Title

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Publication Date

2023-10-22

DOI

10.1145/3597638.3608383

Screen Magnification for Readers with Low Vision: A Study on Usability and Performance

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ABSTRACT

We present a study with 20 participants with low vision who operated two types of screen magnification (lens and full) on a laptop computer to read two types of document (text and web page). Our purposes were to comparatively assess the two magnification modalities, and to obtain some insight into how people with low vision use the mouse to control the center of magnification. These observations may inform the design of systems for the automatic control of the center of magnification. Our results show that there were no significant differences in reading performances or in subjective preferences between the two magnification modes. However, when using the lens mode, our participants adopted more consistent and uniform mouse motion patterns, while longer and more frequent pauses and shorter overall path lengths were measured using the full mode. Analysis of the distribution of gaze points (as measured by a gaze tracker) using the full mode shows that, when reading a text document, most participants preferred to move the area of interest to a specific region of the screen.

CCS CONCEPTS

• **Human-centered computing → Accessibility technologies** ; *Human-centered computing*.

KEYWORDS

screen magnification; visual impairment; reading

ACM Reference Format:
Meini Tang, Roberto Manduchi, Susana Chung, and Raquel Prado. 2023. Screen Magnification for Readers with Low Vision: A Study on Usability and Performance. In *The 25th International ACM SIGACCESS Conference on Computers and Accessibility (ASSETS '23), October 22–25, 2023, New York, NY, USA.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3597638.3608383

1 INTRODUCTION

For many people living with low vision, reading can be a major challenge, affecting quality of life and independence [9, 14]. Traditional magnification devices such as hand-held or stand magnifiers are increasingly being replaced by tools such as CCTV magnifiers [18], smartphone and tablet magnification apps [33, 52], or head-mounted displays [12] for reading text printed in physical form; and by screen magnification software for reading onscreen content. Indeed, a recent survey [53] of 130 people with low vision showed that 94% of this group used at least one type of digital content magnifier.

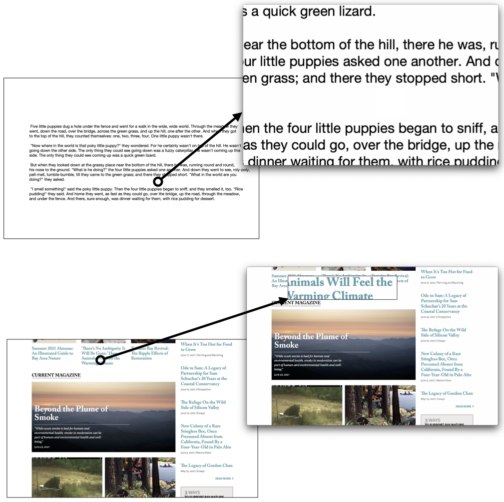

Figure 1: Screen magnification with the *full* (top) and *lens* (bottom) modalities. The center of magnification (shown as a circle in the un-magnified screen) is controlled using the mouse.

We focus here on screen magnification techniques for laptop or desktop computers, where the pointer (and thus the center of magnification) is controlled with a mouse or trackpad, rather than through touchscreen. While more and more textual content is consumed on smartphones and tablets (especially news and social media [15]), information access through computers remains very relevant (e.g.,

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ASSETS '23, October 22–25, 2023, New York, NY, USA

ACM ISBN 979-8-4007-0220-4/23/10.
https://doi.org/10.1145/3597638.3608383

computers were responsible for almost 30% of website visits globally in 2020 [15].) The ability to read on a computer screen is critical for professional activities, entertainment, and information access. An alternative to magnifying text is to use a screen reader, such as JAWS, Apple VoiceOver, or NVDA. For example, in a 2021 WebAIM survey with 1,568 screen reader users [50], 344 (22%) self-reported as having low vision / being visually impaired (as compared to 78% of the respondents self-reporting as being blind). While screen reading technology can be very helpful, many people with low vision still prefer, if given the opportunity, to read directly on the screen, possibly using magnification [47].

In this contribution, we present the results of a study with 20 participants with low vision, who were tasked with accessing two types of documents (a text document and a web page) using two magnification modes (*full* and *lens*) on a laptop computer (see Fig. 1). The *full* screen magnification mode expands the whole screen content, while the *lens* mode only magnifies a rectangular portion around the pointer. While other magnification modalities have been studied (see Related Work section), we concentrate on full and lens magnification here as they are relatively simple and intuitive to use, and they are already available under any operating system. We note that the common practice of expanding a pdf document or an image within a window, then moving the magnified content with the mouse or trackpad, is akin to full screen magnification, though limited to that window frame.

We had three main purposes for this study. First, we wanted to discover whether either of these two magnification modalities leads to more efficient reading; whether the participants had preferences for either modalities; and whether the participants' preferences were consistent with what was measured by the chosen metrics. Each mode has specific pros and cons. The *full* mode affords a magnified view of a relatively large portion of the screen, but provides no contextual cues about the location of the center of magnification in the un-magnified screen; while the *lens* mode lets the user see a large portion of the un-magnified screen, which can be used for spatial reference, but obscures a substantial portion under the lens window, and requires the user to precisely center at each time the area that needs magnification. Understanding this trade-off in both quantitative and subjective terms is a relevant scientific quest.

Our second purpose was to analyze the mouse traces while operating the magnifier, which may cast light on the preferred dynamics of text reading and screen exploration under magnification. This is particularly relevant in view of new, proposed technologies that aim to replace manual mouse control for magnified screen access. One such technology is *dynamic scrolling* [24, 41, 49] (or *drift* [45]), which simply presents a magnified text line scrolling right-to-left at constant speed. Another approach is to use the user's eye gaze to directly control the center of magnification [2, 37]. We believe that the design of these and similar systems should be informed by how users themselves control the location of the center of magnification through the mouse. We argue that an automatic control mechanism should, as much as possible, mimic the way users operate it manually, rather than impose a control policy that may feel unnatural and thus be poorly accepted.

Our third purpose was to evaluate the distribution of gaze points (or points of regard) on the screen while our participants were using the *full* mode magnifier. At large enough magnification levels, one has the freedom to move the magnified content of interest (i.e., the content currently being gazed at) in different areas of the screen. The distribution of gaze points tell us whether or not the participants preferred to move the center of magnification such that the portion of interest was always located within a certain region of the screen. This could inform the design and/or evaluation of an automatic magnification controller.

To accomplish these purposes, we collected a number of measurements. These include: the preferred magnification factor and (for the lens mode) the lens window size; reading speed for text documents, also taking into account the time spent while *retracing* (moving from the end of a text line to the beginning of the next one); consistency and uniformity of horizontal scrolling (panning); total path traversed with the mouse; total exploration time; and subjective assessments of difficulty. These measurements not only allow us to compare the two chosen magnification modes, but also give us precious insight into the way users operate these interface mechanisms.

2 RELATED WORK

2.1 Screen Magnification: Background

Screen magnification comes in various forms. Following the taxonomy proposed in [8], the *full screen* modality (or *full* for short; see Fig. 1) simply expands all of the screen content by a certain magnification factor (k) around a certain point (*center of magnification).* If the physical screen has size of $W \times H$, only a magnified portion of size $W/k \times H/k$ of the original onscreen content is visible within the screen viewport. The viewer controls the location of the center of magnification using the mouse or trackpad to ensure that the content of interest is visible in the viewport. Note that this is functionally identical to the familiar act of enlarging a picture or a PDF document in a viewer app (e.g., using pinch-to-zoom on the trackpad), then moving the picture or document within the window frame. The difference is that a screen magnifier expands the whole screen content, rather than only what is visible within a window. We should note that Responsive Web Design (RWD [17]), when available, represents an attractive alternative to the *full* magnification modality. While a screen magnifier increases the length of text lines proportionally to the magnification factor, RWD re-wraps the text content as it is magnified, in such a way that the horizontal extent of text lines remains constant (e.g., to fit the fixed size of a browser window). This eliminates the need for horizontal scrolling when reading magnified lines of text, a practice that is notoriously poorly accepted [46]. Unfortunately, RWD (or similar technologies) are not available for reading documents that cannot be reformatted (e.g., PDF documents).

