older adults utiltze coarser, contextual based information (low-medium spatial frequencies). Although letter sizes across our study and theirs show a modest difference (0.09°), the critical cut-off frequency of 1.06 cpl in our young adults data approximately translates to 4.88 cpd, which is similar to their medium spatial frequency range (5.0–10.0 cpd). This is analogous to our findings: younger adults showed a sharper decline in reading speed past the critical cut-off in right HVFD, compared to older adults. It should be noted that Paterson et al., used a series of sentences, rather than entire paragraphs. Our findings suggest that attenuation difference across spatial frequency between young and old readers extends to more complex reading tasks, where crowding effects and fatigue are more commonly experienced.

The steeper decline in younger adults beyond the critical cut-off could also be related to the starting performance level of reading: the average reading speed was 337 wpm in young adults compared to 283 wpm in older adults. With maximal blurring, reading speed drops to a similar floor in both age groups. At that point, reading speed is likely determined by a common factor across all subjects. However, because the reading speed in the unblurred condition is much higher in younger subjects, the performance loss appears to be more precipitous. Additionally, it should be noted that the younger adults in this dataset are University students, who are likely to possess a higher reading level than the average population, thereby contributing to the higher average reading speed in the control condition, compared to the older adults.

It is important to note that our filter manipulation is *simulating* a visual field deficit in participants with normal vision. This approach cannot entirely mimic the actual impairments that arise from HVFD, which may not be limited to a loss of spatial vision. As pointed out by Schuett et al. (2008a), while the visual field deficit plays a key role in hemianopic dyslexia, it is not the only cause. In a few cases where occipital white matter, occipitoparietal structures, or the posterior thalamus is spared, individuals are capable of developing efficient and spontaneous oculomotor adaptation to compensate for the deficit (Corbetta & Shulman, 2002; Schuett et al., 2008a; Zihl, 1995, 2010). Some oculomotor adaptations involve switching to ‘safe-but-slow’ saccadic eye movements (Meienberg et al.,1981) while more efficient adaptations involve top-down guided predictive saccade overshoot into the blind field (Zangemeister et al., 1995). These forms of compensation do not occur in the majority of cases and reading impairment persists in many with HVFD (Horton et al., 2021; Zihl, 2010). That said, it is clear that the changes in eye movement patterns we observe are more likely to reflect early stages of visual loss and not compensatory eye movement strategies that subsequently develop over time. It is possible that through chronic exposure to hemianopic blur (a representation of partial visual function), new oculomotor reading behaviour could develop, but this would require a longitudinal design where participants are repeatedly trained to read in the presence of blur. Interestingly, when testing healthy controls samples using a simulated enviorment, adapted oculomotor behaviour is probably the only route to improved performance, since there is effectively no perceptual learning for targets subjected to image blur (Westheimer, 2014).

The methods presented here for measuring the critical cut-off for reading speed have some potentially interesting implications for restitutive strategies in the blind field of stroke survivors (Barbot et al., 2021; Huxlin et al., 2009). Studies that have attempted to restore visual function in the blind field via training, have demonstrated robust sensitivity improvements for specific types of visual information (e.g. luminance and motion detection, coarse orientation discrimination) when spared cortical regions still respond to visual stimuli in the blind field (Barbot et al., 2021; Beh et al., 2022; Papanikolaou et al., 2014). An important next step would be to ask whether recovery of function inside the blind field through restorative strategies (Barbot et al., 2021; Huxlin et al., 2009) has a beneficial, knock-on effect, on text reading. Our data show that beyond the cut-off frequency, small improvements in the representation of stimuli can have a dramatic impact on the pattern of eye movements and reading performance. At present there is insufficient data to guide recovery of reading performance in HVFD.

What level of visual recovery would be required in order to observe any improvement in reading performance? How much improvement is required to regain fluent reading capabilities? This study seeks to act as a starting point to explore the effects of partial visual restoration on reading with hemianopia and other forms of vision loss. By systematically degrading visual information, the point where eye movement patterns change and reading performance is reduced can be measured in healthy volunteers. Strategies to improve reading capability could then be tested in scenarios where vision is artificially degraded. For example, in right HVFD with macular sparing (due to preserved perfusion from the middle cerebral artery), reading performance is often normal (Horton et al., 2021; Leff et al., 2000; Trauzettel-Klosinski & Reinhard, 1998). This suggests a set of experiments with testable predictions: any enhancement of the reading span in the right hemifield in patients with reduced macular sparing is likely to be highly beneficial.

