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Reading with optical magnifiers: page navigation strategies and difficulties

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Abstract

Purpose—To read efficiently with a simple hand or stand magnifier, people with visual impairment have to move (navigate) the device along each line (forward phase) and back to the correct position at the start of the next line (retrace phase). Page navigation difficulties have been implicated as limiting factors when reading with hand and stand magnifiers, but have not been objectively measured.

Methods—Magnifier movements were recorded using a 3SPACE Isotrak system for 43 participants with age-related macular degeneration (AMD) who read two short stories using their habitual hand or stand magnifier. Page navigation was quantified in terms of magnifier movements and navigation errors for the forward and retrace phases. Visual acuities and visual fields were measured, and magnifier usage and page navigation difficulties were surveyed.

Results—During the forward phase participants primarily used either a straight (47%) or diagonal downward (46%) movement, whereas during the retrace phase the majority (56%) used a downward movement. On average, forward navigation time was four times longer than retrace navigation time ($p < 0.001$). The most common navigation error was incorrect positioning of the magnifier at the end of the retrace movement. Near word acuity correlated strongly with forward time ($r = 0.78$), and moderately with retrace time ($r = 0.53$) and forward errors ($r = 0.50$). Vertical field of view correlated with retrace errors ($r = -0.53$). Participants' estimates of page navigation difficulties were not predictive of objective measures of performance.

Conclusions—We quantified page navigation strategies and difficulties of people with AMD reading with magnifiers. Retrace, which presents the most common difficulty, is not well predicted by vision measures or magnifier characteristics; future studies should investigate the relationship between motor skills and navigation performance, and the impact of training or devices on reducing retrace navigation difficulties.

Keywords

Macular degeneration; reading; page navigation; magnifiers

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Introduction

Optical magnifiers, such as hand and stand magnifiers, are commonly prescribed to assist visually impaired people with reading. The task for which a magnifier is used may vary from spot reading, such as finding the total on a utility bill, to fluent reading of a newspaper or a novel[1]. Due to the restricted field of view, the magnifier has to be moved to locate the required information (e.g., the total on the utility bill) or the start of a new line, and/or read a line of text. Good control and the adoption of efficient patterns of magnifier movement are fundamental to the successful use of both hand and stand magnifiers. Clinical experience suggests that some patients have difficulty with navigating a magnifier around the page, reporting that they miss lines or repeat lines when reading[2]. An understanding of how visually impaired readers actually use their hand and stand magnifiers is relevant to the development of improved methods of training.

Previous studies of magnifier movements have either used fully-sighted participants reading with optical magnifiers[3, 4] or visually impaired participants reading with closed-circuit television (CCTV) systems[5, 6]; to our knowledge magnifier movements of visually impaired readers using optical magnifiers have not been investigated. Optical magnifiers tend to be prescribed more commonly than CCTVs[7, 8] and the method of using an optical magnifier is very different from that of a CCTV. In the study by Neve[3], hand magnifiers were moved across a glass plate, which was positioned parallel to and at a fixed distance from the text; thus the participants did not have to maintain the magnifier at the correct distance from the page, which removed one of the usual requirements of using a hand magnifier.

In this study we recorded the magnifier movements of visually impaired participants with age-related macular degeneration reading short paragraphs of text with optical magnifiers. The primary aim was to provide an objective quantification of page navigation performance in terms of magnifier movement patterns, navigation times and navigation errors. The navigation movements necessary to read a paragraph can be divided into two phases[6]: the forward phase during which the magnifier is moved from left to right as the user reads along each line (reading English), and the retrace phase when the magnifier is moved to the left from the end of one line to the start of the next line. We expected that the primary navigation movement in the forward phase would be in the horizontal direction (along the line) with little vertical displacement, while in the retrace phase the navigation movement would include both vertical and horizontal components to return the magnifier to the start of the next line.

Secondary aims of the study were to examine the relationships between objective navigation performance measures and self-ratings of perceived navigation difficulties, and to evaluate factors affecting page navigation performance, including vision measures (visual acuity and central field loss), magnifier characteristics (field of view and equivalent viewing distance) and magnifier usage (frequency and experience of use). As visual and cognitive processing requirements are greater in the forward than the retrace phase, we expected that vision measures would be more strongly related to forward than retrace navigation performance (time and errors). Previous studies reported a strong dependence of navigation times on horizontal field of view[4–6], but the impact of a restricted magnifier field on navigation errors has not been investigated. Due to potential difficulties in finding the start of a new line within a restricted vertical field, we predicted that vertical field of view would be associated with errors in retrace but not forward navigation. Furthermore, we predicted that participants who used their magnifiers less frequently or had been newly prescribed a magnifier would demonstrate and report poorer navigation skills (more errors and less efficient movement patterns).

Methods

Participants

Forty-three visually impaired participants with a primary ocular diagnosis of age-related macular degeneration were recruited through the Vision Rehabilitation Centre (VRC) at Queensland University of Technology (QUT). The main inclusion criteria were that participants used an optical magnifier as the primary low vision device for reading, threshold print size with the magnifier was 0.75M (N6) or better and critical print size (minimum print size for maximum reading rate) was 1.5M (N12) or better. The latter criteria ensured that reading rate was not limited by print size as participants could comfortably read the 1.5M print of the test passages with their magnifiers.

All participants had received a comprehensive low vision assessment at the VRC within the 6 months prior to participation in the study. Participants were generally in good health with no cognitive problems that might affect their ability to participate in the study (as determined from record cards, self-reports and clinical observations). All participants had received instruction in how to use their magnifiers as part of their routine clinical care at the VRC, but none had undergone any formal skills training in navigation strategies. They were all fluent English speakers and gave signed, informed consent to their participation in the study. The study followed the tenets of the Declaration of Helsinki and was approved by the QUT Human Research Ethics Committee.

Magnifiers

Participants used their preferred magnifier for the study, i.e. the magnifier they used most frequently, in conjunction with their habitual spectacles (if any). Ten participants used a hand magnifier and 33 used a stand magnifier. Magnifiers were characterized in terms of field of view and equivalent viewing distance. Horizontal field of view, measured in character spaces, was determined by each individual participant while reading blocks of 1.5M letters through the magnifier at the self-selected, habitual viewing distance used in the reading task. In addition, the first 20 participants also determined the vertical field of view, measured in lines of single-spaced text. The magnifying effect of the magnifier-spectacle lens combination was specified in terms of the equivalent viewing distance (EVD), the viewing distance at which the original object would subtend the same angular size as that subtended by the enlarged image formed by the magnifier-lens system[9] (the equivalent power of the system is the reciprocal of the EVD). EVD was determined taking account of the equivalent power of the magnifier, the object distance from the magnifier and the magnifier-eye distance used during reading[9]. Magnifier usage was quantified in terms of frequency of use (rated on a 4-point scale) and experience of use (participants who had been prescribed a magnifier within the previous 2 months were classified as new users).