The *lens* magnification modality [8] only expands a (typically rectangular) portion of the screen content, centered at the location of the pointer. This is akin to using a magnifying glass. The user can select the width and height of the *lens window.* A desirable property of the *lens* modality is that, by leaving most of the un-magnified screen visible, it makes it easier (in principle) to maintain awareness of one's location on the screen and thus to manage the "page navigation problem" [6]. In contrast, using the *full* magnification mode, only the magnified screen portion is visible. It should be noted, though, that only the portion of the un-magnified content outside the lens window is visible [44]. If the window has size of $w \times h$ for a magnification factor of k, only a $w/k \times h/k$ portion of the screen under the lens window is visible (within the lens window, magnified by k), while the rest is obscured by the window (see Fig. 1).

In order to mitigate the problem of obscured content under the lens window, various techniques have been proposed. For example, the *area* magnification mode [7, 8] expands the area under the pointer, but displays it in a different region of the screen. One can then maintain awareness of the content in the vicinity of the pointer, while reading its magnified version in another location. Experiments comparing this modality with the *lens* mode showed that, due the ensuing back-and-forth gaze motion between the pointer location and the magnified area, the *area* modality substantially reduces the speed of discovering and reading onscreen text. Another approach is to apply a non-isotropic transformation such as a fisheye lens [2, 19, 28], which however distorts the screen content without offering noticeable benefits in terms of usability [27].

2.2 Text Reading Performance

Early work from the 1970s and 1980s [29, 35, 38] studied the efficiency of text reading using CCTV magnifiers. These devices have an horizontally movable plate over which a document is laid face up. A downward pointing camera acquires images of the document, which are shown on a screen with the desired magnification. Users move the plate to center the desired portion of text under the camera. These studies focused in large part on the effect on reading speed of magnification, field of view (spatial extent of the magnified text), character spacing, and contrast polarity, among others.

A comparison between CCTV and three types of screen magnification modalities for text reading was presented in [22]. These modalities were: *MOUSE* (equivalent to *lens* in [8]); *DRIFT* (or *dynamic scrolling*, with text scrolling right-to-left at constant speed [24]); and *RSVP* (words of text shown one at a time at constant pace [16]). This study was highly controlled: for example, the lens size and magnification factor were fixed for all participants. Results with 12 participants with low vision showed a main effect of modality, though no significant pairwise differences between modalities were found. In particular, the *MOUSE* modality led to a 6% slower reading speed compared to CCTV. This work was extended to the task of finding all hyperlinks in a web page in [10].

Morrice et al. [40] compared reading speed using traditional magnifiers (e.g., magnifying lens), a CCTV device, and a 10 inch Apple iPad (where presumably users were able to choose the desired magnification.) A large sample of 100 participants with low vision was considered. No significant reading speed difference across the three modalities was found.

Zhao et al. [55] compared two screen magnification modalities: *overlapping* (equivalent to *lens*) and *parallel* (equivalent to *area* in [8]: the magnified area, selected via mouse, is displayed in a fixed position on the screen). In this work, the task was to find and read all pieces of text (in Chinese) randomly scattered across the screen. It was shown that the *overlapping* mode led to significantly lower time to complete the task.

2.3 Usability Studies

Szpiro et al [47] conducted a study with 11 people living with low vision, operating different types of access technology (screen magnification on computers and smartphones, inverted screen colors, text to speech). This analysis highlighted several issues when using these technologies, including: difficulty with gestures; feeling confused or not in control; inefficiency at performing specific tasks.

Hallett et al. conducted two studies comparing Responsive Web Design (RWD [17]) against a standard screen magnifier. The first study, with 16 participants with normal vision on a text reading task, found that reading was slower and less accurate when using screen magnification than with RWD [20]. However, a second study with 8 participants with low vision [21] showed no significant difference in the time to complete the reading task between the two modalities. Higher usability levels and lower level of nausea (due to horizontal scrolling) were reported using RWD.

2.4 Alternative Control Modalities

While the center of magnification is normally controlled using a mouse or trackpad, other input modalities are possible. For example, Kurniawan et al. [30] experimented with a joystick-controlled magnifier. Aydin et al. [3] recently proposed to identify regions of interest (using video saliency models), which can be automatically tracked and magnified in videos. MagPro [32] is an interface augmentation to office productivity tools that facilitates access to important application commands while using a screen magnifier.

There has been recent interest in methods to control the center of magnification of a screen magnifier using the user's own gaze, rather than a mouse or trackpad [1, 36, 37, 43, 45]. These proposed systems use the *lens* modality, except for [36], which experimented with both *lens* and *full* modalities.

3 METHOD

3.1 Population

We recruited 20 participants (8 female, 12 male) from our University's Optometry clinic. The participants' characteristics are reported in Tab. 1. The median age was 68 (min: 28; max: 95). 8 participants were diagnosed with central vision loss. Visual acuity in better eye varied from 0.26 logMAR[1] ($20/40^{+2}$ in Snellen units) to 1.04 logMAR ($20/200^{-2}$).

Upon arrival in the laboratory, we first obtained oral and written consent from the participants. We then measured the participants' visual acuity using the Bailey-Lovie Visual Acuity Chart [4] (only the high contrast version) and contrast sensitivity using the Mars test [13]. These measurements were performed monocularly under standard office lighting. A screening test to screen for the presence of central scotoma (field loss) was also performed using a MAIA microperimeter [39] for those subjects with a diagnosis of macular disease. The results from the MAIA test were used to determine whether a participant had central vision loss. Central vision (field) loss is the consequence of disturbances to the central macular area. Individuals with central vision loss usually complain of the disappearance of an object when they look directly at the object.

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[1] logMAR (logarithm of minimum angle of resolution) is a commonly used measure of visual acuity. Compared with Snellen units, 0 logMAR is equivalent to 20/20, while 1 logMAR maps to 20/200.

ID	Age	Gender	Diagnosis	CVL	VA (logMAR)	Expert
P1	57	F	Stargardt disease	Y	1.04	Y
P2	69	M	X-linked retinoschisis	Y	1	N
P3	86	M	Age-related macular degeneration	Y	0.62	N
P4	28	F	Congenital glaucoma + 2° nystagmus	Y	0.76	Y
P5	61	M	Retinitis pigmentosa	N	0.42	N
P6	71	M	Optic nerve atrophy	N	1.04	Y
P7	69	M	Age-related macular degeneration	Y	0.26	N
P8	74	F	Age-related macular degeneration	Y	1	Y
P9	54	M	Retinopathy of prematurity	N	0.7	N
P10	82	F	Glaucoma	N	0.38	N
P11	47	M	Ocular albinism	N	0.72	N
P12	31	M	Achromatopsia	N	0.9	Y
P13	93	F	Age-related macular degeneration	Y	0.36	N
P14	42	M	Congenital nystagmus	N	0.44	Y
P15	37	F	Retinopathy of prematurity	N	0.42	N
P16	71	F	Glaucoma	Y	0.3	Y
P17	85	M	Glaucoma	N	0.5	Y
P18	68	M	Oculocutaneous albinism	N	0.6	Y
P19	55	F	Optic neuritis	N	0.4	Y
P20	95	M	Age-related macular degeneration	Y	0.8	N

Table 1: Participants' characteristics. CVL: Central Vision Loss. VA: Visual Acuity in better eye (measured in logMAR units). Expert: Uses some form of screen magnification on a regular basis.

However, if they look slightly away from the object, then they can see the object, although the object may not appear very clear to them.

Participants were then asked a series of questions related to their use of the computer. 16 participants said that they used a computer daily (at home or at work), while 4 used it once a week or less. As for the computer type, 12 used a desktop computer, 4 used a laptop computer with an attached monitor, and 4 a laptop without an external monitor. 10 participants were Mac users, the rest used Windows machines. 10 participants regularly used some form of screen magnification: 3 used ZoomText, 4 used the MacOS native screen magnifier, 2 used the Windows native screen magnifier, and one used pinch-to-zoom on a touchscreen PC. One participants said that he occasionally used a magnifying glass when looking at the computer screen.