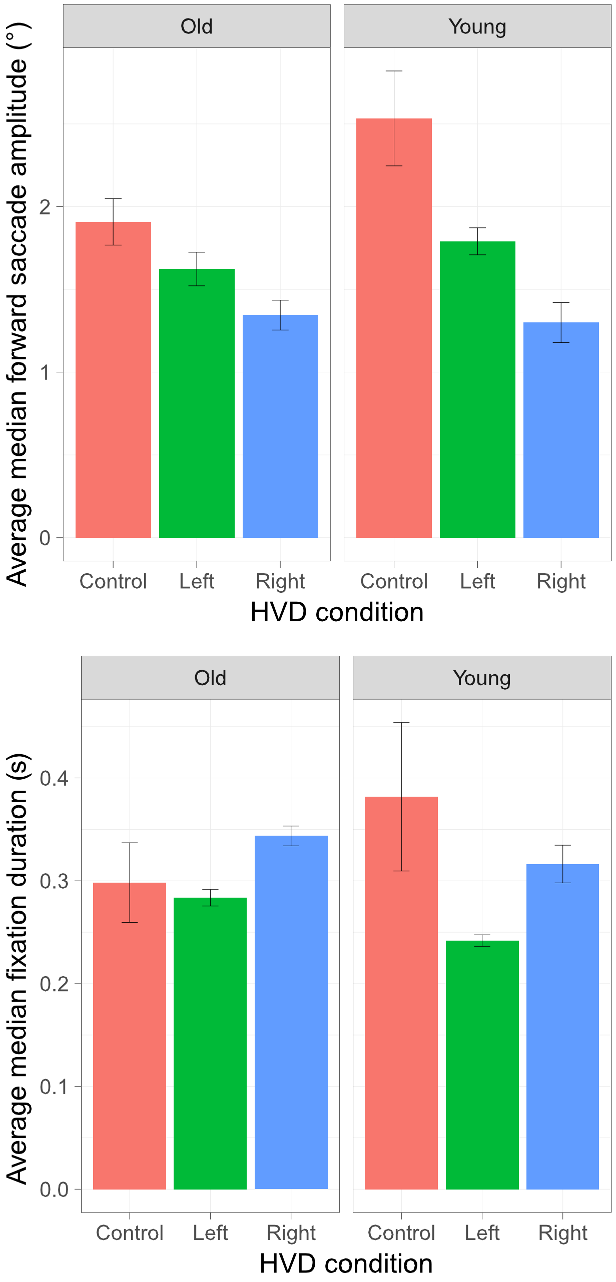
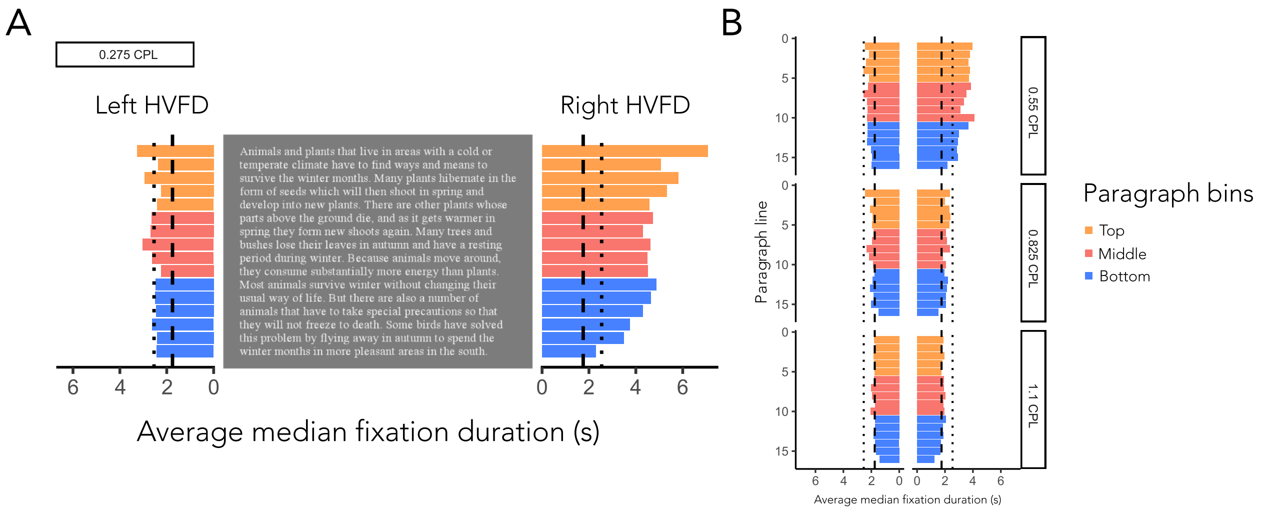


Fig. A1. *Average median forward saccade amplitude* (above) and *average median fixation duration* (below) across simulated HVFD sides for both old and young adult groups. Error bars, ± 1 standard deviation. The median values for each measure across groups were aggregated into the mean.

Previous work that investigated training-related changes under simulated hemianopia have demonstrated oculomotor adaptation and task-dependent transfer effects (reading task: Schuett et al., (2009a); visual search: Nowakowska et al., (2019)). Although eye movement patterns post-training have been reported to be suboptimal to control conditions (Nowakowska et al., 2019), it is possible that we observe differential training-related outcomes depending on the level of artificial degradation (partial visual restoration), given the findings of this study. Perhaps we might observe a lower critical cut-off frequency as a function of training-related changes?