Vision assessment

Visual acuity was recorded monocularly and binocularly using the habitual spectacle prescription (corrected for viewing distance when necessary). Distance visual acuity was measured using a Bailey-Lovie distance letter chart[10] and near word visual acuity using a Bailey-Lovie word chart[11], scored to the nearest letter and word respectively. Near threshold print size and critical print size were recorded with the preferred magnifier when reading single sentences on the MNRead chart[12, 13]. Central visual fields were assessed monocularly using 5mm and 10mm white targets on a Tangent screen at a viewing distance of 1m. A large letter "E" (20/400) was used for fixation; participants were instructed to maintain their gaze so that the target was as clear as possible, using either central or eccentric viewing. Central field loss was categorised as the presence or absence of scotoma within the central 5° radius.

Measurements from the eye used for reading, or the eye with the better near acuity if the participant read binocularly, were included in data analyses.

Subjective assessment of page-navigation difficulties

Subjective difficulties with page navigation were determined prior to any experimental testing by asking participants to rate on a 5-point scale the difficulty they experienced in their day-to-day use of their magnifier in: a) moving the magnifier from word to word along a line (forward navigation) and b) moving the magnifier back to find the start of the next line (retrace navigation). They were also asked to indicate, on a 5-point scale, the frequency with which they tended to lose their place, miss or repeat a line (i.e. make an error of navigation) when reading with their magnifier.

Reading task

Participants completed two reading trials, reading one short story in each trial with the aid of their magnifier. The two stories were derived from standardized children's reading material (Oxford Progressive English Readers, Grades 3 and 4). Each story was about 90 standard words in length (a standard word contains 6 characters[14]) and was printed in 1.5M (12 point) Times Roman font, formatted in one paragraph (7 lines of text) with a line length of 15cm and single line spacing. The reading material was placed on an inclined wooden reading stand (Figure 1). As far as possible participants adopted habitual eye-magnifier and magnifier-page distances when reading, viewing either monocularly or binocularly, as they normally did when reading with their magnifier at home. The posture adopted depended on the eye-magnifier and magnifier-page distances used (from bent over the magnifier for very short viewing distances to upright posture for longer viewing distances). Extra illumination was provided (on a case-by-case basis) by an angle-poise lamp positioned to suit the individual. Participants were instructed to read aloud at their normal reading speed and to read for understanding. All participants were given adequate time to become familiar with the experimental set up and they all read a complete practice passage before recording commenced.

Recording of magnifier movements

Magnifier movements were recorded using a 3SPACE Isotrak system (Polhemus Navigation Sciences Division, Kaiser Aerospace, Vermont, USA) while participants read each of the stories. This instrument comprises a source, which generates a low frequency (10 Hz) electromagnetic field, and a sensor. The source was securely attached to the rear of the reading stand with its X, Y and Z planes aligned to the X, Y and Z planes of the reading stand (and hence the reading material). The sensor was firmly attached to the participant's own magnifier in such a way that it did not interfere with the balance or handling of the magnifier (Figure 1). As the magnifier was moved across the page, the sensor sampled the magnetic field produced by the source, giving a continuous output of sensor position, and hence magnifier position, in 3D space. Magnifier position was sampled at a frequency of 10 Hz and the spatial resolution of the system was 1mm over the range of distances used in the study.

Analysis of magnifier movements

The first stage in the analysis was a visual inspection of magnifier movement traces to gain an overview of the magnifier movements before quantitative analyses were performed. Magnifier X-, Y- and Z-positions were plotted as a function of time, representing horizontal left and right movements across the page, vertical movements up and down the page (between lines), and movements towards and away from the page, respectively. In addition a 2D representation of magnifier movements (a plot of X-Y positions) was used to aid interpretation of movement patterns, with any ambiguities being resolved by watching the path of a cursor moving from point to point along the path taken by the magnifier.

After visual inspection, magnifier movement categories and parameters were then quantified from raw data recordings using Matlab and Excel routines. Forward and retrace magnifier movements were analyzed for five lines of text starting from the initiation of the first clear rightward (forward) movement at the beginning of the second line to the termination of the retrace movement after the 6^{th} line, just before the start of the forward movement on the 7^{th} (last) line.

i) Magnifier movement categories—Magnifier movement patterns for the forward and retrace phases were categorized from X-Y plots as straight (if there was no difference in vertical position between the start and end of the movement across a line), upward (if the end position was higher than the start position), or downward (if the end position was lower than the start position). The vertical distance between the centers of adjacent lines was 5mm; therefore a 3mm change in vertical position (more than half a line) was adopted as the minimum criterion for these classifications. Within the upward and downward categories, the main pattern of across-page movement was along a diagonal path (Figure 2), although arc-shaped and V-shaped paths were also observed. In the latter 2 cases, the categorization was made on the basis of the direction of the initial movement. For participants who did not consistently use the same movement pattern on all lines, the classification was based on the movement used for 50% or more of lines.

ii) Magnifier movement parameters—The main magnifier movement parameters are summarized in Tables 1 and 2. Navigation times and horizontal distance moved on each line during the forward and retrace phases were derived using Matlab routines from plots of magnifier movements in the X-plane (Figure 3). The start of the forward phase was defined as the first clear rightward movement at the start (left hand side) of a line (e.g., points B, D, F) and the start of the retrace phase was defined as the first clear leftward movement at the end (right hand side) of a line (e.g., points A, C, E). Forward navigation time (the duration of the forward phase) and distance were determined for the time period between the start of the forward movement and the start of the retrace movement (B to C, D to E). Retrace navigation time (the duration of the retrace phase) and distance were determined for the time period between the start of the retrace movement and the start of the next forward movement (C to D, E to F).

On some plots of magnifier X-plane movements, there was a period at the end of the retrace movement where there was little change in horizontal position (e.g. Figure 3c, just before points B and D). These sections were classified as part of the retrace phase as they occurred before the initiation of the forward movement. Examination of the Y-position or X-Y position plots revealed that the magnifier was being moved in the Y-plane during this period; the user was finding the correct vertical position for the magnifier at the start of the next line to be read (Figure 2).

In addition, the following parameters were determined for the first 20 participants (10 using hand and 10 using stand magnifiers): the change in vertical position (vertical displacement) of the magnifier between the start and end points of the forward and retrace phases for each line, and the standard deviation (variability) of the distance of the magnifier from the reading material between the start and end points of the analysis (Table 1). The variability of the distance of the magnifiers from the page was expected to be greater for hand-magnifier users than stand-magnifier users.