3.2 Apparatus

The study was conducted in a small quiet lab space. The room had no windows, and was illuminated by fluorescent light. We used a MacBook Pro with 13.3 inch screen (285 × 179 mm pixel area, 2560 × 1600 pixels) running MacOS Catalina (10.15.7). The laptop computer was placed on a stand with adjustable height. Participants sat on a chair in front of the computer, and the height of the stand was set such that the center of the screen was approximately at head height. We purposely chose to use a laptop computer with a relatively small screen, rather than using a larger monitor that would facilitate reading with magnification [35], in order to study the participants' performance with screen magnification under challenging (yet realistic) conditions. At the base of the computer screen was attached a gaze tracker (Tobii Fusion), which recorded gaze data at 120 Hz from the participants during the trial. Participants were asked to keep their head within the operating range of the tracker (approximately 500–800 mm from the tracker). While this distance was larger than what some of the participants (especially those with low visual acuity) were used to, they were able to compensate for it by increasing the magnification factor. Participants operated the screen magnifier using a wired mouse connected to the laptop. The tracking speed of the mouse (in the computer's System Preferences panel) was set to 7 on a scale of 1 (slowest) to 10 (fastest).

Screen magnification was obtained using the native MacOS magnifier, which is accessible through the Accessibility System Preferences panel or through appropriate keyboard shortcuts. A Matlab application was used to record all mouse movements (at a rate of 10 Hz), as well as the magnification parameters chosen by the users. Two magnification modalities supported by MacOS (*full* and *lens* [8], which are called *Full screen* and *Picture-in-picture* in MacOS) were considered for this study.

At the beginning of the study, participants went through a standard procedure to calibrate the gaze tracker. Then, the experiment started. An experiment consisted of four trials (two magnification modalities for two document types: text and web page, described in Sec. 3.3). In preliminary studies, we observed that the two magnification modalities are rather different in terms of user experience. Hence, in order to minimize the number of switches between modalities, we decided to pair together, for each modality, the two trials with the different document types. Specifically, one text document and one web page (in random order) were first read using one modality (*lens* or *full*), then the other document and web page (in random order) were read using the other modality. Order of conditions was counterbalanced with random assignment.

Before reading either document (text or web page) with either modality, users were invited to first practice with the same modality on a different document of the same type. During this practice phase, participants were asked to experiment with various magnification factors and, in the case of the *lens* modality, with different width and height of the lens window. To obviate the need for training participants on the correct use of the key shortcuts, the experimenter operated these (to increase or decrease the value of the parameters of interest) as directed by the participants. Participants were advised to spend as much time as they wanted on the practice document. When they felt ready to start the trial (with the same document type and modality as in the practice trial), they were allowed to use the same magnification parameters or to change them before the trial begun. Practice time varied from 30 to 354 s (mean: 142 s). When they were ready to start, the experimenter first moved the mouse to the beginning of the first line (for text documents) or to the top left corner (for web pages), before relinquishing the mouse to the participant. The beginning of a trial was marked by a computer alert sound triggered by the experimenter.

Participants were asked at the beginning of the experiment whether they preferred to invert the color polarity of the screen (using MacOS' Invert Colors setting). Between the two pairs of tests for each magnification modality, participants were invited to take a break of a few minutes. At the end of all trials, participants were asked to answer a questionnaire where they could report (on a scale from 1 to 5) the perceived difficulty with each magnification modality on each type of document. In addition, participants were asked which of the two modalities was easier for each document type, and were invited to elaborate on their comparisons. The whole session was audio recorded for later analysis. The protocol for the experiment was approved by our Institutional Review Board.

3.3 Materials

The two text documents contained 4 paragraphs each from two children's books ("The Poky Little Puppy" and "Jenny and the Cat Club"). This material was selected because it is of easy comprehension and engaging at the same time. The document used for practice was extracted from "The Rainbow Fish" (the same document was used for practice under the two different modalities.) Each document had 14 lines of text, of which one (for each document) was very short (2 or 3 words) while the other lines had 21 words on average. Text was shown in black on white (unless the participant chose to invert polarity), with 20 pt. Helvetica font. On the laptop's screen, this corresponded to a *x-height* (distance between baseline and mean line of lowercase letters) of 2.5 mm. The interline distance (baseline to baseline) was 5.6 mm. The left margin (distance from the left edge of pixel area to the beginning of a text line) was 27 mm. The top margin (midline of first line to top of pixel area) was 54 mm. Text was not justified. The longest text line was 245 mm long. The first two participants (P1 and P2) were asked to read aloud only the first three paragraphs of each document, as we feared that the task of reading the entire document using screen magnification could have been too demanding for the test. After ascertaining that this was not the case, we asked all subsequent participants to read aloud all four paragraphs.

The two web pages used for the tests can be seen in Fig. 1 and Fig. 7. We actually used screenshots of real web sites, since our goal was solely to observe how participants managed exploration of these relatively unstructured layouts. Participants were asked to find and read aloud all main "titles", of which there were 9 in each page. The trial ended when a participant stated that all titles had been read. If one or more titles were missing, the experimenter advised the participant to continue exploring.

3.4 Performance Measures

3.4.1 Text Reading. We considered several quantities to describe the behavior and performance of participants while reading the text documents with either magnification modality. The **Total Reading Speed (TRS)** (units of words/m) is obtained by dividing the number of *standard-length words* in the document by the total time required to read it aloud. The number of standard-length words is obtained by dividing the total number of characters (including spaces and punctuation) by 6 [11]. The total reading time for each document was measured from the audio recordings. The TRS is arguably the most practically relevant outcome. Note that a slow reading speed may be due to multiple factors: difficulty at focusing on characters and words, even when magnified, due to a scotoma [48]; poor mouse control skills while scanning a text line; long retracing time (moving to the beginning of the next magnified line, which involves moving the center of magnification right-to-left using the mouse).

A related quantity is the **Average Reading Speed – Text Lines (ARS-TL)** (also measured in words/m). ARS-TL excludes the retracing periods. Intuitively, it is equivalent to the reading speed if one where to read the text in just one long line. It is measured by determining, for each text line, the start and end reading times, before the participant moved on to the next line. This is done manually, based on the audio recordings, using a stopwatch. The reading speed during each line is computed by dividing the number of standard-length words in the line by the difference between end and start times for that line, then averaging this quantity over all text lines. (We neglected the single short line in each document for these measurements.) ARS-TL is independent of the retracing time, and thus helps understand the effect of retracing on reading speed. The **Reading Speed Deficit** (RSD) due to retracing is measured as: $\mathrm{RDS} = (\text{ARS-TL} - \text{TRS})/\text{ARS-TL}$. Note that $\text{ARS-TL} > \text{TRS}$ and thus $0 < \mathrm{RSD} < 1$.

We also measured all reading errors.

3.4.2 Horizontal Scrolling. Reading with screen magnification requires scrolling the center of magnification left-to-right in each text line. Using the recorded mouse data, we measured the *horizontal scrolling periods* for each text line. Specifically, we manually determined, for each text line, the time a participant begun moving the mouse left-to-right to scan the line, as well as the time they begun a right-to-left retracing motion (see Fig. 2, right panel). The period between these two recorded times is the horizontal scrolling period for that line. We then analyzed the mouse motion within each horizontal scrolling period to produce measures of consistency and uniformity.

We define by **consistency** one's ability to maintain a direction of scrolling that is approximately horizontal. Note that, using the *lens* modality, one needs to ensure that the center of magnification at the pointer is close enough to the line, such that the text characters being read are within the magnification window. Large variations in the vertical coordinate of the pointer would result in the lens moving away from the text being read, requiring the user

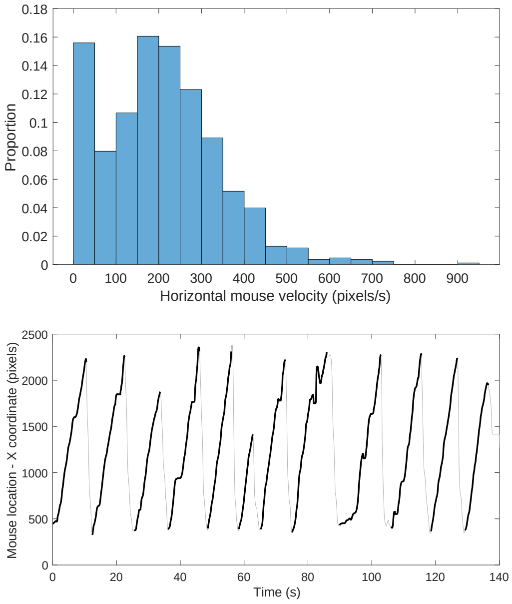

Figure 2: Measurements taken from P4 while reading magnified text using the *lens* modality. Top: Histogram of horizontal mouse velocities. Bottom: X-coordinate of mouse location as a function of time. Horizontal (left-to-right) scrolling periods are shown with a thicker line.

to move it back to the correct location. At times, this may require a time-consuming search and may potentially lead to errors (e.g., landing on an incorrect text line). The *full* magnification modality (which effectively behaves like the *lens* modality with a very large window) may afford larger latitude in the location of the center of magnification, at least for moderate magnification levels. Consistency at each line is measured by the standard deviation of the Y coordinate of the pointer location (**Y-SD**) within the horizontal (left-to-right) scrolling periods. The overall consistency is obtained by averaging this quantity over all text lines.

