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Vision Research 44 (2004) 2691–2705
Vision Research
www.elsevier.com/locate/visres

Development of a viewing strategy during adaptation to an artificial central scotoma

Michael Varsori, Angelica Perez-Fornos, Avinoam B. Safran, Andrew R. Whatham *

Neuro-Ophthalmology Unit, Ophthalmology Clinic, Department of Clinical Neurosciences and Dermatology, Geneva University Hospitals, Rue Micheli-du-Crest 1211, Geneva 14, Switzerland

Received 14 October 2003; received in revised form 26 May 2004

Abstract

Although many individuals with a central scotoma develop eccentric fixation most often beneath or left of the scotoma, little is known about how they come to develop a particular viewing strategy. We investigated this by asking eight subjects with normal vision to read isolated letters, words and text passages while an artificial scotoma covered a central portion of the visual field. We quantified viewing strategy and analysed changes in their viewing behaviour over 8–10 sessions within a two-week period. Subjects read while either a horizontal ($n=4$) or vertical bar scotoma ($n=4$), 10° wide, covered the entire horizontal or vertical meridian of the stimulus field.

For the horizontal scotoma group: (1) there was an increasing preference to use the inferior visual field for isolated letters/words and text passages, which was essentially complete within the test period; (2) the superior visual field was preferred when reading letters/words initially presented in upper visual space and the inferior visual field when reading letters/words initially presented in lower visual space; (3) in general, variation in viewing strategy according to stimulus position diminished over the sessions for all stimuli.

For the vertical scotoma group: (1) two subjects used the left and right visual fields in approximately equal proportion to view isolated letters/words, one subject showed a weak preference to use the left visual field and one subject developed a strong preference for using the right visual field; (2) the text passages could be read with combined use of left and right visual fields in a specific manner; (3) the left visual field was preferred to view stimuli initially presented in left visual space while the right visual field was preferred for words initially presented in right visual space. This effect diminished across sessions.

Overall, these findings indicate that (1) a specific viewing strategy can be developed through as little as 5 hours of reading experience without guided training; (2) two distinctly separate retinal areas can be used in an integrated manner during reading; (4) stimulus position in visual space can influence viewing strategy; (5) in general, reading encourages a preference for the inferior over the superior visual field, but not the left over right visual field. Letter/word/text recognition and reading speeds increased progressively across sessions, even after scotoma lateralisation appeared stabilised suggesting that multiple mechanism are involved in adaptive changes.

1. Introduction

The development of an absolute central scotoma is a feature of macular degenerations such as age-related macular degeneration (AMD) and Stargardt's disease. Following the loss of foveal vision, the vast majority of affected individuals learn to consistently fixate objects of interest with one or more extra-foveal areas termed preferred retinal loci (PRL) (Fletcher & Schuchard, 1997; Timberlake et al., 1986; Timberlake, Peli, Essock, & Augliere, 1987; von Noorden & Mackensen, 1962). In some individuals PRL position can change according to stimulus light level (Lei & Schuchard, 1997), target size

* Corresponding author. Tel.: +41 22 38 28379; fax: +41 22 346 8405.
E-mail address: andrew.whatham@hcuge.ch (A.R. Whatham).

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doi:10.1016/j.visres.2004.05.027

(Trauzettel-Klosinski & Tornow, 1996), the visual task being performed (Cummings, Whittaker, Watson, & Budd, 1985) and during reading tasks (Déruaz, Whatham, Mermoud, & Safran, 2002; Duret, Issenhuth, & Safran, 1999; Safran, Duret, Issenhuth, & Mermoud, 1999). PRL positions in clinical populations are predominantly either to the left, inferior or inferior *and* left of the scotoma in visual space (Fletcher & Schuchard, 1997; Fletcher, Schuchard, & Watson, 1999; Guez, Le Gargasson, Rigaudiere, & O'Regan, 1993; Sunness, Applegate, Haselwood, & Rubin, 1996; Trauzettel-Klosinski & Tornow, 1996).

Reading is an important visually-mediated task such that the impairment of this ability due to visual dysfunction diminishes quality of life. Thus improving reading performance is a major goal of low vision rehabilitation. A question currently being asked, is whether reading performance can be improved in these individuals by changing the location of PRLs through training (Nilsson, Frennesson, & Nilsson, 2003). The working logic so far, has been that PRLs to the left of a scotoma might not be optimally located for reading, as in this adaptation the scotoma position impairs the reading process by obscuring text that is about to be read (Fine, 1999; Fine & Rubin, 1999; Nilsson, Frennesson, & Nilsson, 1998; Nilsson et al., 2003).

Before it can be determined whether untrained oculomotor adaptations observed in the central scotoma population are optimal, it is necessary to understand how an individual comes to use a particular strategy for eccentric fixation. There are many visually-mediated tasks that might influence the type of oculomotor adaptation to a central scotoma, including mobility and reading. Here we investigate whether the reading task alone could determine the clinically-observed pattern of PRL locations. This could be accomplished by examining viewing strategies used by normal subjects during adaptation to artificial central scotomas while reading. If the adaptations observed prove to be similar to adaptations found in clinical conditions, this might indicate that the task of reading encourages the development of inferiorly and/or leftward located PRLs.

In accordance with this approach we asked a group of normal subjects to read isolated letters, words and pages of paragraphed text while an artificial scotoma occluded part of the central visual field. Subjects were split into two groups, according to whether they were presented with a horizontally or vertically oriented bar scotoma. Although this type of scotoma is not physiological, it allows viewing strategies during a reading task to be investigated in terms of two mutually exclusive outcomes as subjects are forced to view text to one side of the scotoma at any instant in time. In this way the experiment is essentially reduced to a forced choice design and allows quantitative analysis of viewing strategy to be carried out.

2. Methods

2.1. Subjects

Eight healthy volunteers, aged 23–30 years, corrected visual acuity better than 0.1 logMAR and normal binocular function participated in the study. They were fluent in French and naive to the study goals. Four subjects were randomly assigned to one of the two simulation groups—reading with either a horizontally or vertically oriented bar scotoma. The study followed the tenets of the Declaration of Helsinki and was approved by the local ethical committee. Informed consent was obtained from all subjects prior to their participation.

2.2. Scotoma simulation

The artificial scotomas were 10° wide and always covered the orthogonal meridian of the stimulus field. Stabilisation of the scotoma on the central field was obtained using a high speed video based eye-tracking system, the SMI EyeLink Gaze tracking system (SensoMotoric Instruments GmbH, Teltow/Berlin, Germany) comprising two computers and a headband mounted measuring unit. The first computer (PIII-450, with a Matrox G200 graphics card) controlled the experiment, and generated visual stimuli on a 22″ high refresh rate monitor (ELSA Ecomo 22H99). Screen resolution was 600×800 pixels and set to a refresh rate of 160 Hz. The display PC was connected via Ethernet to the second computer (Compaq Deskpro EP Celeron-400) that collected and computed the data coming from the measuring unit. The headband mounted measuring unit consisted of three cameras—two for gaze position calculation (one per eye) and the third for head movement compensation. Empirically, accuracy of this system was approximately 1.0° average error or better. The tracking range of the system was ±30° horizontally and ±20° vertically. Gaze position data were transmitted to the display PC every 4 ms (250 Hz) and were available for computing within 10 ms. Thus the maximum lag between a change in fixation and scotoma repositioning was 14 ms. A pilot study in our laboratory has shown this system to be able to accurately stabilise targets in the visual field by online compensation of gaze position (Bagnoud, Sommerhalder, Pelizzone, & Safran, 2001).

Gaze position was used to move the artificial scotoma across the stimulus screen, following the subjects' eye movements. The scotoma was visible to the subject, and examiner, as a black bar on a white background. Eye position data were recorded for later analysis. Background screen luminance was 80 cd/m^2. All text was black (luminance 0.08 cd/m^2) such that Michelson contrast was greater than 99%.

2.3. Stimuli

Stimuli consisted of isolated letters and words, varying in position on the display screen, and pages of paragraphed text. Text stimuli were 1.25° in height (lower case "*x*" or *x*-height) and were in Courier Bold font. This size was above the critical character size at 5° eccentricity (Chung, Mansfield, & Legge, 1998), corresponding to the eccentricity at each edge of the scotoma. A fixed-width font was used so that the same number of character spaces were always covered by the scotoma in the vertical scotoma group. Isolated letters and words were presented one at a time centred on one of 9 positions on the screen, arranged in a 3 by 3 matrix (Fig. 1). The central position corresponded to the primary position of gaze, and the horizontal and vertical separation between adjacent word centres was 7°.