The following magnifier movement parameters (defined in Table 2) were classified as errors of navigation: a missed or repeated line, overshoots and undershoots, pauses and regressive movements, and corrective vertical movements (typically occurring in the middle of the forward movement and at the end of the retrace movement). As errors occurred relatively infrequently, the total numbers of errors per passage for the forward and retrace movements were determined.

Statistical analyses

Analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 11.5. In order to achieve frequency distributions that were not significantly different from normal distributions (Kolmogorov-Smirnov Goodness of Fit test, $p > 0.05$), forward and retrace times were log transformed. Associations between page navigation measures (magnifier movement categories, navigation times and navigation errors) and vision measures (visual acuity and presence of central field loss), magnifier characteristics (EVD and field of view) and magnifier usage (frequency and experience of use) were evaluated using parametric or non-parametric statistics, as appropriate. A probability of less than 0.05 was taken to indicate statistical significance for all analyses.

Results

Sample characteristics

Demographic, functional and magnifier characteristics for the sample are summarized in Table 3. As would be expected for those with age-related macular degeneration, the participants were elderly (75% over 77 years of age), the majority (67%) had a scotoma within the central 5° radius of the visual field and reduced visual acuity (mean near word acuity 0.89 logMAR, 2M or N16 at 25cm, with spectacles only). Those without a scotoma in the central 5° had significantly better distance and near visual acuity than those with scotomas (mean near word acuity 0.61 ± 0.25 and 1.04 ± 0.28 logMAR, respectively; unpaired t-tests, $t = -5.1$, $df = 40$, $p < 0.001$); 14% ($n = 2$) of those without a central scotoma had a paracentral scotoma outside the central 5° radius. Almost one-third of the participants ($n = 13$) were new magnifier users, having been prescribed a magnifier within the past 2 months. The majority (67%) used their magnifier either frequently or regularly (at least once per day for at least 5 minutes at any one time).

Magnifier movement categories

During the forward phase, participants used either straight or diagonal downward movements, whereas during the retrace phase, downward (mainly diagonal) movements predominated (Table 4). The pairings of forward and retrace movement categories, which occurred most commonly, were (Table 4): forward straight with retrace downward (28%; e.g., Figure 2a), forward downward with retrace downward (21%), and forward downward with retrace upward (19%; e.g., Figure 2b). There were no significant differences between the two reading trials in the percentage of participants using each of the main magnifier movement categories (Wilcoxon Signed Ranks Test, Forward $z = -1.3$, $p = 0.2$; Retrace $z = -0.7$, $p = 0.5$); over 80% of participants used the same movement category in both trials (83% and 88% for forward and retrace respectively). For analyses reported below, the magnifier movement category from the first trial was used.

Magnifier movement parameters

In general, magnifier movement parameters were not significantly different for the two reading trials (paired tests; $t < 1.8$, $df = 40$, $p > 0.07$; $z < -1.4$, $p > 0.2$). The only parameter with a significant difference was log forward time, which was slightly shorter (about 0.5s) on the second trial ($t = 2.3$, $df = 40$, $p = 0.03$). Data reported in subsequent analyses were the average of the two trials, except for the 2 participants who did not complete trial 2, in which case data from their only trial were used.

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Although forward and retrace horizontal movement distances were similar (as expected), forward navigation time was about four times longer than retrace navigation time, thus the velocity of movement during the retrace phase was significantly faster than during the forward phase ($p < 0.001$, Table 5). Horizontal movement distance was significantly related to the horizontal field of view of the magnifier ($r = -0.76$, $p < 0.001$); as the field of view decreased, the magnifier had to be moved further across each line. Vertical displacement of the magnifier per line and vertical field of view were measured for 20 participants, but no relationship between these variables was found ($p > 0.1$). The total vertical displacement per line (sum of forward and retrace vertical displacements, Table 5) was 0.4 ± 0.1cm, which is similar to the actual 0.5cm inter-line separation. Vertical displacement was also expressed as a percentage of the vertical magnifier field: a minority of participants, who used magnifiers with a narrow vertical field of view (≤ 2.5cm or 5 lines), displaced their magnifiers vertically by more than 30% of the vertical field of view (Figure 4). This was the case for 3 participants (15%) in the forward phase (of whom 2 also demonstrated poor navigation with either a large number of navigation errors and/or long forward times) and 3 participants (15%) in the retrace phase (of whom 2 also made a large number of retrace errors with long retrace times). Across the 20 participants, the median *absolute* vertical displacements per line in the forward and retrace phases were 13% (IQR 7 to 18%) and 8% (IQR 3 to 21%) of the vertical magnifier field, respectively.

In general, the total number of navigation errors was quite low (23 participants made ≤ 5 errors per passage), with 6 participants making no errors during the forward phase and 4 participants making no errors during retrace. However, a minority of participants did make many errors; 5 participants made a total of 15 or more errors per passage. The errors made during the forward phase were vertical corrective movements, regressions and pauses (Figure 5). The main error made during retrace was vertical corrective movements. Vertical corrective movement size was measured for 20 participants. As might be expected, larger vertical corrective movements were made in retrace than in the forward phase (median (IQR), 0.6cm (0.4 to 0.7cm) and 0.4cm (0.4 to 0.5), respectively). The median vertical corrective movement extents were equivalent to 20% (retrace) and 11% (forward) of the vertical field of view. During the forward phase, there was only 1 participant (5%) who made vertical corrective movements that were greater than 30% of the vertical field of view, whereas, during the retrace phase, there were 5 participants (25%) who did so. Undershoots and overshoots occurred during the retrace movement, but not the forward movement (Figure 5). Missed and repeated lines occurred only rarely: 2 participants missed a line and 1 participant repeated a line.

Subjective ratings of page-navigation difficulties

Participants reported significantly less difficulty with forward movement of the magnifier than with retracing it to the start of the next line (Wilcoxon Signed Ranks test, $z = -4.6$, $p < 0.001$); 65% reported no difficulty with forward movement, but only 19% reported no difficulty with retrace. The navigation error of missing or repeating a line was reported to occur either rarely (32%), sometimes (42%) or frequently (21%); only 5% reported that this error never occurred. Participants who reported greater retrace difficulty also reported a higher frequency of missing/repeating a line (Spearman $r = 0.5$, $p = 0.001$).