Uniformity measures one's ability to maintain an approximately constant horizontal scrolling speed. Since uniform horizontal scrolling is often proposed as an automatic modality of magnified text presentation [24], we were interested in verifying whether this is reflected in the natural scrolling action of our participants. To measure uniformity, we first computed the magnitude of the pointer velocity (in pixels/s) at each time within each horizontal scrolling period. We removed all trailing zeros at the beginning and at the end of the velocity magnitude sequences for each text line, then considered the whole time series of values for the whole document. Analysis of this data typically reveals a sizeable proportion of samples with zero velocity. For example, the histogram of mouse velocities in Fig. 2 shows a narrow mode at 0, and is consistent with a mixture model distribution (in fact, 9% of the measurements have velocity equal to 0 pixels/s.) Accordingly, we computed the proportion of samples with zero velocity (**Zero-Velocity Proportion, ZVP**), along with the mean of the distribution of non-zero velocities (**Non-0 Velocity Mean, N0VM**).

3.4.3 Exploration Time / Path Traversed. For both text reading and web page exploration, we measured the **Total Path Traversed** (TPT), that is the length of the path traversed by the pointer (and thus by the center of magnification) on the screen during the session. For web page exploration, a short TPT value may indicate that the participant was able to move from title to title using direct paths; whereas, if a participant was searching aimlessly on the page, possibly searching multiple times for a title in the same area, one could expect a large TPT. For text documents, a short TPT value indicates parsimonious mouse motion when scanning text lines.

For web pages, we also recorded the **Total Exploration Time** (TET), measured from the beginning of the trial until all titles in the web page were read, as maintained by the participant and confirmed by the experimenter. Efficient exploration of the web site is arguably associated with a short TET. We did not consider this quantity for the text documents, as it is already subsumed by the Total Reading Speed.

3.5 Gaze Point Distribution

When reading text or looking at images on a sufficiently magnified screen using the *full* mode, the user can choose where to place the portion of interest (the word currently being read, or the image being gazed at) on the screen, by moving the center of magnification with the mouse. For example, when reading text, one may choose to move the mouse such that the text of interest is always located in a certain area of the screen, with the magnified text continuously scrolling left to right. Or, one may prefer to keep the mouse still while reading the visible portion of a magnified text line; then move the mouse to the right, thus moving the magnified text to the left, such that the next portion to read moves to the left edge of the screen; and repeat the process until the whole line has been read. Note that if the magnification factor is equal to 2 or larger, any point in the un-magnified central portion of the screen content can be moved anywhere on the screen after magnification. If the magnification is lower than 2, the magnified content can only be moved within a smaller region. For example, with magnification factor of 1.5, a certain point in the un-magnified central portion of the screen can be moved to within ±25% of the screen extent around its original location after magnification.

In order to obtain some insight into the strategies adopted by our participants, we analyzed the distribution of their gaze points on the screen while performing the tasks in the *full* mode (for the *lens* mode, gaze falls on the magnification window that is centered around the pointer location). For reading tasks, we did not consider retracing periods, as we are only interested in gaze behavior during active reading. In the case of the first example discussed above, we would expect gaze points to concentrate in a certain area of the screen. For the second example, we would expect a broader distribution of gaze points across the screen.

3.6 Statistical Analysis

We are interested in identifying factors that are most relevant to each performance measure. Given the large set of factors including personal attributes, experimental settings, and subjective survey results, we use stepwise regression to identify a first reduced set of variables that can be associated to each performance measure. Subsequently, we use an F-test to compare the full model and the nested reduced model selected via stepwise regression. Finally, we look to further reduce additional non-significant variables using t-tests for regression coefficients and use F-tests for model selection. We report the p-values and the adjusted p-values using the Benjamini-Hochberg (FDR) correction to adjust for multiple testing as implemented in the R function `p.adjust`. Another question of interest is to determine if a given single dichotomous factor, such as magnification modality, affects the mean level of a specific performance measure. We address this using paired two-sample t-tests for population means since we have measurements for participants at both levels of the dichotomous factors (e.g., we have the total exploration time during web page exploration under two magnification modalities for each participant).

4 RESULTS

4.1 General Observations

The study proceeded without significant problems, and all participants were able to complete all tasks. Due to an error of the experimenter, window size data for the *lens* modality were not recorded for S9 and S13. In addition, the experimenter neglected to conduct the final questionnaire for S3. The overall sessions (not counting the initial gaze calibration phase, but including the exit questionnaires) lasted between 32 and 83 minutes (mean: 51 minutes). 5 participants chose to invert the color polarity throughout the experiment; one additional participant opted for it only when reading the text document. 6 participants wore their prescription glasses during the study. The distance of the participants' head to the screen (as measured by the gaze tracker during the tests) was between 420 mm and 820 mm (mean: 660 mm).

In order to obtaining meaningful data from the gaze tracker, a calibration procedure is required to estimate the parameters of the function that maps the image location of pupil center and glint with the gaze point on the screen for each eye, as well as information on the IR light reflection properties of the user's cornea [42]. For each participant, we first attempted to use the calibration procedure provided with Tobii Pro SDK. This requires fixating a target appearing at 9 different locations on the screen. This calibration procedure was successful for 13 participants. For the remaining participants, we ran a second calibration procedure, which still involved fixating on a target on different positions on the screen. An affine transformation was then computed to minimize the mean squared error between the measured gaze location and the know target location. In this way, were were able to calibrate the tracker for 4 more participants. For the 3 participants for whom both calibration procedures were unsuccessful (P9, P17, P18) we did bot consider their gaze data in our analysis. The difficulty of calibrating gaze trackers with people with low vision is well known in the literature [12, 26, 34].

4.2 Magnification Parameters Selection

4.2.1 Magnification Factor. The magnification level chosen by the participants for each magnification modality and document type are shown as a function of visual acuity in Fig. 3, top panel (min: 1.11; max: 28.08; mean: 5.67; median: 3.47). To fully appreciate the effect of a certain magnification factor, one should also consider the distance of the viewer to the screen (screen content appears smaller when seen from a longer distance). For the text documents, we computed, for each participant, the *preferred angular print size* (PAPS) [5], which measures the angle subtended by a x-height character at the viewer's location, and thus accounts for the viewer's distance to the screen. These values (expressed in logMAR units) are shown as a function of acuity in Fig. 3, bottom panel.

We considered a linear regression model to study the relationship between the preferred angular print size (response) and the visual acuity taking into account the magnification modality as a factor. The estimated regression coefficient capturing the linear relationship between preferred angular print size and visual acuity (both in logMAR units) is 0.9444 with a 95% confidence interval of (0.7214, 1.1674). We found the magnification modality to be statistically significant at the 0.1 level (p-value: 0.08430 ; adjusted p-value: 0.08432) but not at the 0.05 level, with an estimated change in the expected preferred angular size of 0.1002 logMAR for the *lens* modality with respect to *full* screen. The results of the regression analysis that includes modality as a factor are depicted in the bottom panel of Fig. 3. We see that the preferred angular size linearly increases with visual acuity with the same slope for both modalities but different intercepts for *full* and *lens* (1.0493 logMAR and 1.1495 logMAR, respectively.) We did not find the interaction effect between the visual acuity and the magnification mode, that would lead to regression lines with different slopes according to the magnification modality, to be statistically significant at the 0.05 or 0.1 levels. Note that we did not define the preferred angular print size for web page exploration, since the font size is variable in this case. However, we can still use the actual magnification level, which is defined for both text and web documents, allowing us to study the relationship between actual magnification level and visual acuity taking into account the document types (text and web page). We did not find statistically significant evidence at the 0.05 or 0.1 levels that document type had an impact in the log magnification level.