Letter/word presentation was varied across visual space for two reasons. Firstly, we did not want to have all words presented at the primary position of gaze, where they would have always been fully, or at least partially, hidden by the scotoma at the beginning of each trial. Thus the strategy subjects used might be influenced by what they first tried to do, or in a manner in which they were accustomed to "uncover" the word at the beginning of each trial. Secondly, in everyday situations, words appear at many different locations in visual space (e.g. street signs, product labels, menus), such that all stimuli appearing at one location may be unrepresentative of the varying position of visual stimuli that confront individuals in daily life. Therefore, our approach was to balance the isolated word stimuli across visual space (Fig. 2a). Positioning of stimuli across visual space also allowed the evaluation of the viewing strategy as a function of position in visual space. The viewing strategy used during the reading of the pages of paragraphed text was also analysed as a function of stimulus position in visual space, as text inherently consists of words at different positions in visual space (each line of text is at a different vertical height and all words on a line differ in horizontal position in visual space).

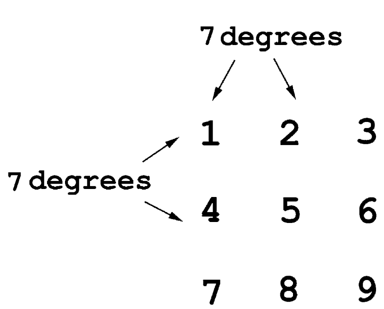


Fig. 1. Relative positions of word centres on the stimulus screen. For reference purposes, each position is numbered from 1 to 9. The horizontal and vertical separation between adjacent word centres was 7.0°.

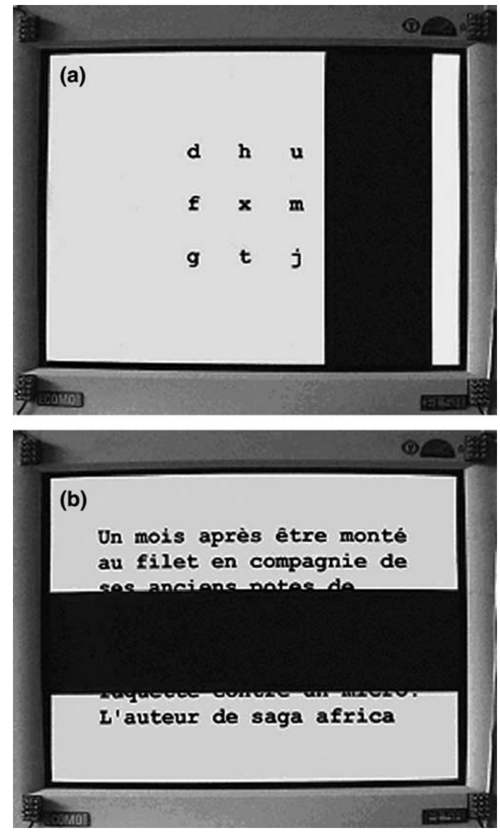


Fig. 2. (a) Stimulus display screen with a sample of isolated letter stimuli at each of the 9 stimulus positions. The 10° vertical scotoma used in four subjects is also visible. (b) Stimulus display screen, as seen by the subjects, during the reading of text passages. The 10° horizontal scotoma used with four subjects is also visible.

Over the course of the sessions isolated words were not presented to each subject more than once although, necessarily, isolated letters were repeated. Text passages were taken directly from local daily French language newspapers, and randomly allocated to each session. Text passages within each session were a continuous article over the four pages. Different passages were used across sessions. The passages read at corresponding sessions differed between subjects. Each page consisted of 8 lines of text, left justified only, with at the maximum 24 characters on each line (see Fig. 2b) and normal interline spacing. Mean word length in the text passages was approximately five letters in each session and word length content was not significantly different between sessions (one-way ANOVA, $p = 0.30$). Stimuli were presented in the following order: 18 single letters, 18 words of 4 letters, 18 words of 7 letters, 18 words of 10 letters and finally four pages of paragraphed text. Within each word length set, two stimuli were presented at each of the nine positions on the stimulus screen (see Fig. 1). Presentation order was randomised within each word length set such that successively-presented stimuli would appear at unpredictable locations. Visibility of the isolated stimuli at the beginning of each trial was dependant upon scotoma orientation, word length and stimulus position. The duration of each session was between 15 and 40 min.

2.4. Experimental protocol

Testing was carried out monocularly, the same eye in each subject being used for all sessions, the contralateral eye being occluded. Each subject read with the eye spontaneously used in a monocular sighting task in the primary position of gaze (viewing through a hole in an opaque sheet). In the horizontal scotoma group 3 subjects read using their right eye (subjects AS, FG, IG) and one subject used his left eye (subject RG). Three subjects in the vertical scotoma group also used their right eye in all sessions (subjects JA, PG, EO) and the remaining subject used her left eye (subject CB). Subjects were seated 57 cm in front of the stimulus display screen and aligned so that the primary position of gaze corresponded as close as possible to the centre of the monitor (position 5 in Fig. 1). They were instructed to maintain a stable head posture and distance from the stimulus display screen, and were observed continuously throughout the experiment to ensure as static a position as possible was maintained. Lateral head movements were measured using the head-mounted cameras, allowing online compensation for head instability.

Prior to the first reading session with the scotoma in place, each subject read an equivalent set of isolated letters, words and text passages to obtain a baseline measure of reading ability. All other sessions involved reading with the scotoma, centred on (foveal) fixation, during the reading tasks. Reading sessions took place on consecutive weekdays such that all sessions were completed within two weeks.

At the beginning of each session the centre of fixation was calculated using a regular 9 point calibration routine as described in (Sommerhalder et al., 2003). The scotoma was centred on this value. All text stimulus presentation trials (each isolated word and page of text) were initiated by the examiner once the subject was accurately fixating a black dot presented on a white stimulus screen, and drift correction was performed. Additional system calibration routines were run whenever it was needed within a session. The text stimulus and scotoma appeared simultaneously on the display screen at the beginning of each trial. As subjects changed gaze position during a trial, the scotoma (Fig. 2) moved so that it followed the centre of gaze. If the subject blinked, rendering the pupil invisible, both the text and the scotoma disappeared leaving the whole screen blank so that subjects could not attempt to "cheat" by forcibly closing or narrowing the palpebral fissure.

Subjects were asked to read the text stimulus once each trial had begun. Subjects were instructed to read all stimuli aloud and to report the stimulus as soon as they recognised it and to guess words that they were unsure of. Once a verbal attempt had been made to read an isolated word the examiner terminated the trial with a key-press. The trial for the text passages began with the presentation of the page of text on the stimulus screen and ended when all words on that page had been attempted. If subjects made an incorrect verbal report of a word during the reading of text passage they were told the correct word by the examiner such that they could continue the reading process without the possibility of getting stuck indefinitely on trying to decipher a particular word.

Subjects were not instructed to read as quickly as possible, but simply to read the presented text. This way the subject's natural viewing strategy was assessed rather than a strategy where they were trying to read as fast as possible in which they may have tried to take shortcuts in order to read faster. The computer screen was videotaped at each session to obtain an audio recording of the reading tasks for use in data analysis and to confirm all viewing strategies.

The examination protocol described above was repeated in each of the following sessions. Throughout the study, no feedback was given at any point to subjects in terms of whether they were reading "correctly" or using a viewing strategy that we hoped or expected them to use. We made every effort to ensure that subjects did not know we were evaluating their viewing strategy and that as far as they were concerned they were simply trying to read the text.

2.5. Data analysis

Viewing strategy was quantified as the proportion of time that a letter, word or line of text was visible to the subject either side of the scotoma while they were trying to read them. This method was carried out on the basis that if subjects developed a consistent viewing strategy, it would be reflected in the position of the scotoma in relation to the text as it was being read.