We hypothesized that participants who were newly prescribed a magnifier, or who used a magnifier infrequently, would report greater page navigation difficulty than more experienced users. However, there were no significant associations between these variables and ratings of perceived forward or retrace navigation difficulties (new user: Mann Whitney U, $z < -0.8$, $p > 0.5$; frequency of use: Kruskal Wallis, $\chi^2 < 3.0$, $p > 0.4$). We also evaluated the relationship between subjective ratings of page navigation difficulties and our objective measures of navigation performance. Contrary to expectations, there were no significant correlations between self-rated forward navigation difficulties and forward time or errors (Spearman $r < -0.2$, $p > 0.3$), and no significant correlations between self-rated retrace navigation difficulties and retrace time or errors (Spearman $r < 0.1$, $p > 0.4$).

Factors affecting page navigation performance

There were no significant associations between magnifier movement categories and vision measures (with one exception), magnifier characteristics or magnifier usage for forward and retrace navigation. The one exception to this was that participants with poorer vision (a central field loss and worse visual acuity) were more likely to adopt an upward retrace movement (CFL: $\chi^2 = 8.9$, df = 2, $p = 0.01$; near word acuity: $F_{(2,40)} = 2.7$, $p = 0.08$). Contrary to our expectations, neither experience nor frequency of magnifier use had any significant association with the movement category for the forward or retrace phases (new user: $\chi^2 < 4$, df = 2, $p > 0.1$; frequency of use: $\chi^2 < 10$, df = 6, $p > 0.1$).

Table 6 summarizes correlations between magnifier movement parameters, vision measures and magnifier characteristics for forward and retrace navigation. As expected, near word acuity was more strongly correlated with forward movement parameters than retrace movement parameters; the worse the near word acuity, the longer the forward time ($r = 0.78$, $p < 0.001$; Figure 6) and the greater the number of forward errors made (Spearman $r = 0.50$, $p = 0.001$). Furthermore, presence of visual field loss within the central 5º radius was associated with longer forward times, but not longer retrace times (unpaired t-tests, $t = -3.3$, df = 40, $p = 0.002$ and $t = -0.9$, df = 40, $p = 0.37$, respectively). As predicted, magnifier characteristics were significantly correlated with navigation times; the narrower the horizontal field of view and the shorter the equivalent viewing distance (higher equivalent power), the longer the forward and retrace times ($r > -0.65$, $p < 0.001$ and $r > -0.43$, $p < 0.005$, respectively). The relationship between vertical field of view and navigation errors was examined for the 20 participants with vertical magnifier field measurements. In line with our predictions, vertical field of view correlated with number of retrace errors, but not forward errors (Spearman $r = -0.53$, $p = 0.02$ and $r = -0.28$, $p = 0.24$, respectively); as the vertical field decreased, the numbers of retrace errors increased (Figure 7). We expected that new magnifier users, or participants who used a magnifier infrequently, would demonstrate poorer navigation skills; however, there were no significant associations between these variables and navigation errors (new user: Mann Whitney U, $z < -0.4$, $p = 0.7$; frequency of use: Kruskall-Wallis, $\chi^2 < 3.3$, df = 3, $p > 0.3$).

Use of hand magnifiers

Although the variation of the distance of the magnifier from the page (movements in the Z-plane) was not the main focus of this study, it is nevertheless an additional measurement of page navigation performance that is important when evaluating participants' ability to use hand magnifiers. Variations in the magnifier-page distance may cause both optical defocus and changes in magnification. As expected, the variability of the distance of the magnifier from the reading material was significantly greater for the 10 hand-magnifier users than the 10 stand-magnifier users for whom the magnifier-page distance was measured (mean standard deviation of magnifier-page distance 0.5 ± 0.3cm and 0.2 ± 0.1cm, respectively; unpaired t-test, $t = -2.9$, df = 18, $p = 0.008$). There were clear variations in magnifier-page distances for the hand-magnifier users. Four participants gradually held the magnifier closer to the page during the reading of a passage (decreasing the magnifying effect and possibly inducing blur), with more than a 10% difference (expressed as a percentage of the mean magnifier-page distance for the whole passage) between the start and end of the passage. Two participants showed the opposite tendency holding the magnifier more than 10% further away from the page at the end of the passage than the start, increasing the magnifying effect and possibly inducing some blur. There were four participants for whom the magnifier z-distance consistently decreased while reading across each line and then increased during the retrace movement as the magnifier was raised back to the original distance from the page, and two participants who showed the opposite behavior.

Discussion

Magnifier movement patterns

When reading along a line (forward phase) participants primarily used either a straight or diagonal downward movement. A straight movement, keeping the vertical positioning of the magnifier constant across the line, is the movement pattern that we expected for the forward phase; the downward movement was surprising. The vertical displacement per line in the forward movement was typically about 13% of the vertical field of the magnifier and would probably have had little functional impact on navigation or reading performance, as the participant would have been viewing through relatively central parts of the lens at all times. Only 3 of the 20 participants for whom vertical field was measured showed vertical displacements of more than 30% of the vertical magnifier field. This might have resulted in the text of interest being viewed through peripheral lens areas with poor image quality, or possibly even outside the field of the magnifier. These 3 participants used magnifiers with very restricted vertical apertures (≤ 2.5cm or 5 lines) and 2 of them demonstrated poor forward navigation performance.

During the retrace phase, the majority of participants used a downward movement, with only a minority using a straight or upward retrace movement, such that the most common forward and retrace movement pairing was a straight movement during the forward phase followed by a downward retrace movement. Some low vision practitioners train patients to use navigation strategies involving a straight retrace movement[2], retracing the magnifier along the line just read and then moving down to the next line. If patients are not taught specific retrace strategies, as was the case for our participants, it appears that they naturally use a diagonal downward retrace movement when using a hand or stand magnifier. A diagonal downward retrace strategy is the most efficient in terms of distance traveled, but is possibly more difficult to perform accurately than a straight retrace strategy. By comparison, Beckmann and Legge[6] reported for low-vision and normally-sighted readers using CCTVs, that the most commonly used retrace movement was the straight strategy of returning along the line just read and then dropping down to the next line, which is probably the easiest strategy when controlling the XY platform of a CCTV.

This is the first attempt to categorize observed patterns of magnifier movements when reading with optical magnifiers and we might have used too stringent a criterion for differentiating straight and non-straight movements. Furthermore, the magnifier movements were only recorded in one set up, which although it attempted to approximate the habitual reading situation, was nevertheless not the participant's usual reading environment. Different movement patterns might have been recorded if we had used a flat rather than an inclined reading stand.

