Psychophysics of Reading-XIX. Hypertext Search and Retrieval With Low Vision

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Invited Paper

Low vision is any chronic form of visual impairment, not correctable by glasses or contacts that adversely affects performance of important everyday visual tasks. Most people with low vision need magnified text to read. On a fixed-size computer screen, the magnification of text trades off against the proportion of the entire screen visible. To read hypertext, simultaneous access to the full-screen page is important for skimming text and for locating hyperlinks. Therefore, people with low vision using magnified text might encounter difficulties reading hypertext, especially when hyperlinks are placed at unpredictable locations (true for most webpages). We investigated hypertext information retrieval as the time taken and number of nodes traversed to answer a series of questions. In Experiment 1, low-vision performance for reading prose and hypertext was compared to normal performance: low-vision performance deficits in hypertext retrieval were predictable from deficits in conventional prose reading. Experiment 2 evaluated the effect of webpage layout on low-vision performance: retrieval performance was severely affected when hyperlinks had unpredictable locations. This extra deficit was eliminated when users were provided with simultaneous access to full-screen layout. Based on these findings, we discuss the accessibility of the Internet by people with low vision.

Keywords*—*Hypertext, low vision, page layout, reading, visual search.

I. MINI REVIEW OF OTHER PAPERS IN THIS SERIES

This paper is part of an ongoing series of research publications dealing with the psychophysics of reading in normal and low vision. These publications report findings at the University of Minnesota's Laboratory for Low-Vision Research by G. E. Legge and his colleagues, supported by the National Institutes of Health. Citations with links to the abstracts for the 20 papers in the series can be found at http://vision.psych.umn.edu/www/people/legge/series.html For convenience, the 20 citations are listed in the Appendix in Roman numeral order and will be referred to by Roman numerals in this mini review (e.g., XIX for the current paper, the nineteenth in the series).

The two main goals of this research are to understand how visual information is used in reading by people with normal and low vision and to understand how different forms of low vision affect reading. One application of this work has been to guide the design of text displays including low-vision reading aids (cf., III).

Our primary measure of reading performance is reading speed in words per minute (Wpm). Reading speed can be measured objectively, is reproducible, and is sensitive to visual parameters. We have developed several methods for measuring reading speed including video/computer-based methods (I, VIII, XIV) and a chart-based method, the MNREAD acuity chart (XV). We have also used the rapid serial visual presentation (RSVP) method (XVI, XVIII, XX). We have shown that reading speed is a more sensitive performance measure than comprehension for assessing effects of visual factors (VII).

We have studied three types of variables that influence reading: text variables, ocular variables, and nonvisual variables.

Text Variables: These are variables that describe the rendering of text in a display. Our approach has been to measure the effect of a text variable for normal vision and then extend the findings to low vision. A theoretical goal has been to link the nature of the empirical results to known mechanisms of visual processing. For example, we have shown that normal reading speed is little affected by text contrast until it drops below 10% of maximum (V, XI, XVI), but some people with low vision have diminished reading speed for any reduction from maximum text contrast (VI). We have related

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Table 1
Text Variables and Corresponding Papers (Roman Numerals)

Text Variable	Normal Vision	Low Vision
Character size	I, V, XV, XVIII	II, XV
Font	XV	XV
Blur	I	
Samples/letter	I	II
Window size [a]	I, XIV	II, XIV
Contrast	V, XI, XVI	VI, XI, XVI
Contrast polarity [b]	I	II
Luminance	IV	
Color of letters or background	IV	IV
Color contrast between letters and background	XI	XI

[a] Number of letters simultaneously visible in the field of a magnifier or other "window" that moves across a line of text.

[b] Dark letters on a bright background or bright letters on a dark background. See also [1]

these contrast effects in reading to known properties of contrast coding in human vision (V, XI). Table 1 lists the main text variables studied and the papers reporting the findings.

Ocular Variables: These refer to properties of the eye or visual system that influence the visual processing of text. Deficits in three ocular measures account for most reading problems in low vision—reduced acuity, reduced contrast sensitivity, and visual-field loss. Letter acuity is the traditional yardstick for measuring visual function. It specifies the smallest print size for which letters can be recognized at a particular distance. A person's visual acuity is closely related to their reading acuity, the tiniest text letters they can read at all, and to their critical print size, the character size at which reading speed becomes independent of print size (II, XV). However, letter acuity is not a good predictor of reading speed (II, XII, XIII). In other words, knowing a person's acuity is not predictive of their reading speed for suitably magnified text.

Severely reduced contrast sensitivity has an impact on reading speed (VI, XI, XVI). In fact, the reading deficits of a subset of people with low vision—typically those with severe light scatter from cataracts or other media opacities—can be entirely attributed to reduced retinal-image contrast (VI). People with light scatter in the ocular media also tend to read better for contrast-reversed text, i.e., white letters on a black background (II and see [1]).

Intact central vision is critical for good reading. People with central-field loss (blind spots in central vision) almost invariably read slowly (II, XII). Age-related macular degeneration is the primary cause of central-field loss and afflicts a large number of older people. Individuals with central-field loss must use peripheral vision to read. Even if text is magnified to compensate for the lower acuity of peripheral vision, reading is slow. Similarly, maximum reading speed is slow, even in normal peripheral vision (XVIII). We ascribe this important deficiency of peripheral vision to a reduction in the number of text letters that can be recognized in parallel on one fixation, reduced "visual span" (XX).

Nonvisual Variables: Although old age has only a minor impact on reading speed for normal vision (X), old age *per se* is associated with slower reading in low vision (XII). The reason for this difference remains speculative.