The time period during which subjects were attempting to read stimuli was defined as the *reading period. The reading period for words* was defined as the time taken from the presentation of each letter or word until it had been audibly read—correctly or incorrectly. Once a verbal attempt had been made, the examiner immediately terminated the trial with a key press, which denoted the end of the reading period in the data set. Relying on the subject's verbal response enables a consistent endpoint to be made regarding when a word has been correctly read—however any potential impact of a delay between eye movements and verbal response (easily observed while observing fixation behaviour during oral reading through a scanning laser ophthalmoscope) on the measurement of viewing strategy needs to be considered. Essentially, this means that a subject may have finished reading a word and fixation may be somewhere else while they are actually saying the word. For the isolated letter/word series we considered such a delay to add noise randomly to the measurements, as no other stimuli were on the screen such that there was no predictable location for fixation to be after each word had been read. For the paragraphed text tasks, any movement from one line of text to the next, down the page may occur before a subject has finished saying the final word on the previous line. This might have the effect of producing a small bias in measures of viewing strategy in the direction of increased use of the superior visual field during reading. However, we used the same stimulus presentation paradigm and analysis procedure at each session so that these factors could be considered equivalent across sessions so that consistent changes in viewing strategy across sessions would not be related to any delay between eye position and verbal report.

In each scotoma group the reading period for the isolated stimuli can be divided into three components: the time text was visible on one side of the scotoma, the time text was visible the other side of the scotoma and the time text was hidden by the scotoma. Thus for the horizontal scotoma group:

$$\text{Reading period} = t_A + t_B + t_C$$

where t_A = time scotoma above text; t_B = time scotoma below text; t_C = time scotoma covered the text.

For the vertical scotoma group:

$$\text{Reading period} = t_R + t_L + t_C$$

where t_R = time scotoma to the right of text; t_L = time scotoma to the left of text; t_C = time scotoma covered the text.

The times the letter/word stimuli were hidden and visible were determined and analysed over sessions. The time words were hidden by the scotoma, t_C, was subtracted from the reading period so that the relative use of the visual fields either side of the scotoma could be compared. A software program developed in our laboratory calculated the percentage of time the text stimulus was visible left/right and above/below the scotoma during each task. The equation used to determine the relative proportion of viewing time either side of the scotoma was as follows:

Horizontal scotoma group:

$$\%\text{viewing time below scotoma} = \left(\frac{t_A}{t_A + t_B}\right) \times 100$$

Vertical scotoma group:

$$\%\text{viewing time left of scotoma} = \left(\frac{t_R}{t_R + t_L}\right) \times 100$$

In the horizontal scotoma experiment, words were defined as being visible above or below the scotoma if at least half the text x-height was visible. In the vertical scotoma group, words were defined as visible if a single letter of the word was visible to the left or right of the scotoma. In this group, any part of the words of 1, 4 and 7 letters could not be visible on both sides of the scotoma at the same time. The isolated words of 10 letters could not be analysed in the above way because letters or parts of letters could be visible on both sides of the scotoma (7–8 character spaces wide) at the same time, and consequently subjects could have been attending to text on either side (or perhaps both) of the scotoma. The texts were analysed line by line. For the text passages the *reading period for each line of text* was defined as the time after the last word of the previous line had been read (or the appearance of the page of text in the case of the first line) until the last word on the current line had been read. Next, the percentage of time the relevant text was visible above or below the scotoma during this time was calculated. Although the vertical group could not be analysed in this way due to the left to right nature of the reading task and the fact that some text on each line being read was necessarily visible to the left and right of the scotoma, these subjects were still required to read four pages of text each session as this provided an equivalent amount of reading experience as the horizontal scotoma group, as well as enabling word recognition and reading speed to be measured. However it was possible to determine in this group whether both sides of the scotoma were used, or only one side by calculating the number of times the first word on a line was visible to the right of the scotoma as this word as being read, and the number of times the final word on each line was visible to the left of the scotoma as it was being read.

In addition to the quantification of viewing strategy—letter/word/text recognition, reading times and reading speeds were also determined. For the purpose of determining word recognition accuracy, errors during reading were scored according to whether they were correct at the first complete verbal attempt. A word was also scored as correct if subjects began to erroneously report a word and spontaneously changed to saying the correct word before they finished reporting the first attempt. Reading time for isolated stimuli was measured in milliseconds and was taken as the time from the beginning of each trial until the word had been read aloud, correctly or incorrectly. Reading speed was calculated in words per minute as the number of words correctly read over all four pages of text divided by the total reading time. Statistical analyses were performed using SPSS version 11.5.

3. Results

3.1. Word recognition—isolated letters/words and text

Recognition for isolated letters/words and paragraphed text, without the scotoma in place, was 100% for all subjects. With the scotoma, recognition for both reading tasks was 90–100% for all subjects across all sessions. Recognition for isolated letters/words (Fig. 3) significantly improved over the course of the sessions (Spearman rank correlation: $r = 0.95$, $p < 0.0001$), from a mean value of 93.3–99.5% at the first and tenth sessions respectively. There was also an improvement in word recognition for the text passages (Spearman rank correlation $r = 0.77$, $p < 0.01$), from 98.7% in the first session to 99.4% by the tenth session.

3.2. Viewing preferences—horizontal scotoma group

The viewing strategies used across sessions by these subjects for isolated letters/word reading are shown in Fig. 4a and b. During the first reading session one subject had no viewing preference (subject FG), where the scotoma was positioned above and below the words for approximately equal amounts of time. The three remaining subjects (AS, RG, IG) tended to put the scotoma under the words and lines of text. The range of values for viewing strategy at the first and the last session for all four subjects did not overlap—15–52% use of the inferior visual field compared to 64–87% use. Three subjects (AS, RG, IG) clearly shifted their viewing strategy towards increased positioning of the scotoma above the letters/words across sessions (Spearman rank correlation, $p < 0.05$ for each subject). Subject FG showed no preference for either visual field at the first session but increased use of their inferior visual field (52.2–73.1%) by the final session. This increase occurred within the first three sessions after which viewing strategy was relatively stable, remaining between 65% and 75% use of the inferior visual field, although there was no significant monotonic increase in use of the inferior visual field (Spearman rank correlation, $p = 0.52$). The average viewing strategy for this group increased significantly from 31.6 ± 7.9% (SE) at the first session to 77.2 ± 5.1% at the ninth session (repeated measures ANOVA on sessions 1–9, $p < 0.001$; Spearman rank correlation $p < 0.001$) and the average change in viewing

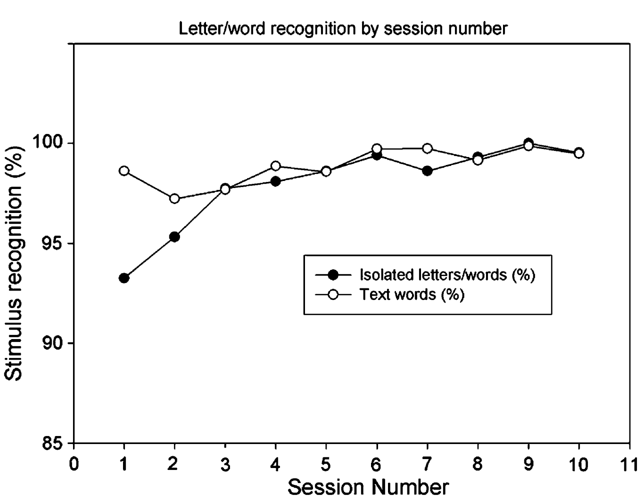
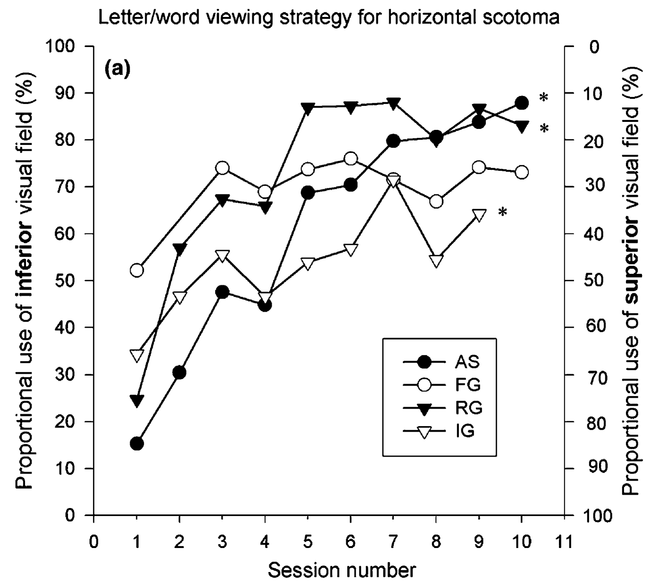


Fig. 3. Stimulus recognition across reading sessions for both isolated letters/words (filled symbols) and text passages (open symbols). The plotted symbols represent those of all stimuli read by all subjects in both groups combined. Recognition improved for both the letters/words and text over the course of the sessions.