Errors of navigation

The main errors of navigation during the forward phase were regressions, pauses and variations in the vertical position of the magnifier, which usually resulted in corrective vertical movements that were smaller than the 0.5cm inter-line separation. Pauses and regressions are evidence of poor coordination between hand (magnifier) and eye movements, e.g., the magnifier was moved too quickly such that a word was missed or there were difficulties with visual word recognition (if part of the word fell within the scotoma). By comparison the main navigation error during retrace was incorrect vertical positioning of the magnifier at the start of the next line resulting in a number of corrective vertical movements at the end of the retrace phase that typically were larger than the 0.5cm inter-line separation. The retrace movement (unlike the forward movement) is a fast movement and is unlikely to be closely visually guided, resulting in position errors which are only detected and corrected at the end of the retrace when close visual guidance is again engaged prior to reading the next line. For normally-sighted participants using hand magnifiers, Neve[3] also reported a greater number of pauses and corrections at the start of a new line, than the middle or end of the line.

Our magnifier movement recordings show clear evidence that some participants had difficulty finding the start of the next line (e.g. Figures 2b and 3c). It is possible that retrace performance could be improved by skills training to use specific retrace strategies[2] (but to our knowledge this has never been evaluated with magnifier movement recordings), or by using additional devices such as a finger placed at the start of the line just read[2], a typoscope placed under the line[2] or a line guide fitted to the base of a stand magnifier[15].

Subjective ratings of page navigation difficulties

Subjective estimates of page navigation difficulties were not related to any of the objective measures of page navigation performance. Given that 63% of participants reported missing a line sometimes or frequently when reading and 81% reported at least some difficulty with retrace, we expected to find more evidence of page navigation difficulties from the magnifier movement recordings. In fact only a minority of participants (12%) made a large number of navigation errors and there were very few missed or repeated lines. There are a number of reasons why this might be the case. Participants based their ratings of perceived difficulty on their experience of using the magnifier at home. These ratings were made prior to the reading test so it is possible that difficulty estimates might have been lower if based on the passages and reading environment used in the study. Participants probably read more carefully under the experimental conditions than they would at home, therefore fewer navigation errors might have been recorded than would normally occur. Our assessment and data analysis methods may have been insensitive to evaluating relevant page navigation skills, e.g. it is possible that our passages were too short to properly evaluate navigation problems. On the other hand, it is not surprising that some visually impaired people may overestimate the difficulties they encounter when using their magnifiers. Previous studies have demonstrated that subjective responses do not necessarily agree with the objective findings[16–18]. The discrepancies between self-reported and measured functions may be due to different underlying expectations and experiences[18]. Clinical experience suggests that many patients may have unrealistic expectations about reading with magnifiers and become frustrated by the slow reading speeds, short working distances and the need to move the magnifier about the page, which may contribute to overestimation of their difficulties.

Factors affecting page navigation

As expected, forward navigation time was longer than retrace navigation time and vision measures (primarily near word acuity) were more strongly associated with forward navigation performance than retrace navigation performance, reflecting the greater degree of visual and cognitive processing that occurs when reading along a line than the minimal processing that occurs during retrace. Although horizontal field of view was related to navigation times, especially forward navigation time (consistent with previous studies[4–6]), it was unrelated to either forward or retrace navigation errors. In general navigation errors were not well predicted by any of the vision or magnifier measures we evaluated. We did find a modest correlation between vertical field of view and retrace errors (narrower field, more errors), suggesting that the vertical magnifier field is important in the retrace phase of navigation; however, vertical field was measured for only 20 of the 43 participants. Navigation errors might be better predicted by other factors that we did not evaluate in this study, in particular motor skills including hand-eye coordination[3, 19] and manual dexterity[20]. The relationships between visual impairment, manipulative skills, hand-eye coordination and page navigation skills is an important area for future investigations.

Contrary to our expectations, neither experience nor frequency of magnifier use had any significant association with magnifier movement patterns, magnifier movement parameters or navigation errors. Page navigation skills might develop rapidly in the first few weeks after a magnifier is prescribed[4, 21, 22], but we had only 4 participants whose magnifier had been prescribed within the previous 2 weeks so we could not assess this in our sample. A longitudinal study, following participants from the time when the magnifier is first prescribed, would enable changes in navigation skills and magnifier movement strategies to be examined as participants learn to use the device.

This is the first study that has recorded magnifier movements from a relatively large sample of older visually impaired patients using optical magnifiers. We were able to quantify page navigation strategies, difficulties with page navigation and the ability of patients to hold a hand magnifier at a constant distance from the page. In the clinical setting it would not be practical to record magnifier movements. However, we suggest that in addition to assessing reading speed, low vision practitioners should routinely observe how patients move their magnifier when reading a short paragraph. Although we used experimental conditions that approximated real-world reading conditions and participants who represent the majority of elderly visually impaired people, our findings are limited to one set of reading conditions - reading short passages with hand or stand magnifiers. Nevertheless, this study provides a strong basis for future investigations, including changes in navigation skills after a magnifier is first prescribed, the impact of training specific navigation strategies, the use of devices to aid navigation and the relationship between motor skills and navigation skills[23].

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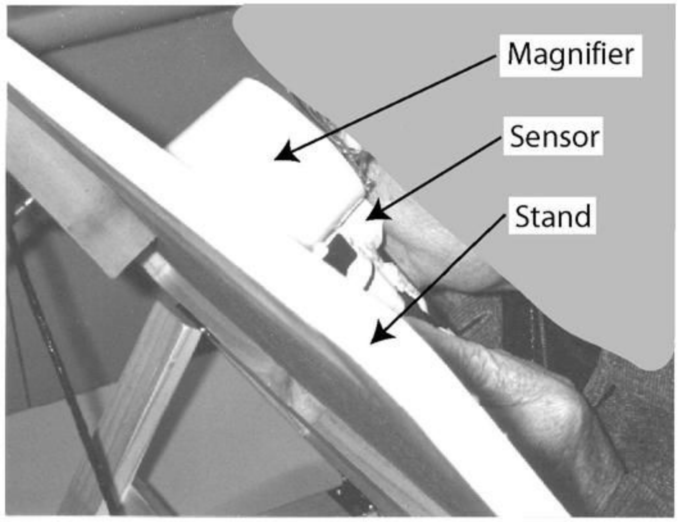

Figure 1.
Experimental set up used when recording magnifier movements. The position sensor was firmly attached to the participant's own magnifier (in this case a stand magnifier). The source was attached to the rear of the inclined reading stand on which the reading material was placed. Participants were encouraged to use habitual posture and eye-magnifier distances; in this case the eye-magnifier distance was very short (< 1cm).