4.2.2 Lens Window Size. The window sizes (for the *lens* mode) chosen by the participants are shown in Fig. 4 (top panel, units of pixels). The mean value of the horizontal and vertical window sizes were 629 and 257 pixels, respectively. From the figure, it can be seen that the aspect ratio (horizontal size divided by vertical size) was always larger than 1 (min: 1.38; max: 3.75; mean: 2.63). For the tests involving text documents, it is useful to also consider the number of magnified text characters and lines contained within the magnification window. This can be easily computed given the known average character width and the interline distance. Note that the same lens window contains more or fewer characters/lines depending on the

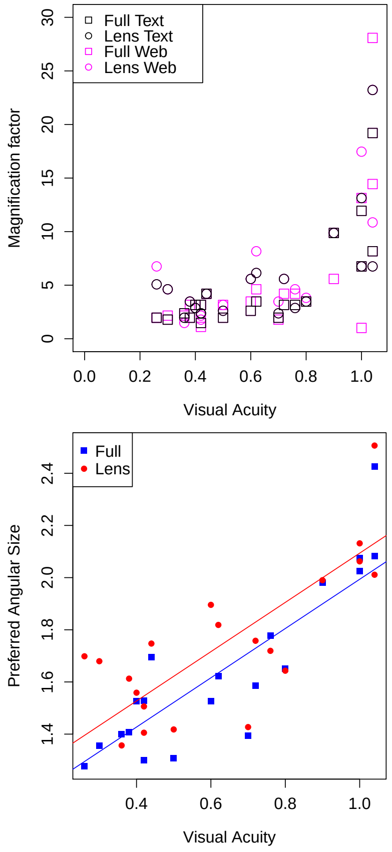

Figure 3: Top: The magnification factors chosen by the participants, plotted against their better eye visual acuity (in logMAR units) for different modalities and document type. Bottom: Preferred angular print size (in logMAR units) plotted against better eye visual acuity (in logMAR units) for different magnification modalities. Linear regression lines (with a slope of 0.944) are also plotted in the figure.

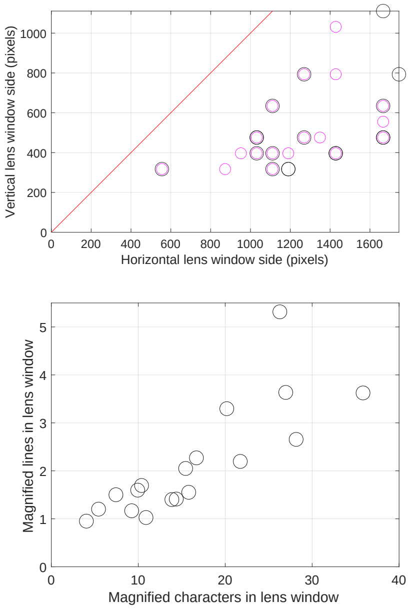

Figure 4: Top: Vertical vs. horizontal lens window sizes chosen by the participants when reading text (black circles) or web pages (magenta circles) using the *lens* modality. The diagonal line shows the locus of lens windows with aspect ratio equal to 1. Bottom: The set of lens window sizes chosen by participant when reading text, expressed in terms of characters within the window width (X-axis) and number of text lines within the window height (Y-axis).

chosen magnification level. We plotted the number of text lines vs. the number of characters within the magnification window in Fig. 4 (bottom panel; mean of 2.14 and 16.26, respectively).

4.3 Text Reading

4.3.1 Total Reading Speed (TRS). The measured Total Reading Speed ranged from 20 to 175 words/m (mean: 82 words/m). These values are consistent with similar measurements reported in the literature (e.g., [40]).

For this quantity, we considered a multiple regression model that included the following explanatory variables: magnification modality (*lens* or *full*), reading material (text or web), ordering indicating whether each participant used lens or full screen first, the participants' subjective ratings of the easiest modality based on the exit questionnaires (see Section 4.5), the preferred angular print size, age, status of central vision loss, visual acuity, and the standard deviation of the Y-coordinate (Y-SD). Using stepwise regression that removes/adds variables based on the Akaike's Information Criterion (AIC) as implemented in the function `step` of R package, we reduced the original model to a model that only includes preferred angular print size, age, central vision loss and visual acuity as the relevant explanatory variables. In addition, the individual p-values based on t-tests for central vision loss and visual acuity indicate that these covariates are not significant, so we considered an F-test that compares the model with preferred angular size, age, central vision loss, and visual acuity to a further reduced model that only includes preferred angular print size and age. The resulting p-value of 0.4226 indicates that the smaller model is preferred, and so, the only significant variables for total reading speed are preferred angular print size and age. The corresponding estimates for the parameters of this reduced regression model, as well as their p-values and FDR adjusted p-values, appear on Table 2. We see that both preferred angular size and age decrease the total reading speed. At a fixed age, for an increase of 1 logMAR unit in angular print size, the expected decrease in total reading speed is 70.0223 words/m. Similarly, at a fixed angular print size, the expected decrease in total reading speed is 0.9502 words/m per year of age.

	Estimate	Std. Error	p-value	adjusted p-value
(Intercept)	261.0357	31.2134	4.72e-10	1.42e-09
PAPS	-70.0233	14.6380	2.75e-05	4.12e-05
Age	-0.9502	0.2287	0.000184	1.84e-04

Table 2: Estimates from a linear regression model that considers Total Reading Speed (TRS) as response variable and age and preferred angular print size (PAPS) as explanatory variables.

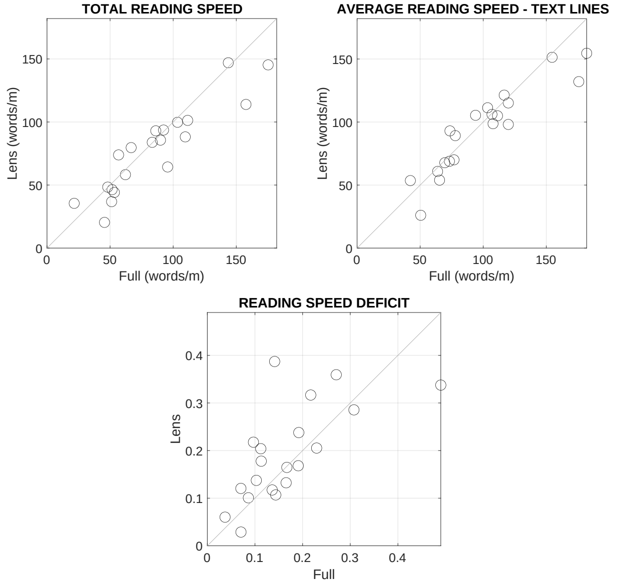

Figure 5: Reading speed measurements for the text documents. Top left: Total Reading Speed (TRS). Top right: Average Reading Speed – Text Lines (ARS-TL). Bottom: Reading Speed Deficit (RSD). In this and in the next two figures, the relevant quantity when using the *lens* modality is plotted against the same quantity when using the *full* modality for each participant. No significant difference in mean between the two modalities was found for these measurements.

	Estimate	Std. Error	p-value	adjusted p-value
(Intercept)	-3.8452	0.4163	3.81e-11	1.14e-10
PAPS	1.0854	0.2507	0.000109	1.64e-04
Central Vision Loss	0.3601	0.1584	0.028871	0.028871

Table 3: Estimates from a linear regression model that considers the log Reading Speed Deficit (RSD) as response variable and preferred angular print size)PAPS) and central vision loss as explanatory variables.