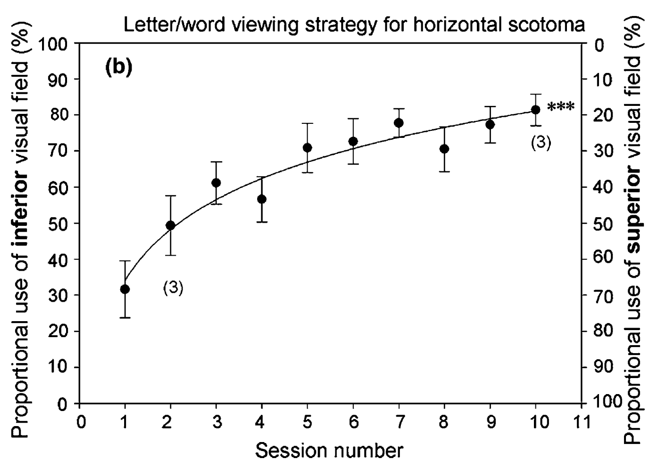


Fig. 4. (a) Individual viewing strategy during letter/word reading for each subject in the horizontal scotoma group. The percentage of the reading period in which the scotoma was positioned above isolated words is plotted on the ordinate as a function of reading session. (b) Average viewing strategy for the horizontal scotoma group while reading the isolated letter/word stimuli. Data points represent the mean ± SE for this group (four unless otherwise stated) at each session. Also plotted is the best fitting logarithmic function. The "∗∗∗" symbol indicates significance at the $p < 0.001$ level.

strategy followed a logarithmic progression ($r^2 = 0.94$, $p < 0.0001$).

Viewing strategies in this group for the isolated letters/words were clearly influenced by the stimulus position (Fig. 5). It was evident in all sessions that isolated letters/words that were presented in the upper part of the screen had a greater tendency to be read with the scotoma under it (positions 1–3 in Fig. 1), while letters/words presented in lower visual space (positions 7–9 in Fig. 1) were predominantly read with the scotoma positioned above the stimuli. Over the course of the sessions proportionally more time was spent viewing the upper stimuli, middle stimuli and lower stimuli beneath the scotoma (Spearman rank correlation, $p < 0.001$ for each stimulus category). The session at which subjects first shifted towards increasing use of the inferior visual field differed for the lower, middle and upper words. For the lower words this was from sessions 1–2, for the middle words this was sessions 2–3, and for the upper words this was sessions 4–5.

During the first session, subjects in this group tended to position the scotoma both above and below the lines of text with either no clear preference or a preference to use the superior visual field during the reading period in the paragraphed text-reading task (see Fig. 6a). Viewing strategy at the first session was between 20% and 60% use of the inferior visual field. As session number increased, each subject increasingly tended to position the scotoma above lines of text as it was being read, such that the scotoma was positioned above lines of text between 84% and 97% at the final session for each subject. Subjects RG and IG showed a significant monotonic shift in viewing strategy across sessions (Spearman rank correlation, $p < 0.001$). Average viewing strategy changed from 40.1 ± 10.7% (SE) at the first session to 94.6 ± 3.0% (SE) at the final session (Fig. 6b) in a progressive manner (Spearman rank correlation, $p < 0.001$). This shift was effectively complete, however, by the fifth session as the strategy changed progressively from 41.0% at the first session to 92% at the fifth session and then fluctuated between 85% and 95% for the remainder of the sessions.

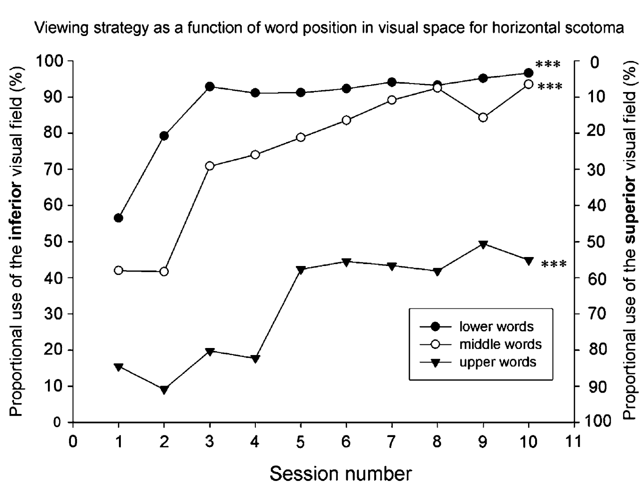


Fig. 5. Viewing strategy as a function of letter/word position in visual space for the horizontal scotoma group across the reading sessions. Each data point represents the mean value of all subjects.

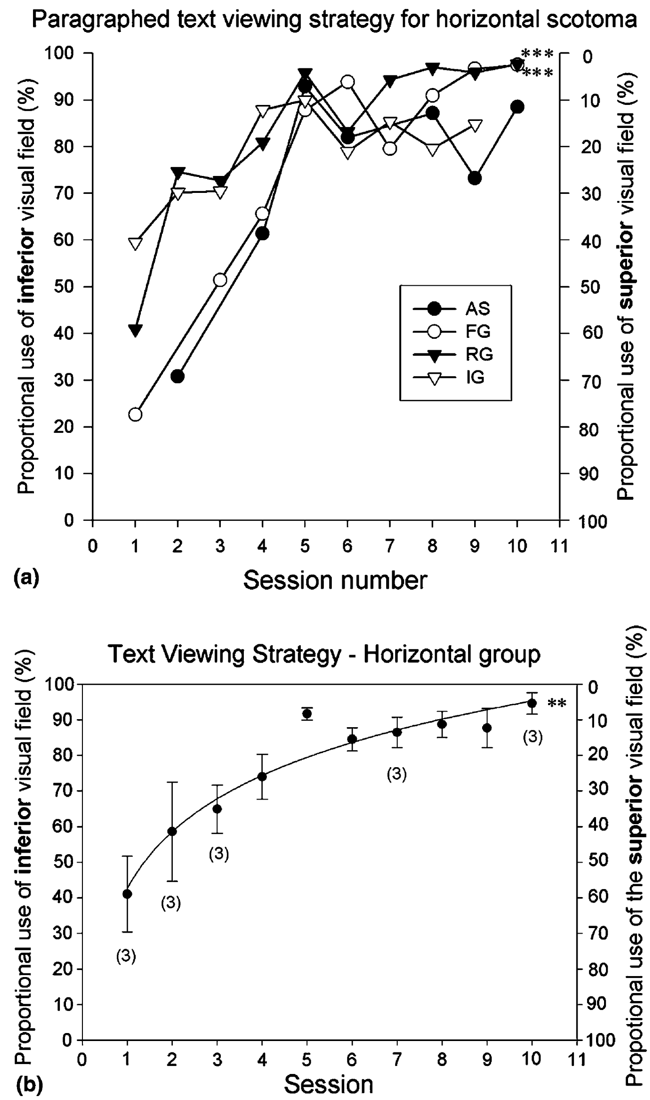


Fig. 6. (a) Individual viewing strategy during the reading of text passages in the horizontal scotoma group across reading sessions. Percentage of reading time in which the scotoma was positioned above the line of text being read is plotted on the ordinate and session number plotted on the abscissa. Data points are missing for sessions 1, 3, 7 for AS and session 2 for FG due to technical problems with either the eye movement recording apparatus or the audiorecording which prevented the determination of the reading period in the pages of text. However at each of these sessions the subjects completed a full amount of reading experience (72 isolated words + 4 pages of continuous text). The "∗∗∗" symbol indicates significance at the $p < 0.001$ level. (b) Average viewing strategy while reading text passages with a horizontal scotoma. Data points represent mean ± SE for all the subjects in this group (four unless otherwise stated) at each session. Also plotted is the best fitting logarithmic function. The "∗∗" symbol indicates significance at the $p < 0.01$ level.