Our findings also suggest a difference in resilience to the loss of spatial information in the right hemifield across younger and older adults. Hence it is important to test these paradigms on age brackets that have shown high stroke incidence rates, so they can be translated into



Animals and plants that live in areas with a cold or temperate climate have to find ways and means to survive the winter months. Many plants hibernate in the form of seeds which will then shoot in spring and develop into new plants. There are other plants whose parts above the ground die, and as it gets warmer in spring they form new shoots again. Many trees and bushes lose their leaves in autumn and have a resting period during winter. Because animals move around, they consume substantially more energy than plants. Most animals survive winter without changing their usual way of life. But there are also a number of animals that have to take special precautions so that they will not freeze to death. Some birds have solved this problem by flying away in autumn to spend the winter months in more pleasant areas in the south.

Fig. B1. Average median fixation duration across paragraph sections for both left and right HVFD at different cutoff frequencies (excluding the control-unfiltered condition). Paragraph sections are binned into 3 groups: *top, middle* and *bottom*; each group consists of 5 lines, the 16th line is excluded in the analysis but shown here in the *bottom* group for visualisation purposes. (A) (0.275 cpl) Measurements from the left and right HVFD conditions are displayed respectively to the left and right of the text stimuli. The dashed line represents the overall average median fixation duration in the control condition (unfiltered – 5.5 cpl) while the dotted line is 1 sd above the mean. (B) (0.55, 0.825, 1.1 cpl) Measurements are displayed in the same format without the text stimuli in between the two HVFD conditions.

patient groups. The general approach in this study could also be extended to different configurations of visual manipulations. Other aspects of the stimuli that are pivotal to reading, such as contrast sensitivity, spatial context or the shape of the visible aperture could be used to mimic different types of visual field defect, such as quadrantanopia or other patterns of visual field loss seen in glaucoma or macular disease.

Public Health England. (2018).

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A

This appendix includes the figure depicting additional comparisons between right HVFD, left HVFD and control conditions across both age groups for: (i) *median forward saccade amplitude* and; (ii) *median fixation duration*. Both variables were calculated for each line and then aggregated for the analysis (see Fig. A1).

Appendix B

Median fixation duration while paragraph reading.

This appendix details further analysis of *median fixation duration*. In the previous analysis, no statistical differences were found in *median fixation duration* between HVFD conditions. However, this could have been due to data averaging across different segments (lines of the text), hiding any difference in durations. To clarify this, we performed a separate analysis that looked at median fixation duration across each line, instead of averaging across the paragraph. As there was no significant main effect of age on median fixation duration, we considered the complete data set (collapsed across age groups) for this analysis.

We found that the median fixation duration was longer for simulated loss on the right side than the left. Fig. B1 shows average median fixation durations across different paragraph sections for both left and right HVFD at different cut-off frequencies. Paragraph sections consisted of 5 lines of text binned into 3 groups: *top, middle and bottom*. The 16th line of text was excluded from the analysis, as its length varied in the number of words across the different stimuli. To investigate the relationship between HVFD side, cut-off frequency and paragraph section on fixation duration, we ran a three-way repeated measures ANOVA. We found a significant three-way interaction between simulated HVFD side, cut-off frequency and paragraph bin, $F(56, 1568) = 1.86$, $p < .001$.

To understand the interaction effects across these 3 variables, we ran a simple two-way interaction analysis between simulated HVFD side and paragraph bin for each cut-off frequency level (0.275, 0.55, 0.825 and 1.1 cpl, control condition was excluded). A Bonferroni correction was applied and the level for statistical significance was set to $p < 0.0125$. Firstly, differences in fixation durations were only observed in the the 0.275 and 0.55 cpl cut-off frequency, smallest $^*F(1.3, 36.45) = 8.40$, $p = 0.003$. The right HVFD had higher median fixation durations compared to the left HVFD side, while the top paragraph section shows higher median fixation durations compared to the middle and bottom section. No statistical differences were found across HVFD side and paragraph bins at higher cutoff frequencies (>0.825 cpl). Secondly, we found a significant interaction effect (between simulated HVFD side and paragraph section) at 0.275 cpl, $^*F(1.43, 39.98) = 6.6$, $p = .007$; the *top* (557 ms, SD = 277) paragraph section had significantly longer median fixation duration compared to the *middle* (453 ms, SD = 245) and *bottom* (421 ms, SD = 225) paragraph bin in the right simulated HVFD condition, while in the left simulated HVFD, median fixation duration was similar across the 3 sections (*top*: 265 ms, SD = 101, *middle*: 265 ms, SD = 110, *bottom*: 249 ms, SD = 100). This suggests that as the subjects gained experience reading with the simulated HVFDs, any differences in fixation duration became negligible.

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