4.3.2 *Average Reading Speed – Text line (ARS-TL).*

ARS-TL values ranged from 26 to 182 words/m (mean: 97 words/m), with the associated Reading Speed Deficit (RSD) varying between 3% and 49% (mean:18%). See Fig. 5 for plots of these values. The estimated mean difference between ARS-TL and TRS is 14.6792 words/m with a 95% confidence interval of (12.5743,16.7841) words/m.

For the natural logarithm of the Reading Speed Deficit (RSD) we considered a regression model with the following explanatory variables: magnification modality, ordering indicating whether each participant used lens or full screen first, the participants' subjective rating of the easiest modality based on the exit questionnaires, preferred angular print size, age, status of central vision loss and visual acuity. Using stepwise regression that removes/adds variables based on the AIC as implemented in the function `step` of R package, we reduced the original model to one that includes all the original variables listed above except magnification modality, the participant's subjective rating of easiness, age, and visual acuity. Based on the individual p-values we can further remove additional variables to obtain a model that only includes preferred angular print size and central vision loss. We used an F-test to compare the original full model with the model that only includes preferred angular print size and vision loss. The resulting p-value of 0.3361 indicates that the smaller model is preferred and so, the only significant variables for the natural logarithm of RSD are preferred angular size and central vision loss. The corresponding estimates for the parameters of this reduced regression model appear on Table 3. We can see that increasing the preferred angular print size and having central vision loss increases RSD. An increase of 1 logMAR unit of angular print size leads to an expected increase of 1.0854 in the log RSD (approx. 2.96% in speed reduction) for individuals with no central vision field loss. At a fixed preferred angular print size, participants with central vision loss have an expected increase of 0.3601 in the log RSD (approx. 1.43% in speed reduction) over participants with no central vision field loss.

4.3.3 *Reading Errors.*

We recorded a total of 43 reading errors (with a maximum of 4 errors within the same trial). These errors were for the most part minor (such as missing or misreading a word). However, we also recorded 3 instances in which participants skipped a half line (S3, S10, S13), and 2 instance of a whole line skipped (S10, S17). Note that in these cases, the FRS and ARS-TL values where computed only considering the lines that were actually read.

4.3.4 *Consistency and Uniformity.*

We assessed the effect of the magnification modality on the horizontal scrolling consistency measurement Y-SD (standard deviation of the Y coordinate of the pointer location), and on the uniformity measurements ZVP (proportion of samples with zero velocity) and N0VM (mean of the distribution of non-zero velocity samples) using individual paired two-sample t-tests for each variable (see Fig. 6 for plots of the measurements, and Fig. 7 for sample mouse traces). We found a significant difference between the *screen* and *lens* modalities for Y-SD, with the Y-SD mean being lower for the *lens* modality (p-value: 0.000714) and the ZVP mean also being lower for the *lens* modality (p-value: 0.000545), but no significant difference in modalities for N0VM (p-value: 0.416272).

4.4 Other Measurements

The Total Exploration Time (TET) ranged from 42 to 562 seconds (mean: 132 s), while the Total Path Traversed (TPT) ranged from 15,393 to 63,877 pixels (mean: 41,329) for text documents, and from 4,778 to 66,305 pixels (mean: 17,385) when exploring a web page (see Fig. 8).

Using a paired two-sample t-tests, we find that the mean total path traversed (TPT) varies by magnification modality (p-value: 0.0387, with an estimated mean difference of 6,414 pixels between *lens* and *screen*). Similarly, using a paired two-sample t-test we did not find that there was a significant difference in the mean total exploration time (TET) by modality (p-value: 0.3935).

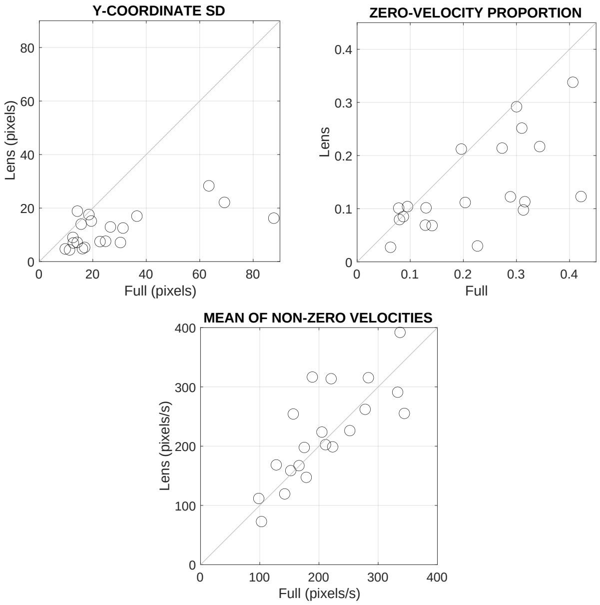

Figure 6: Horizontal scrolling measurements when reading text documents. Top left: Standard deviation of the Y-coordinate (Y-SD). Top right: Proportion of zero-velocity measurements (ZVP). Bottom: Mean of the magnitude of non-zero velocities (N0VM). All quantities measured within (left-to-right) horizontal scrolling periods. A significant difference in mean between the two modalities was found for Y-SD and ZVP.

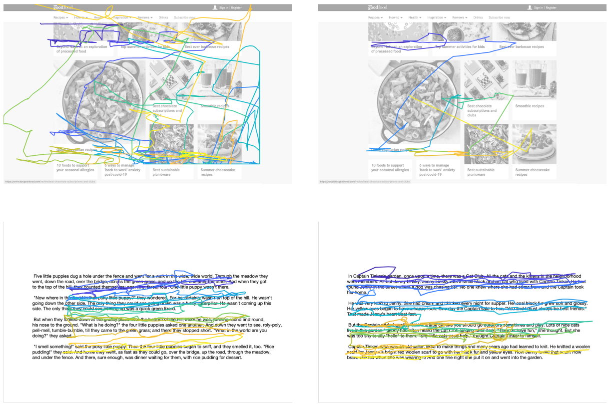

Figure 7: Tracks of mouse location (indicating the position of the center of magnification) shown on the un-magnified pages, with color changing from dark blue to yellow as a function of time. Top row: Web page exploration using the *lens* modality (left: P1; right: P12). Bottom row: Text document reading for P3 using the *full* modality (left) and the *lens* modality (right). Note: the web page is shown in greyscale and with dimmed contrast to enhance visualization.

4.5 Gaze Point Distribution

In Fig. 9 we plotted probability density functions fitted to the distributions of X- and Y-coordinates of gaze points (left eye) for all participants for whom calibration was successful. For the case of text reading, it is seen that the distribution of X-coordinate of gaze points is generally non-uniform, and in fact a relatively narrow mode can be noted for some participants. Remarkably, almost all densities have mean (shown by vertical lines) and mode to the right of the mid third of the screen (shown by a yellow band). Some have relatively high peaks, denoting high concentration around the mode. For what concerns the Y-coordinate of gaze points, most distributions appear to be relatively uniform, with a few participants keeping the magnified text of interest in the top portion of the screen (as seen by the peaked modes of the densities located in the left side of the plot). The mean value of Y-coordinate was located within the central third of the screen for most participants. Representative samples of gaze point distributions are shown for P5 and P15. P5 used a small magnification factor (1.5), which, as explained above, constrains the amount of motion allowable for the magnified screen. He moved the center of magnification such that he would scan the screen left to right for almost its full extent while reading the text. In contrast, P15 (magnification factor: 3.2) moved the center of magnification so as to keep the portion of text being read within a restricted location of the screen.

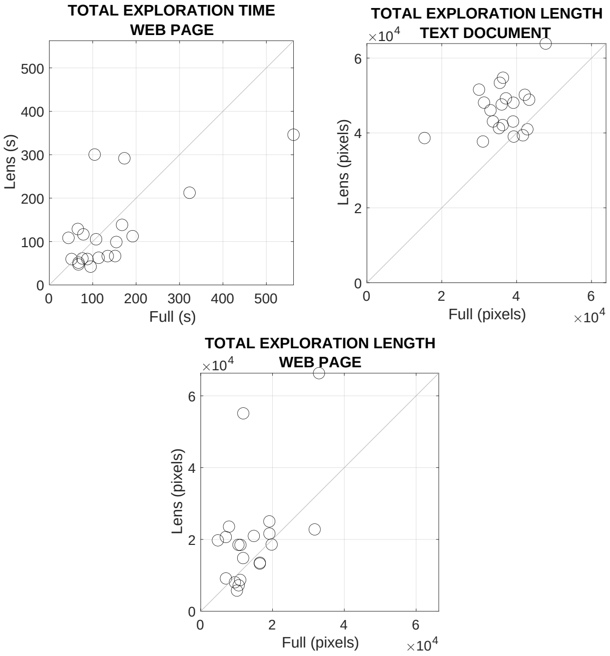

Figure 8: Top left: Total Exploration Time (TET) when exploring a web page. Top right: Total Exploration Length (TEL) when exploring a text document. Bottom: TEL when reading a web page.