An obvious effect of text position on viewing strategy was also measured during paragraphed text reading (Fig. 7). This was particularly evident during the first session, where viewing strategy was considerably different for the first two lines of text as opposed to the last two lines. For the first two lines (lines 1, 2) the inferior visual field was only used 7.6% of the time text was visible to the subject, indicating a strong preference to use the superior visual field to view these lines, whereas the inferior visual field was used 78.2% of the text visibility time while reading the lowest lines of text (lines 7, 8), indicating a strong preference to use this visual field for stimuli in lower visual space. The viewing strategy for the middles lines of text was between these values—8.7% use of the inferior visual field for lines 3 and 4 and 51.0% use of the inferior visual field for lines 5 and 6. This considerable variation in viewing strategy employed across the pages of text diminished during the sessions as the inferior visual field was increasingly preferred to the superior visual field for all lines of text (Spearman rank correlation, lines 1 and 2, lines 3 and 4, $p<0.01$; lines 5 and 6, lines 7 and 8, $p<0.05$). This was most notable for the upper lines which were read with 7.6% use of the inferior visual field at the first session and increasing to 80.5% at the final session, while the lowest lines of text only increased from 78.2% use of the inferior visual field at the first session to 93.4% at the final session—such that there was little variation in viewing strategy as a function of stimulus position at the final session. The viewing preferences for the different lines of text converged towards a value of almost complete positioning (close to 100%) of the scotoma above lines of text (see Fig. 7), reflecting the emergence of a consistent viewing strategy of using the inferior visual field exclusively for all lines of text on the screen.

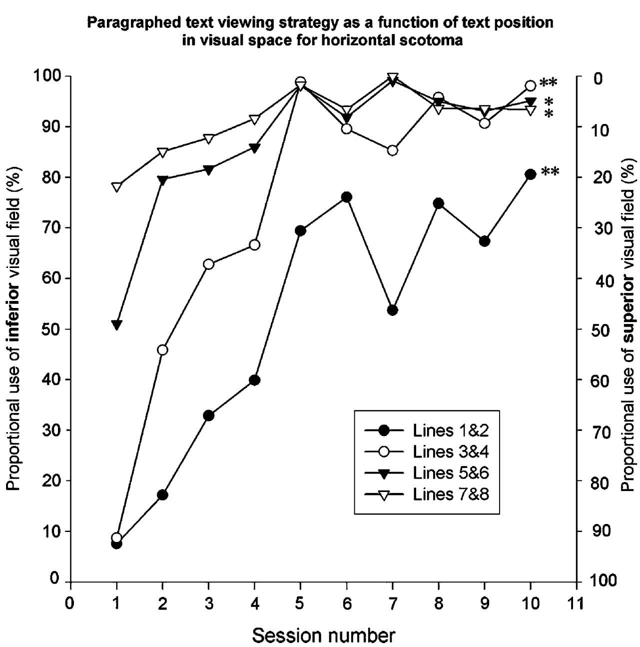
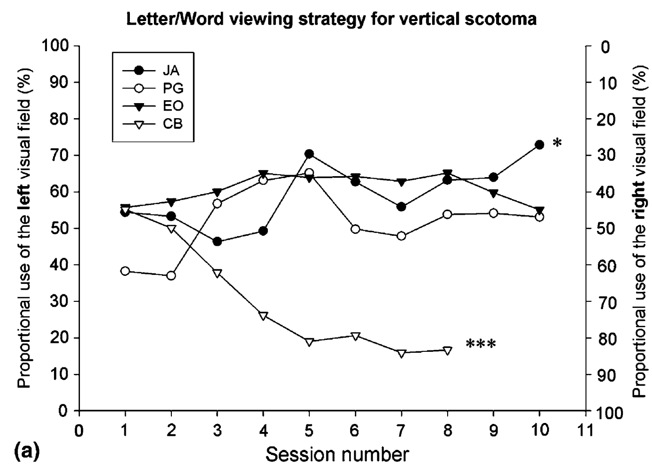


Fig. 7. Viewing strategy as a function of text position in visual space for the horizontal scotoma group. Data from all four subjects are grouped together. The eight lines of text on each page were grouped into four line pairs. Line one refers to the uppermost line of text, and line 8 the lowermost line of text, on the stimulus screen. The "∗∗" and the "∗" symbols indicate significance at the $p<0.01$ and $p<0.05$ levels respectively.

3.3. Viewing preferences—vertical scotoma group

Subjects EO and PG viewed the isolated letter/word series using both sides of the scotoma in approximately equal proportion, with no evidence of a clear change in viewing strategy across sessions (Fig. 8a). The scotoma



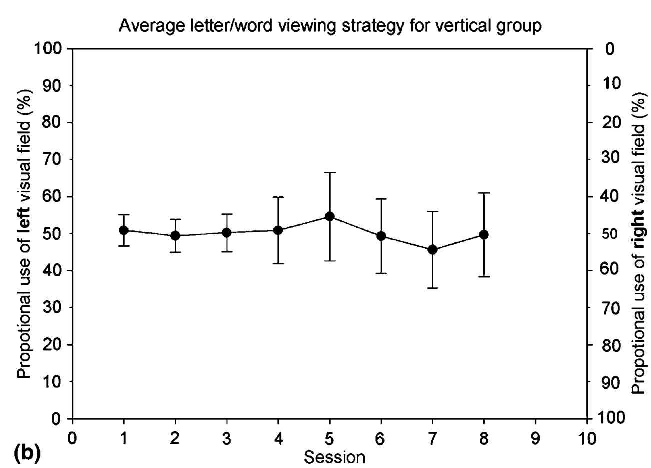


Fig. 8. (a) Individual letter/word-viewing strategy for the vertical scotoma group. The percentage of time in which the scotoma is positioned to the right of isolated letters and words (i.e. text visible to the left of the scotoma) is plotted as a function of reading session. Note there was little change in overall viewing strategy in three subjects over the reading sessions (text was consistently visible on both side of the scotoma), while CB developed a strong preference for viewing text to the right of the scotoma. The "∗∗∗" and the "∗" symbols indicates significance at the $p<0.001$ and $p<0.05$ levels respectively. (b) Average viewing strategy for the vertical scotoma group while reading the isolated letter/word stimuli. Data points represent the mean ± SE for all four subjects at each session.

was positioned to the right of words from 38% to 55% during the first session and from 54% to 55% at the final session. Subject JA developed a slight preference to use the left visual field (from 54% rising to 73% over the sessions; Spearman rank correlation, $p < 0.05$). In contrast subject CB developed a strong preference for using the right visual field (Spearman rank correlation $r^2 = 0.91$ $p < 0.001$), positioning the scotoma to the right of the letters/words 55% of the time at the first session, and 17% at the final session. Average viewing strategy did not change over the course of the sessions (repeated measures ANOVA on sessions 1–8, $p = 0.99$), but remained at approximately 50% use of the left and right visual fields (Fig. 8b).

Viewing strategy for the vertical scotoma group was highly dependent on stimulus position in visual space (Fig. 9). More time was spent viewing words of 1, 4 and 7 letters appearing on the left of the screen (positions 1, 4, 7 in Fig. 1) with the left visual field than either the centrally positioned words (positions 2, 5, 8 in Fig. 1) and even more so than the words on the right (positions 3, 6, 9 in Fig. 1) which were more often viewed using the right visual field. For the stimuli presented to the left of fixation, viewing strategy changed to increasing use of the right visual field over the sessions (decrease from 82.5% to 67.9% use of the left visual field; Spearman rank correlation, $p < 0.001$), while viewing strategy for the stimuli presented to the right of fixation changed in the direction of increasing use of the left visual field (increase from 11.5% to 28.9% use of the left visual field; Spearman rank correlation, $p < 0.05$). The viewing strategy for the centrally positioned words showed no monotonic change over the sessions (Spearman rank correlation, $p = 0.57$). Although 10 letter words could not be analysed in the above way because they were wider than the scotoma, it was clear that both sides of the scotoma were used during the reading of these isolated words as subjects could read them without viewing the entire word on one side of the scotoma by making small left to right movements to visualise the beginning of the word using the left visual field and the end of the word using the right visual field.

We could not analyse the viewing strategy during paragraphed text reading for the vertical scotoma group in the same way—as words on each line could be visible either side of the scotoma during the reading of each line of text. However, it was clear that each subject made use of both the left and right visual fields during this reading task. More than 95% of the first words on each line of text read by each subject were not visible in their entirety to the right of the scotoma, indicating that the left side of the scotoma must have been used to some extent in the reading of these words (Fig. 10). Two subjects (EO, CB) did not view the last word on any line of text in its entirety to the left of the scotoma, indicating use of the right visual field during the reading of these words (Fig. 11). The other two subjects (JA, PG) did not view the entire final word to the left of the scotoma on 16% and 78% (respectively) lines, indicating some use of the right visual field during the reading of these words (Fig. 11).