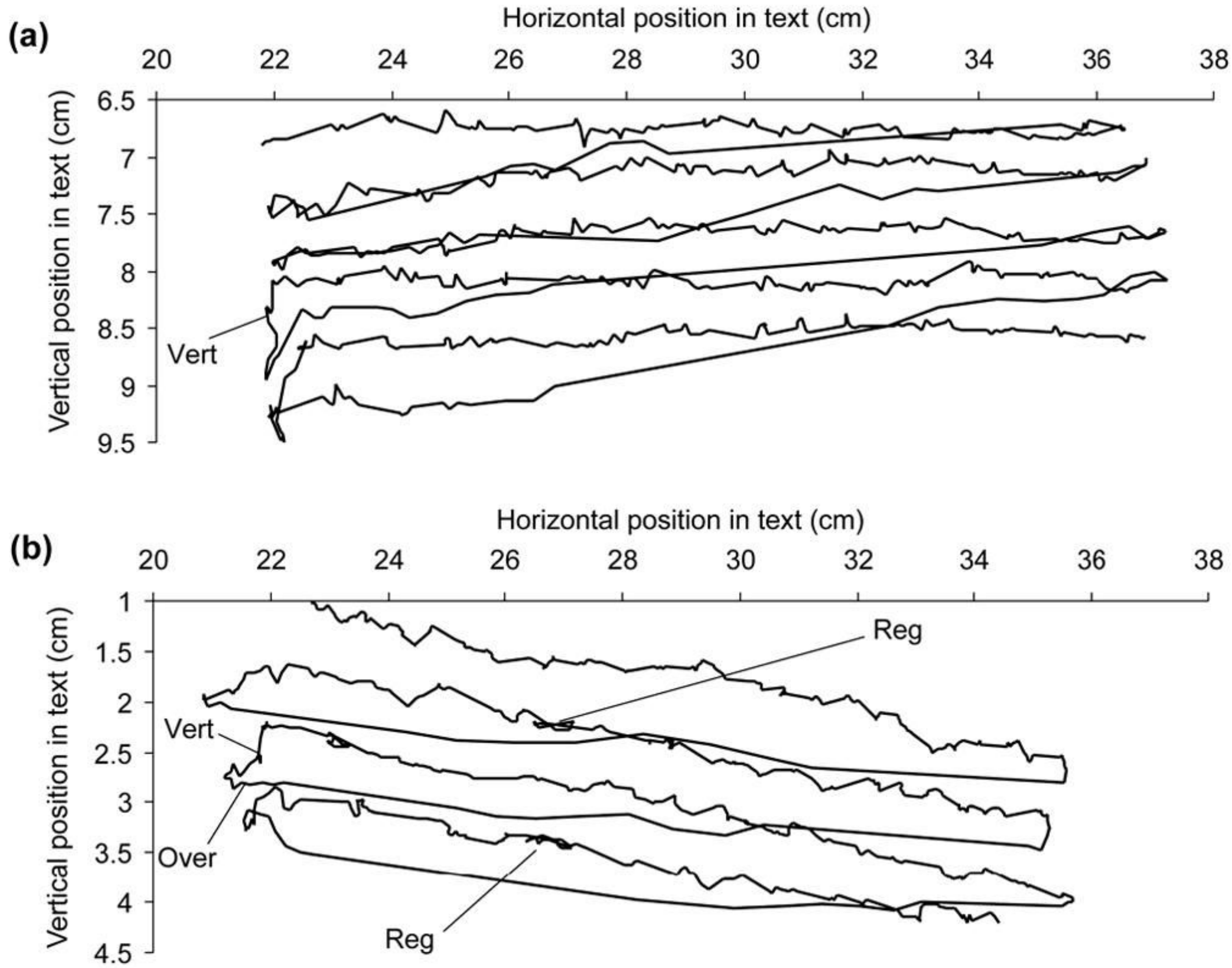

Figure 2.
Magnifier movement traces showing horizontal (X) and vertical (Y) positions of a magnifier as it was moved slowly forward to the right along each line of text and then retraced more quickly to the start of the next line. To enhance visibility of details, the vertical axes are on a larger scale than the horizontal axes. **(a)** Participant A32 using a hand magnifier (EVD 5cm) with a predominantly straight movement during the forward phase and a downward (diagonal) movement during retrace; corrective vertical movements (Vert) were used at the end of the retrace to place the magnifier at the correct vertical position at the start of the next line. **(b)** Participant A1 using a stand magnifier (EVD 2.5cm) with a downward (diagonal) movement during the forward phase and a predominantly upward movement during retrace; regressive movements (Reg) occurred during the forward phase, and an overshoot (Over) and corrective vertical movements (Vert) at the end of the retrace.