For the case of web exploration, gaze points were generally more uniformly distributed across the screen, with the mean values of both X- and Y-coordinates located within the mid and center third of the screen, respectively, for the vast majority of participants. Representative examples of point gaze distribution on the screen are shown for P10 (magnification factor: 3.16) and P2 (magnification factor: 6.7).

4.6 Exit Questionnaires

The quantitative results from our final questionnaire are presented in Fig. 10. We should note that three participants (P2, P13 and P19) gave higher score to the *full* mode when asked to evaluate the difficulty of each individual task, yet they said that that the *full* mode was easier when asked to compare it against the *lens* mode.

Among those who preferred the *lens* modality, P4 commented that using the *full* magnification, she was more likely to lose her position in the page. Similarly, P6 found it easier to figure out where he was on the page using the *lens* mode. According to P15, the *lens* modality allows one to see a full sentence, while with the *full* mode it is hard to find things and get a sense of a web page as a whole. This sentiment was echoed by P16, who said that the *lens* mode made it easier to walk through the screen. In addition, P16 commented that the *lens* mode simplified the task of finding the new line when reading text. A majority of participants, though, found the *full* modality easier to use, sometimes using similar arguments as those advanced by those who preferred the *lens* mode. For example, P7 stated that the *full* mode lets one “live in the context” and see the totality of the document. Likewise , P13 said that the *full* mode is more cohesive and lets one’s eyes “take more” of the page, while P19 claimed that it made him aware of the larger context, especially for the text document. According to P18, a problem with the *lens* mode is that it doesn’t let one read “in chunks” but rather “in words”, due to the limited extent of the lens window. Concerning finding the beginning of the next text line, whereas P16, as mentioned earlier, found it easier using the *lens* mode, P7 and P11 had the opposite

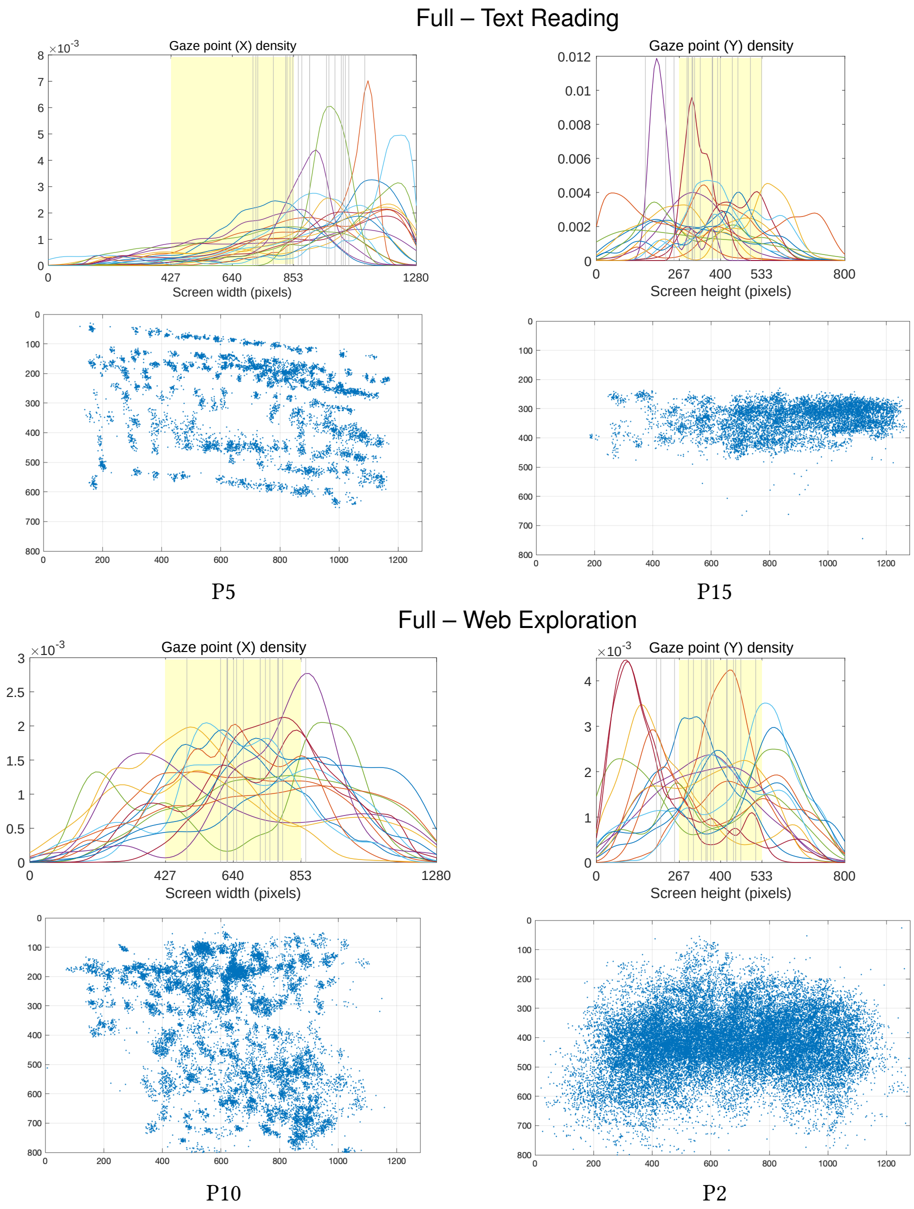

Figure 9: Plots of probability density functions fitted to the X-coordinate (left) and Y-coordinate (right) of gaze point data (left eye) for all participants for whom calibration was successful. Top: Text reading (excluding retracing periods). Bottom: Web exploration. The yellow areas represent the central third portion of screen width or height. Individual mean values are marked with vertical lines. Under each pair of plots, we show examples of gaze point distribution on the screen.

opinion, claiming that the *full* mode was better suited to this task. P8 found that using the *lens* mode, one is more "constrained" on the text characters (which must be contained within the lens window). The larger extent of the magnified text with the *full* modality also allowed her to get a better sense of the punctuation using peripheral vision. P9 observed that, using the *full* mode, one does not need to worry about moving the window around constantly – one can just concentrate on reading. Similarly, P10 and P11 commented that the *full* mode makes it easier to know where one is on the page while reading, without the need to constantly "search" with the lens window. P12 said that, using the *lens* mode, he would get distracted by the small print around the magnification window. P20 gave the highest score for difficulty (5) to using the *full* mode when looking at the web page, explaining that the titles to be read were associated with pictures in the page, which were more difficult to see jointly with the text using the *full* than with the *lens* mode. However, she said that the *full* mode was easier for reading text, as it helped her with "lining" – identifying and following each line correctly.

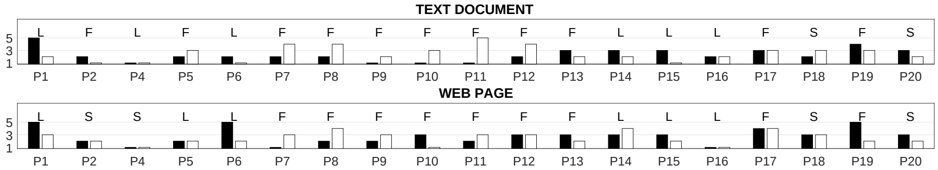

Figure 10: Quantitative outcomes of the final questionnaire. Each participant (except for P3) was asked to rate with a scale of 1 to 5 the difficulty of using each modality on each document type (with 1 denoting "very easy" and 5 "very difficult"). Difficulty values indicated for *full* and *lens* modalities are shown with filled and empty bars, respectively. Participants were also asked which of the two modalities was considered to be easier for the each document type. Their answers are shown on top of the bars (L: lens is easier; F: full is easier; S: same difficulty).