3.4. Reading rates across measurement sessions

There was a significant effect of word length on reading time across sessions (repeated measures ANOVA on log-transformed data, $p < 0.001$), with the single letters

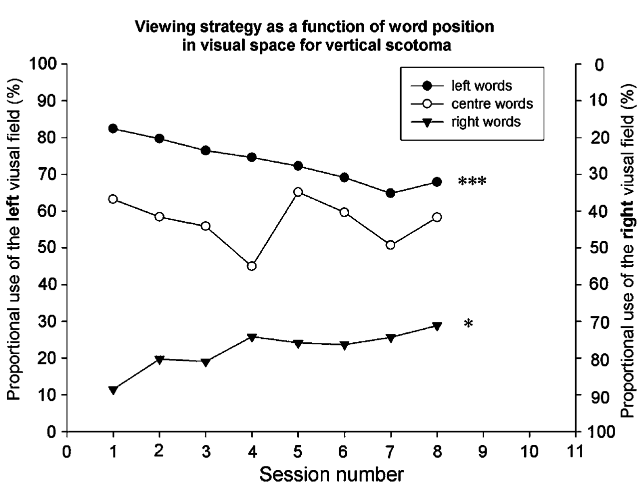


Fig. 9. Viewing strategy as a function of letter/word position in visual space for the vertical scotoma group across the reading sessions. Each data point represents the mean value of all four subjects. There was a distinct effect of stimulus position on viewing strategy across all sessions. The "∗∗∗" and the "∗" symbols indicates significance at the $p < 0.001$ and $p < 0.05$ levels respectively.

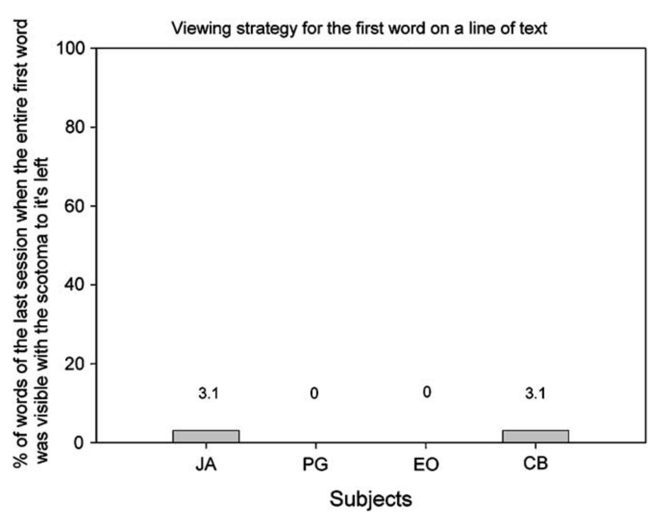


Fig. 10. Visibility of the entire first word on each line in the right visual field for each subject in the vertical scotoma group at the final session. Actual percentage values are shown above each data bar. The high preponderance of first words that were not visible to the right of the scotoma indicates the left visual field must have been used in the successful reading of these words.

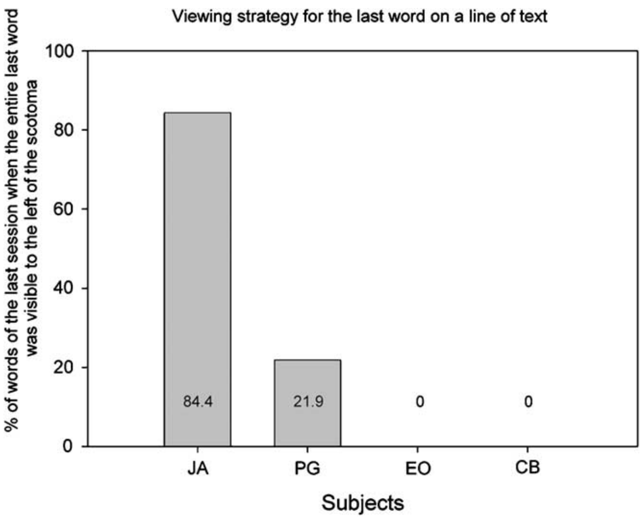


Fig. 11. Visibility of the entire last word on each line in the left visual field for each subject in the vertical scotoma group at the final session. Actual percentage values are shown on or above each data bar. The high preponderance of words which were not visible to the left of the scotoma indicate the right visual field must have been used in the successful reading of these words.

being read fastest and reading time increasing with increasing word length (Fig. 12). Reading time decreased for all word lengths as session number increased in a log-linear fashion (repeated measures ANOVA on sessions 1–8, $p<0.001$, linear contrast, $p<0.01$). There was no significant difference in reading times across sessions between the two scotoma groups (repeated measures ANOVA, $p=0.99$), or in the rate at which reading times improved (repeated measures ANOVA, session by scotoma type, $p=0.26$).

The average total time per session that the isolated letters and words of 4 and 7 letters were visible, and the time these stimuli were hidden by the scotoma for all eight subjects across sessions is shown in Fig. 13. The time isolated stimuli were visible to the subjects before the stimulus was read decreased across sessions in a logarithmic fashion (repeated measures ANOVA on log-transformed data for sessions 1–8, $p<0.001$, linear contrast, $p<0.001$). The average time the scotoma covered the letters/words during each session also decreased across sessions in a logarithmic manner (repeated measures ANOVA on log-transformed data for sessions 1–8, $p<0.001$, linear contrast, $p<0.001$). Across sessions stimuli were hidden by the scotoma for longer periods than they were visible during the reading period, (repeated measures ANOVA sessions 1–8, $p<0.05$). The ratio of time hidden vs. time visible appeared to change across sessions (Figs. 13 and 14), towards equivalent values, but this did not reach statistical significance (repeated measures ANOVA sessions 1–8, $p=0.19$).

Reading speeds ranged from 155 to 205 words per minute with a mean value (±SE) of 179 ± 7.6 words per minute for reading without the scotoma. At the first session with the scotomas in position, mean reading speed (±SE) was 29 ± 7.2 words per minute (17% of mean reading speed attained without the scotoma in place) and increased to 63 ± 6.3 words per minute at the final session. Mean reading speed significantly increased across sessions (Fig. 15), for all subjects together, in a linear fashion (repeated measures ANOVA on sessions 1–8; $p<0.001$; Pearson correlation $r^2=0.94$, $p<0.0001$). The individual measures of reading speed for both scotoma groups (Figs. 16 and 17) reveal

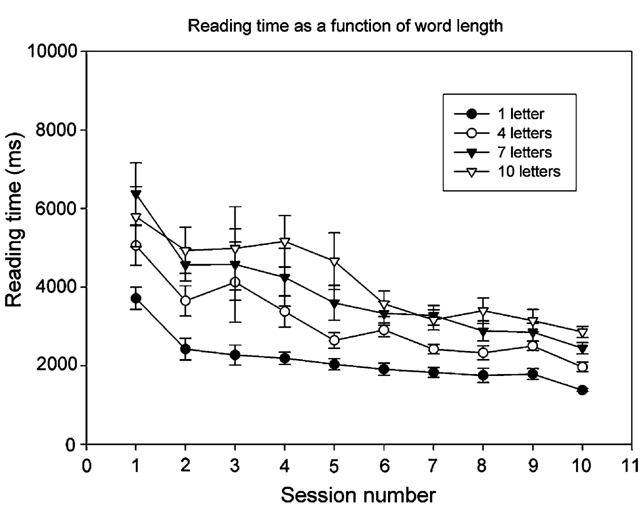


Fig. 12. Reading time, in milliseconds, for isolated stimuli as a function of reading session for both scotoma groups combined. Data are plotted as a function of word length and each symbol and associated error bars represent the mean value ± SE for eight subjects. Reading time was a function of word length across sessions, with longer reading times associated with longer words. Reading time decreased for all word lengths over the course of the sessions.

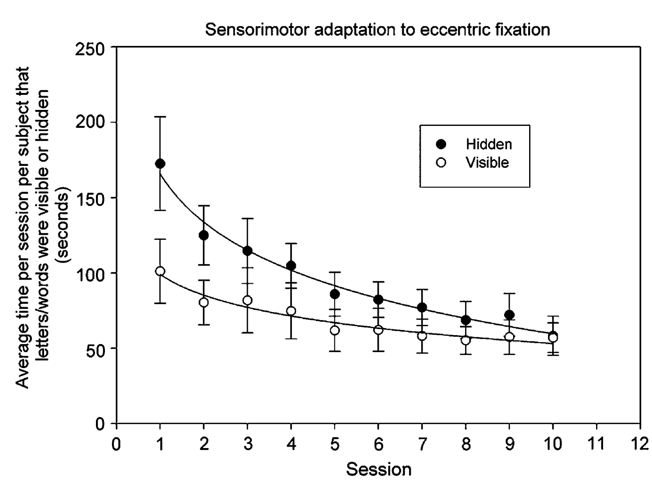


Fig. 13. Sensorimotor adaptation to eccentric fixation. The average total time (±SE) that the single letters and 4 and 7 letter words were hidden (filled symbols) and visible (open symbols) during each session for all eight subjects is plotted as a function of session number. The best fitting logarithmic function for each data set is also plotted.