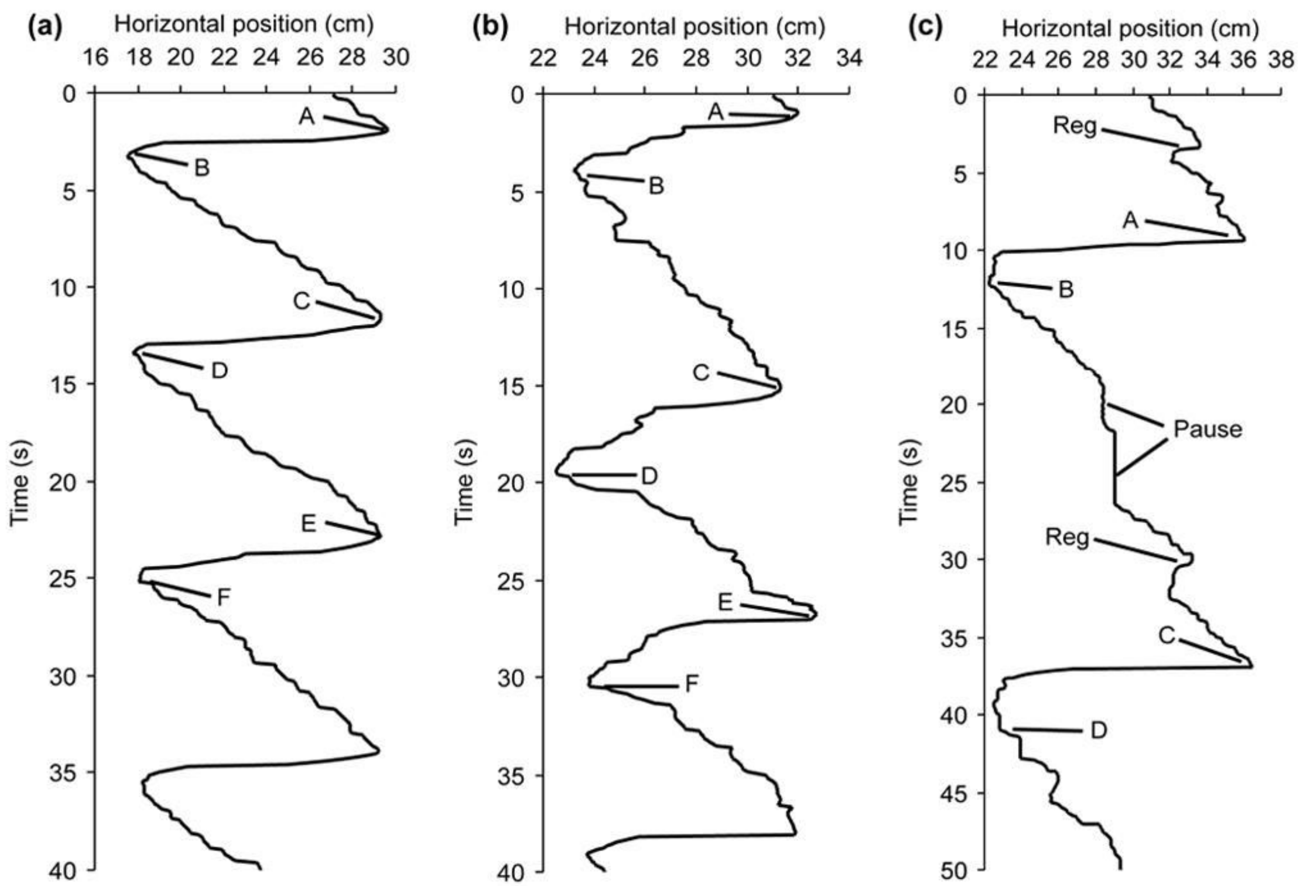

Figure 3.

Magnifier movement traces showing horizontal (X) position of magnifier as it was moved slowly forward to the right along each line (B to C, D to E) and then retraced more quickly to the start of the next line (C to D, E to F). (a) Participant A5 using a hand magnifier (EVD 10.5cm) with good navigation skills: forward movements were fairly smooth and the magnifier was moved at a constant rate without pauses or regressions and retrace was accomplished in a single movement. (b) Participant A16 using a hand magnifier (EVD 16cm) with poor retrace skills: retrace was slow and comprised more than one movement (c) Participant A8 using a stand magnifier (EVD 5cm) with poor forward and retrace navigation skills: forward movements were not smooth and included pauses and regressions (Reg); retrace was inaccurate with a period at the end of the retrace (just before B and D) during which there was no horizontal movement while the magnifier was being moved in the Y-plane to find the correct vertical position at the start of the next line.

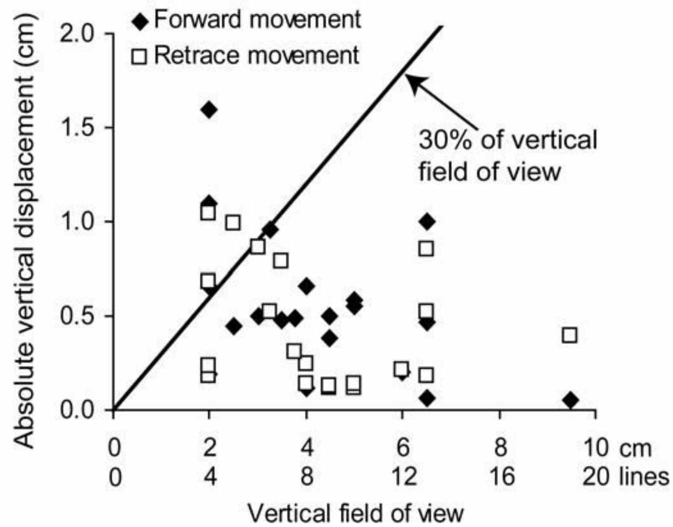

Figure 4.
Vertical displacement of magnifier per line for forward and retrace movements as a function of vertical field of view (n = 20). There was no relationship between vertical displacement and vertical field of view (p > 0.1). Three participants during the forward movement and three during retrace displaced their magnifiers by an amount that was more than 30% of the vertical field; all these participants used magnifiers with narrow vertical fields (£ 5 lines). The diagonal line across the plot represents vertical displacement values equivalent to 30% of the vertical field. To simplify the plot, the absolute values of the displacements are plotted.

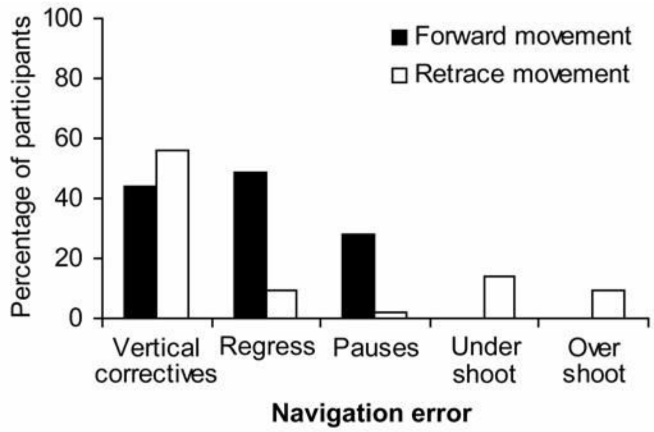

Figure 5.
Navigation errors: the percentage of participants who made each type of error at least once in both trials. Vertical corrective movements were the most frequently occurring error.

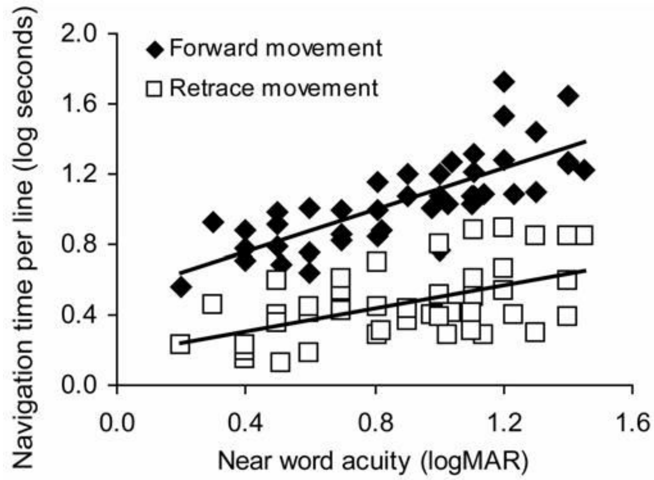

Figure 6.
Relationship between near word acuity and navigation times (n = 43). Near word acuity was strongly correlated with forward navigation time ($r = 0.78$, $p < 0.001$) and moderately correlated with retrace navigation time ($r = 0.53$, $p < 0.001$).