Using t-tests for means we did not find any evidence (all corresponding p-values were above 0.05) that having prior experience changed the mean difficulty level for any of the different combinations of magnification modality (*lens* or *screen*) and reading medium (text or web). Again, based on t-tests for means, we also see that participants found that using a *full* screen magnifier during text reading was easier than under web page exploration. On the other hand, we found no statistically significant evidence indicating that the there was any difference in the participants subjective difficulty levels for web page exploration and text reading when using a *full* screen magnifier. Results are shown on Table 4.

We found no significant differences in the mean difficulty level between full and lens modalities for text reading (p-value: 0.599). Similarly, we found no significant differences in the mean difficulty level between full and lens modalities for web page exploration (p-value: 0.3566). These results were obtained using paired t-tests.

	Estimate	2.5%	97.5%	p-value
document - webpage, **full**	-0.4737	-0.9384	-0.0089	0.0462
document - webpage, **lens**	0.0526	-0.4916	0.5968	0.8413

Table 4: Comparison in mean difficulty levels for document reading vs. web page exploration according to magnification modality (*full, lens*).

5 DISCUSSION

5.1 Magnification Level

Choosing an appropriate magnification level is critical for comfortable and efficient reading. It is remarkable that the preferred angular print size (a measure of magnification that accounts for the distance to the screen) correlates linearly (on a logarithmic scale) with visual acuity, with a slope close to 1, and intercepts of 1.0493 logMAR and 1.1495 logMAR for *full* and *lens*, respectively (though the difference is significant only at the 0.1 level). Note that the difference between critical print size (the font size below which reading speed starts declining) and acuity, sometimes called *acuity reserve* [51], was reported in [54] to be equal to 0.3 logMAR units for people with intact central field, and 0.5 logMAR units for those with central field loss. Although [31] reports that critical print size is consistent with patient-identified "comfortable" print size, our results suggest that our participants chose to magnify the screen at a level that is substantially above the critical print size. Not surprisingly, larger magnification levels (as measured by the preferred angular print size) had a significant negative impact on reading speed.

For what concerns lens window size, our data show a wide variability in terms of number of characters and number of text lines contained in the window. The mean values of these measurements (16 characters per window width, 2 lines per window height) could be used as a default baseline for a *lens* mode magnifier.

5.2 User Experience

All participants, even those who had not used screen magnification before were able to manage the reading and exploration tasks without particular problems. The responses to the questionnaire highlighted that the experience of reading a text document or a web site using screen magnification is rather different between the *full* and the *lens* modalities. Quantitative measurements of mouse motion confirm this. For text reading, the *lens* modality requires more precise mouse control (as shown by the lower variability in the Y-coordinate), and more uniform motion (as reflected by the lower portion of samples with zero mouse velocity). Screen magnification using *lens* requires moving the center of magnification over or very close to the areas to be read. In contrast, the location of the center of magnification in *full* mode is much less constrained: the only requirement is that the magnified area of interest should appear within the screen viewport. This relaxed constraint is reflected by the more parsimonious strategy of mouse motion adopted by our participants when operating the *full* mode magnifier, as shown by the Total Exploration Length measurements (see e.g. Fig. 7, bottom panels.)

5.3 Comparative Assessment

In spite of the differences in mouse control strategies, there was no agreement among our participants as to which magnification modality is the most appropriate for either document type. Our performance tests (using reading speed as a metric for text documents, and total exploration time for web pages) did not find a significant difference between the two modalities, either. Magnification level (as expressed by the preferred angular print size) and age appear to be the main factors affecting reading speed. As expected, retracing is responsible for a substantial portion of reading speed reduction, as expressed by the reading speed deficit (18% on average, with participants with central vision loss affected the most).

Hence, mechanisms to facilitate retracing may help increase the total reading speed. For example, ZoomText allows one to lock the X-coordinate of the mouse cursor while scanning a line, which may help with retracing. Again, no significant effect of magnification modality was measured on reading speed deficit.

5.4 Guidelines for Magnification Control Design

Our analysis of the mouse motion patterns may provide useful guidelines for designers of systems for automatic magnification control (e.g., based on eye gaze tracking or dynamic scrolling [24]). It seems advisable that these systems should try to generate motion patterns that resemble those used by humans when operating the magnifier. For example, an automatically controlled *lens* mode magnifier should be designed to ensure consistent patterns (small variation in Y). We note that the authors of the gaze-based control system of [36] reported worse results for the *lens* modality as compared with *full*, possibly because of the stricter consistency requirements for the *lens* mode.

The fact that our participants moved the mouse less uniformly (with longer or more frequent pauses) using the *full* modality should be considered when designing an automatic control mechanism based on dynamic scrolling, which needs to include options for pausing scrolling when desired.

Our measurements show that, when using the *full* mode, our participants moved the center of magnification only by the amount necessary for the relevant magnified portion to appear within the viewport. This suggests that algorithms for automatic control of full screen magnification should also produce parsimonious motion patterns for the center of magnification. Minimizing motion may also limit the risk of motion sickness [23, 25]. Note that none of our participants reported any symptoms of motion sickness in this study.

A magnification controller needs to decide where to place the magnified area of current interest (i.e., the area being gazed at) at each time. Our analysis of gaze point distributions shows that the preferred location on the screen depends on the content (web page vs. text document) and on individual preferences (with some, but not all, of the participants moving it to a particular sector of the screen, especially when reading a text document.) A gaze-based magnification control system could use this information to provide a personalized experience that would match the individual preferences of each user.

5.5 Limitations

We restricted the variety of magnification modalities to *full* and *lens* to ensure that the experimental activities would be manageable by our participants without too much effort, also considering that several participants were of advanced age (25% older than 80 years). This excluded other modalities such as *area* [8] or *hover* (basically, a *lens* mode magnifier that is activated only when one one presses a certain key). While we are not aware of studies that included the *hover* mode, prior work [55] showed that the *area* mode, where the magnified area is shown in a fixed location, results in lower reading speed than the *lens* mode, presumably due to the requirement of shifting gaze continuously between the magnified area and the pointer location.

Due to the use of a gaze tracker, our participants were asked to keep at a distance from the screen (660 mm on average) that was larger that what some of them would normally adopt. We don't expect that this changed the way they would operate the magnifier. Participants could compensate for the longer distance by increasing the magnification factor and the lens window size. Note that our measurements of preferred angular size and number of magnified text characters/lines (Sec. 4.2) are effectively independent of distance. However, the increase in magnification means that a smaller amount of magnified content fits within the screen viewport. In practice, reading from a longer distance with larger magnification compares with reading from a shorter distance with smaller magnification, but with a smaller screen.

6 CONCLUSIONS

We presented the results of a study with 20 participants with low vision, who read two text documents and explored two web pages on a laptop computer using two standard screen magnification modalities: *full* and *lens*. Our main purpose for the study was to evaluate whether or not either modality was considered superior for either document (in quantitative terms, via reading speed and exploration time/length metrics, and in subjective terms, via a questionnaire). A second purpose was to analyze the strategies adopted by our participants for moving the center of magnification using the mouse.

We didn't find any significant differences in the considered performance metrics between use of *full* vs. *lens* modality, and our participants were split on which modality was considered to be more acceptable. This confirms that both modalities should be supported by future screen magnification software, to accommodate for individual user preferences. Our analysis did show measurably different motion patterns using the *full* vs. *lens* modality; this information could be useful for designers of systems for the automatic control of screen magnification (e.g., using the reader's eye gaze).

In future work, we plan to extend our analysis to reading with screen magnification on smartphones and tablets. We expect that, due to the smaller screen size and touch-based (vs. mouse-based) input, the users' strategies for controlling the center of magnification may be substantially different than those observed when using a computer. In addition, we will perform further analysis on the recorded gaze data, in order to highlight additional features that could inform the design of gaze-based magnification control systems.

ACKNOWLEDGMENTS

Research reported in this publication was supported by the National Eye Institute of the National Institutes of Health under award number R01EY030952-01A1 The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. We would like to thank the participants who volunteered for this study.

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