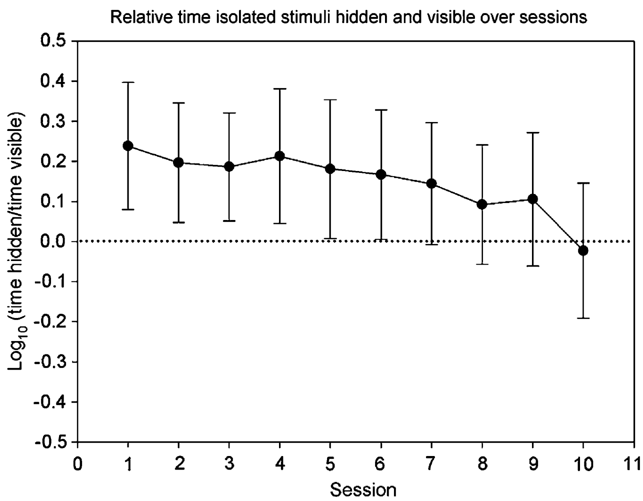


Fig. 14. The log ratio of time (±SE) the letters/words (1, 4 and 7 letter stimuli only) were hidden and visible during the reading period for all eight subjects is plotted as a function of session number. Note the tendency for the stimuli to be less hidden by the scotoma over the course of the sessions.

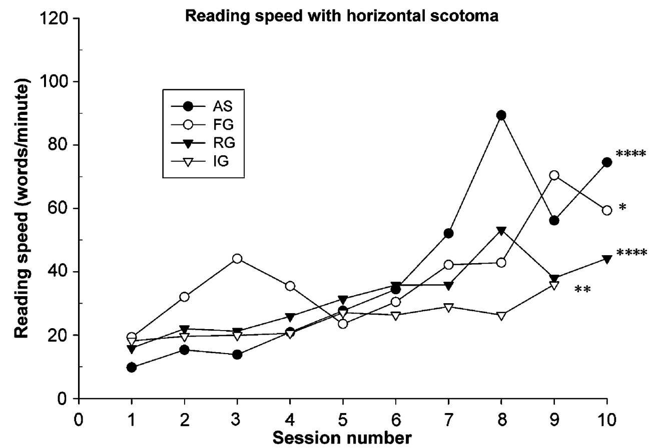


Fig. 16. Reading speed for paragraphed text across practice sessions for each subject in the horizontal scotoma group. Note the general increase in reading speed with session number in all subjects. The "*", "**" and "****" symbols indicate statistically significant improvements in reading speeds at the $p<0.05$, $p<0.01$ and $p<0.0001$ levels of significance respectively.

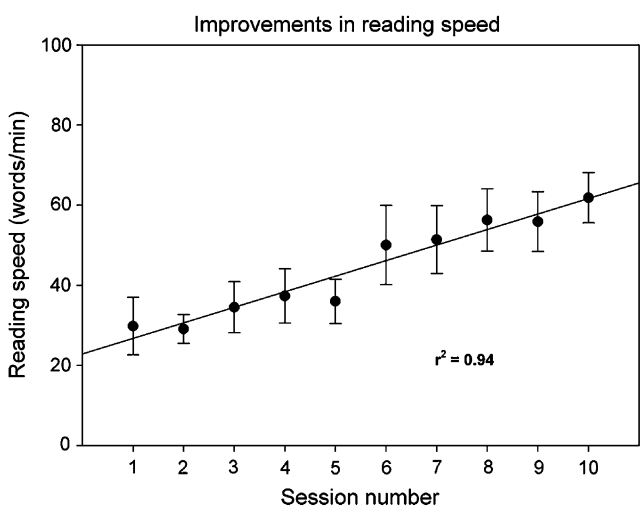


Fig. 15. Reading speed, in words per minute, for the text passages as a function of reading session for both scotoma groups combined. Note that reading speed increased in a linear fashion over the course of the sessions, approximately doubling the starting value at the final session.

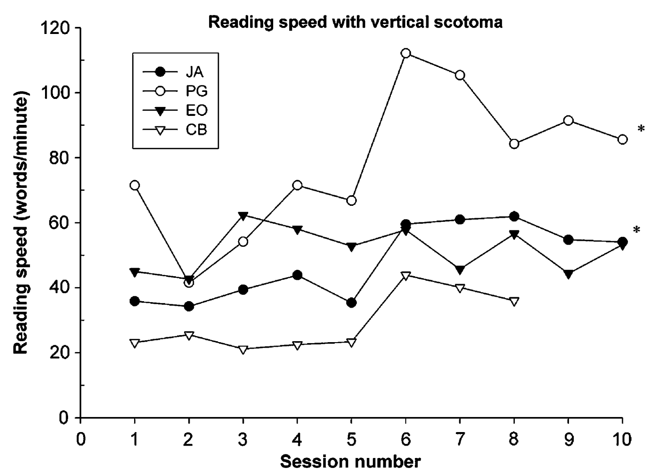


Fig. 17. Reading speed for paragraphed text across practice sessions for each subject in the vertical scotoma group. Statistically significant increases in reading speed with session number in this group occurred in two subjects, JA and PG. The "*" symbol denotes significance at the $p<0.05$ level of significance.

that reading speed improved to some extent in most subjects across sessions. In the horizontal scotoma group reading speed at the first session was between 9 and 18 words/min while reading speed at the final session for the group ranged from 35 to 74 words/min. Reading speed significantly improved in each subject from the first to the last session (Spearman rank correlation; AS, RG—$p<0.0001$; IG—$p<0.01$; FG—$p<0.05$). In the vertical scotoma group initial reading speed was 23–73 words/min and increased slightly to values of 36–85 words/min at the final session. The reading speed for two subjects in this group significantly increased across sessions (Spearman rank correlation; PG, JA—$p<0.05$). There was no significant difference in rate of improvement in reading speed between the two scotoma types (repeated measures ANOVA on first 8 sessions: session by scotoma type, $p=0.08$).

4. Discussion

4.1. The inferior visual field is naturally preferred to the superior visual field to effect the task of reading

All subjects in the horizontal scotoma group developed a viewing strategy over the course of the sessions in which they preferred to position the scotoma above isolated letters/words and lines of text. However in neither case was the preference immediate, with either no preference at the first session or a preference to use the superior visual field. Initial preference to use the superior visual field may have been related to the possibility that in unrestrained reading in normal vision, gaze angle is often below the primary position of gaze. The tendency to change viewing strategy over the sessions to greater use of the inferior visual field, may indicate that these subjects learned that they could read better if they only used the inferior visual field. When the subjects were asked after the end of the final session why they put the scotoma above the text stimuli, they replied that "it seemed easier". Thus they appeared conscious, to some degree, of the relative ease with which they could read using either visual field so that their change in viewing preference over the sessions may have reflected a conscious decision. The eventual preference to use the inferior visual field agrees with published data from perimetric (Li, Wu, & Jiang, 1997), psychophysical (visual acuity (Low, 1943; Millodot & Lamont, 1975; Wertheim, 1894), contrast sensitivity (Skrandies, 1985), reaction times (Tartaglione, Favale, & Benton, 1979), rapid serial presentation of text information (Fine, 1999)) and electrophysiological studies (focal ERG (Miyake, Shiroyama, Horiguchi, & Ota, 1989), pattern ERG (Yoshii & Paarmann, 1989) and multifocal ERG (Nagatomo, Nao-i, Maruiwa, Arai, & Sawada, 1998) and VEP (Eason, White, & Oden, 1967; Lehmann & Skrandies, 1979; Skrandies, Richter, & Lehmann, 1980; Yu & Brown, 1997)), showing that for many visually-based tasks the inferior visual field is functionally better than the superior visual field. Our results also agree with data from central scotoma populations in whom PRLs are more frequently observed in the inferior visual field compared to superior visual field (Fletcher & Schuchard, 1997; Guez et al., 1993; Sunness et al., 1996; Trauzettel-Klosinski & Tornow, 1996). Clearly, individuals with a real central scotoma perform many visually-mediated tasks each day other than reading which may also influence where PRLs develop. However our results indicate that the task of reading, alone, is sufficient to encourage the development of PRLs inferior compared to superior to a central scotoma.