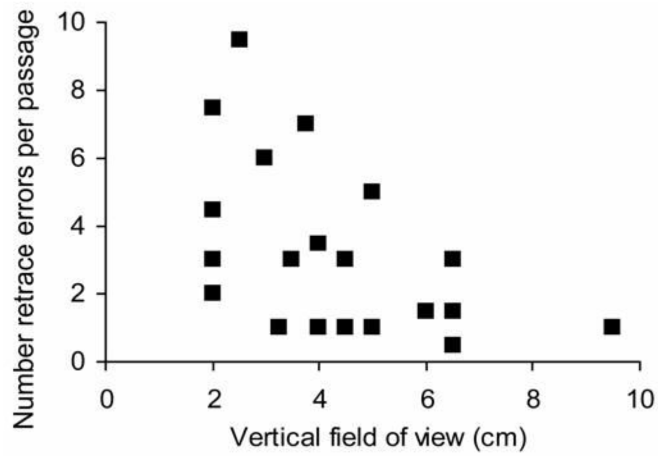

Figure 7.
Relationship between vertical field of view and retrace navigation errors (n = 20): errors increased significantly as the vertical field of view of the magnifier decreased (Spearman r = −0.53, p = 0.02).

Table 1

Summary of magnifier movement parameters: navigation distances and times

Parameter	Units	Description
Horizontal distance per line	cm	Difference in X-position per line between the initiation and termination of the forward or retrace movement
Vertical displacement per line	cm	Difference in Y-position per line between the initiation and termination of the forward or retrace movement
Magnifier-page distance variability	cm	Standard deviation of the distance of the magnifier from the reading material in the Z-plane
Navigation time per line	s	Time period between the initiation and termination of the forward or retrace movement

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Table 2

Summary of magnifier movement parameters: navigation errors

Parameter	Description
Pauses	A period of at least 2 seconds where the magnifier remained stationary in the X-plane during the forward or retrace movement across a line
Regressive movements	Movements (≥ 5mm) in the X-plane in the opposite direction to that in which the magnifier should have been moving in the forward or retrace phase.
Overshoots	Movements in the X-plane where the magnifier was moved too far beyond the end (forward phase) or start (retrace phase) of a line and there was a compensatory movement (≥ 10mm) in the opposite direction to bring the magnifier back to the correct X-position.
Undershoots	Movements in the X-plane which were not sufficient to bring the magnifier to the end (forward phase) or start (retrace phase) of the line and a compensatory movement (≥ 10mm) in the same X-direction had to be made
Vertical corrective movements	Movements primarily in the Y-direction of greater than 3mm that corrected an error in the vertical positioning of the magnifier.

Table 3

Demographic, functional and magnifier characteristics for the sample (n = 43)

Variable	N (%)	Descriptive statistics Mean ± SD	Median (IQR[a])
Demographic Characteristics			
Age (years)		80 ± 7	81 (77 – 84)
Gender			
Female	24 (56%)		
Months since onset of vision impairment		31 ± 47	20 (12 – 30)
Months since magnifier prescribed		7.6 ± 9.5	5.0 (1.4 – 8.3)
Functional Characteristics			
Distance visual acuity (logMAR)		0.74 ± 0.35	0.74 (0.42 – 1.06)
Near word acuity without magnifier (logMAR)		0.89 ± 0.33 (2M at 25cm)	0.98 (0.60 – 1.14) (2.5M at 25cm)
Threshold print size with magnifier (M units)		0.50 ± 0.17	0.50 (0.38 – 0.63)
Critical print size with magnifier (M units)		0.99 ± 0.26	1.0 (0.75 – 1.25)
Field loss in central 5° radius[b]	28 (67%)		
Magnifier Characteristics			
Type of magnifier			
Hand	10 (23%)		
Stand	33 (77%)		
Field of view			
Horizontal (character spaces)		19 ± 11	15 (10 – 26)
Vertical (lines)[c]		8.6 ± 4.0	8.0 (5.3 – 11.5)
EVD (cm)		10.3 ± 6.5	8.9 (4.6 – 15.9)
Eye-magnifier distance (cm)		13.4 ± 9.0	14.0 (4.0 – 20.0)
Reading speed for short paragraphs			
With habitual magnifier (words per minute)		67 ± 34	63 (40 – 85)

[a] Interquartile range

[b] Data not available for 1 participant

[c] Only assessed for first 20 participants

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Table 4

Percentage of participants using each of the main magnifier movement categories during forward and retrace navigation for trial 1 (n = 43)

		Retrace movement			Total
		Straight	Downward	Upward	Forward movement
Forward movement	Straight	12	28	7	47
	Downward	6	21	19	46[a]
	Upward	0	7	0	7[b]
Total	Retrace movement	18	56[c]	26[d]	

[a] All were diagonal downward

[b] All were diagonal upward

[c] 37% diagonal downward and 19% V shape

[d] 12% diagonal upward and 14% inverted arc shape

Table 5

Summary (mean ± 1SD) of magnifier movement parameters for forward and retrace navigation (n = 43)[a]

Parameter	Forward	Retrace	Paired tests (difference between forward and retrace)
Horizontal distance per line (cm)	11.4 ± 2.1	11.4 ± 2.1	t = 0.45, df = 42, p = 0.65
Vertical displacement per line (cm)[b]	0.4 ± 0.6[c]	0.0 ± 0.6	t = 1.23, df = 19, p = 0.23
Navigation time per line (log s)	1.05 ± 0.26	0.47 ± 0.21	t = 21.1, df = 42, p < 0.001
Velocity of movement (cms^{-1})	1.1 ± 0.5	4.1 ± 1.6	t = −14.8, df = 42, p < 0.001
Total number of errors per passage[d]	2.5 (0.5 – 6.5)	1.5 (1.0 – 3.0)	z = −2.3, p = 0.02

[a]Mean data of 2 trials for 41 participants and data from the only trial for 2 participants who completed only 1 trial.

[b]N = 20 (participants for whom vertical field of view was measured)

[c]Positive value indicates downward displacement

[d]Median (IQR)

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Table 6

Correlation coefficients[a] between magnifier movement parameters, vision measures and magnifier characteristics (n = 43).

	EVD	Horizontal field of view	Vertical field of view[b]	Log forward time	Forward errors	Log retrace time	Retrace errors
Near word acuity	−0.87***	−0.66***	−0.54*	0.78***	0.50**	0.53***	0.12
EVD		0.74***	0.64**	−0.73***	−0.30*	−0.51***	−0.14
Horizontal field of view			0.89***	−0.65***	−0.22	−0.43**	−0.11
Vertical field of view[b]				−0.67***	−0.28	−0.37	−0.53*
Log forward time					0.57***	0.71***	0.23
Forward errors						0.29	0.39**
Log retrace time							0.38**

[a]Pearson coefficients, except for correlations with forward errors and retrace errors which are Spearman

[b]N = 20

*p ≤ 0.05

**p ≤ 0.01

***p ≤ 0.001