4.2. Are PRLs to the left of a central scotoma naturally preferred to PRLs to the right for reading?

In central scotoma populations, eccentric PRLs are more frequently located to the left, compared to the right, of the scotoma, (Fletcher & Schuchard, 1997; Guez et al., 1993; Sunness et al., 1996; Trauzettel-Klosinski & Tornow, 1996). In our study, one subject developed a clear preference to use the right visual field to view letters/words during the reading task over the course of the sessions, one subject a weaker preference to use the left visual field and the other two showed no change across sessions. There was evidence for using the left and right visual fields on different occasions during the reading task in all subjects. The lack of a clear and consistent unilateral viewing preference for using the left visual field to view isolated letters/words across subjects and the development of a clear viewing preference for one subject to the right of the scotoma, indicates that viewing to the left of a scotoma, as is often observed in central scotoma populations, is not clearly preferred to the right of the scotoma as a natural adaptation. This suggests that a left over right preference in clinical populations is driven by non-reading factors. However we only examined viewing strategy in response to one scotoma size (10°) and one text size (1.25°). Perhaps adaptation to other scotoma and text sizes might result in the development of a unique PRL to the left of the scotoma.

4.3. Areas left and right of a central scotoma can be used together in a specific strategy

The viewing strategies for both reading tasks in the vertical scotoma group indicate that separate areas in the left and right visual fields, adjacent to a central scotoma, can be used together in a specific viewing strategy. For each subject the first word on each line was rarely visible to the right of the scotoma and the final word on each line was never visible to the left of the scotoma for two subjects (EO, CB), infrequent for one subject (PG) and occasionally for the remaining subject (JA). Thus, in general, subjects changed from using the left visual field to read the first part of the line to the right visual field to read the last part of the line, because overall, the scotoma remained within the boundaries of the pages of text during the reading of most lines of text. As this was a repeated finding over the four pages of text, this represented a specific strategy of using both visual fields in a combined manner during a single reading task. It was clear that during letter/word reading, the left and right visual fields were used. When both were used while subjects were reading a single letter or 4 or 7 letter word, this appeared to be simple alternation as these stimuli could not be visible on both sides of the scotoma at once. However a combined strategy appeared to be used for some 10 letter words, which were read without ever being entirely visible on one side of the scotoma.

4.4. Word recognition and reading speed can improve during adaptation to a central scotoma

Recognition accuracy and reading speeds improved in all subjects, as a group, across sessions. Improvement in isolated letter/words recognition was greater than that for the text passages, principally due to poorer recognition in the first sessions. Recognition accuracy was similar at the final session. Better recognition for text in the early sessions may have been due to the use of the content of a text passage to make more educated guesses of words that were difficult to discriminate, compared to attempting to guess the isolated stimuli where no such help was available. Improvements in word recognition with eccentric viewing practice have been reported for normal subjects attempting to read pixelised text, stabilised at 15° eccentricity (Sommerhalder et al., 2004).

In all eight subjects grouped together, reading time for the isolated letters/words and reading speed for the text passages at the final session had improved by approximately a factor of two over that in the first session. This improvement appeared to be associated to an increased ability to position targets on an eccentric retinal area—because the duration of time the scotoma covered the letters/words during the reading period decreased across sessions and an increased ability to decipher text information viewed in the peripheral visual field—because the time text was visible, before a letter/word could be identified, also decreased across sessions. Other factors that we did not measure, such as improved fixation stability, which has been shown to occur after the abrupt onset of a central scotoma in macaque monkeys with foveal lesions (Heinen & Skavenski, 1992), and an increased ability to allocate attention to peripheral retinal areas might have also contributed to improvements.

Our results show that it is possible in simulations for subjects to develop a consistent viewing strategy, within ten (approximately) 20 min reading sessions, as well as increased reading speeds without any viewing instructions. This indicates that viewing strategies can change and reading speeds improve, without guidance, during adaptation to an artificial scotoma and to using eccentric fixation. Thus it is important to distinguish between simulations with and without adaptation. Simulation studies in unadapted subjects may only be applicable to performance immediately after scotoma onset in clinical populations. Better text recognition and reading speeds with eccentric viewing practice in simulated visual loss may have implications for understanding the natural adaptation to a real central scotoma. Even though the scotomas that our subjects had to adapt to were not circular, as might best approximate central scotomas in clinical patients, subjects read without a portion of their central visual field and relied on extra-foveal areas alone to read, as individuals with a real central scotoma must also do. As our subjects were not given any instructions as to how to use eccentric vision, it appears possible for text recognition and reading speed to improve in the clinical population after the onset of a central scotoma without training a specific viewing strategy. It will be important in the clinical evaluation of any eccentric viewing technique to separate an increase in visual and/or oculomotor perfromance associated with a natural adaptation to the scotoma from that due to the particular training procedure.

4.5. Relative speed of stabilisation of viewing strategy and reading speed

The horizontal scotoma group developed a consistent viewing strategy to read the text passages by the fifth session with little evidence of a change in strategy after that. Thus although the average strategy for this group could be well fitted with a logarithmic function (Fig. 6b), the individual data (Fig. 6a) and the outlying mean value for the fifth session suggest that a shift in viewing strategy had largely been complete in all subjects at the fifth session. In contrast reading speed for this group continued to improve beyond the fifth session. This suggests that some components of the adaptation process develop relatively quickly whereas others require more time. This observation bears some similarities with the results of a study examining oculomotor adaptation following the onset of bilateral macular scotomas in macaque monkeys (Heinen & Skavenski, 1992), where it was observed that monkeys consistently viewed objects beneath the scotoma within the first days following the lesion, but other aspects of eye movement adaptation, such as the ability to consistently make saccades to a single extra-foveal location rather than the lesioned fovea, required several additional weeks of adaptation. Our results also suggest different rates of adaptation to a central scotoma, suggesting that sensorimotor plasticity is taking place in multiple steps.

4.6. Position in visual space influences viewing strategy

The position of words in visual space clearly influenced viewing strategy for isolated letters/words and paragraphed text in the horizontal and in the vertical scotoma groups. Subjects in the horizontal group positioned their scotoma above the letters/words and text more frequently for stimuli positioned inferiorly in visual space compared to superiorly-positioned stimuli. Subjects in the vertical group positioned their scotoma more frequently to the left or to the right for stimuli in right and left visual space respectively. For the horizontal group this dependence upon stimulus position diminished over the sessions between the middle and lower words as they attained approximately 95% viewing time using the inferior visual field, whereas the viewing strategy for the upper words appeared to plateau between 40% and 50% use of the inferior visual field. A diminished effect of visual space on viewing strategy over the sessions was obvious for the horizontal group for the text passages. For the vertical group, the effect of visual space also diminished, yet to a lesser extent, across sessions for the letter/word reading tasks. A decreased dependence of viewing strategy on stimulus position may directly reflect the emergence of a similar viewing strategy across different positions of gaze. Stimulus position in visual space has also been shown to influence viewing strategy during reading in a well-adapted patient with a central scotoma (Déruaz et al., 2002).

The effect of stimulus position on viewing strategy may be related to a preference to view stimuli adjacent to the closest scotoma border. Once a stimulus appeared above fixation, for example, in the case of the horizontal scotoma, the vertical component of a saccade required to position the upper scotoma border adjacent to the centre of the word was 2° (7°—1/2 scotoma width), compared to a required vertical component of 12° to position the lower scotoma border adjacent to the word centre. Thus subjects may have chosen to use the visual field to the side of the scotoma that required the smallest eye movement, and perhaps also the least effort or fewest refixation movements before the stimulus could be deciphered.

The effect of stimulus position could also indicate that orbital eye position influences viewing strategy. Subjects may try to keep the eye as close as possible to the primary position of gaze. Perhaps it is less demanding to keep the eye stable during eccentric fixation when the eye is centred in the orbit. As little information exists regarding the effect of visual space, or position of gaze, on viewing strategy in clinical patients, this should be further investigated.

Acknowledgments

This study was possible through the generous financial support of the Pro Visu Foundation. Thank you also to Anouk Déruaz for her critical reading of the manuscript.

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