Reading of continuous text involves moving from word to word and sentence to sentence, a process we term "page navigation." Normal reading relies on eye movements for page navigation. People with low vision typically use magnifiers, either optical (XIII) or computer/video-based (XIV, XVII). Although the motor demands for page navigation with magnifiers limit reading speed by normal subjects, we have found that visual limitations, not the demands of page navigation with magnifiers, limit reading speed for most people with low vision (XIV, XVII). One consequence is that text-presentation methods that reduce the demands on page navigation do not provide major benefits for low-vision reading speed.

Theory and Modeling: The empirical findings from this series and related work in the literature provide a substantial database for motivating and constraining theories for the role of vision in reading. Recent theoretical analyses from our laboratory include simulations from an ideal-observer model of reading named Mr. Chips [2], [3] and a model linking letter recognition to reading speed (XX).

Present Paper: The present paper (XIX) focuses on the tradeoff between magnification of the local features of a text display and visual access to the global layout. The task here is hypertext retrieval involving nonsequential access to text. The previous work in this series (and most work elsewhere on reading) has relied on sequential reading of conventional text.

II. INTRODUCTION

Low vision can be defined as the inability to read the newspaper with the best optimal correction at a regular reading distance of 40 cm. About 3.5 million people in the U.S. fall into this category [4]. Most of them require magnifiers to read regular print. Nearly all magnifiers work by enlarging a part of the text through a window whose boundary is determined by the magnifier's field of view. Hence, low-vision readers only see a small amount of text at one time through the magnifier. They scan this limited size window across the text. Reading hypertext differs from reading regular print in the need to locate hyperlinks. This might cause additional challenges for people with low vision. In this paper, we will investigate low-vision hypertext performance and describe an interface design to optimize hypertext information search and retrieval.

People with normal vision read continuous prose word by word and line by line. The reader's eyes move through the text in a pattern of fixations and saccades [5]. The fixation being the period during which the eyes are stationary and words are recognized and the saccade being the period during which the eyes jump to a new location in the text. We, therefore, describe reading prose as the sequential processing of text.

For many types of print, such as manuals and dictionaries, the text is not read sequentially. Typically one searches through such documents for specific information. The reader takes advantage of page layout to move the eyes from one important part of the text to another (skipping[1]). When page layout is insufficient, one will scan lines of text looking for specific words (skimming). Especially skipping, but also skimming are reading strategies that could be described as nonsequential processing of text.

Hypertext documents on the Internet are usually not read line by line from start to finish. People search hypertext, moving from node to node (a node is a page in a hypertext document) by locating and selecting hyperlinks that are represented as textual or graphical objects across the screen. To locate key information on a node, users jump from hyperlink to hyperlink, thereby skipping most of the other text. We will refer to this as browsing the Internet.

For sequential reading, low-vision readers move the magnified window along a line of text and return to the beginning of the next line quickly and accurately. However, despite magnification, people with low vision usually read more slowly than people with normal vision. Reading speed is limited by: 1) deficits in visual decoding [6], [7]; 2) the size of the magnified window [8]–[10], [11]; and 3) the mechanics of moving the magnified window [12], [13].

There is a lack of research on nonsequential reading and low vision, particularly, how the tradeoff between magnification and display of page layout impairs skimming and skipping. Magnifiers with restricted fields usually enlarge the letters while hiding the layout structure [13], [14]. Yet many people with low vision have enough residual vision to identify the global characteristics of page layout, such as the structure of columns, paragraphs, and headings, even if their acuity is insufficient to recognize individual letters.

Brinker and Bruggeman [15] investigated the tradeoff between magnification and page layout for a reading task where participants with normal vision were instructed to find a specific heading or word in the text. With increased magnification, the time to find the information grew exponentially. A followup study [16] investigated the benefits of a visual aid that combined both text magnification and access to page layout. With this tool, low-vision participants were about twice as fast at searching.

The main question of this paper is whether the requirements of skimming and skipping inherent in hypertext search and retrieval place low-vision readers at a more severe disadvantage than reading sequential text. If so, a secondary question is whether access to global characteristics of page layout can offset such a disadvantage.

A common use of the Internet is to look up specific information. To simulate such behavior in our experiments, we created two hypertext websites on distinct topics and asked participants questions regarding these topics. Our empirical measures were the time taken and the number of nodes traversed to answer a question.

All websites that were used in this study contained only text. Although Internet navigation often involves graphics as well as text, the interpretation of graphics may pose qualitatively distinct problems for people with low vision and will not be addressed in the present paper.

III. EXPERIMENT 1—COMPARING HYPERTEXT RETRIEVAL SPEED IN NORMAL AND LOW VISION

People with low vision usually read more slowly then people with normal vision, even when the text is adequately magnified [6]. We will use a speed ratio (low vision/normal vision) as a common metric for comparing relative performance of the two groups in prose reading and hypertext search.

In Experiment 1, we tested the following two predictions. First, low-vision search and retrieval performance with hypertext will be more adversely affected (lower speed ratio) than reading continuous text. Second, low-vision performance in locating hyperlinks will benefit from a tool integrating magnification for text recognition and overview to access page layout.

In Experiment 1, a hypertext was designed so that all hyperlinks were placed along the left border of a node. Although the hyperlinks were often outside the magnified window, such a layout made the location of hyperlinks predictable and hence simplified visual search. This design enabled us to isolate the use of hyperlinks as the key distinction between reading prose and hypertext.

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[1] This definition of skipping refers to large eye movements in text, guided by page layout features. This use of the term skipping should be distinguished from word-skipping behavior in sequential reading in which some words (typically short function words like "the" or "at") are not fixated.

Table 2
Characteristics of Low-Vision Participants, Experiments 1 and 2.

ID	Disorder	Snellen Acuity	Prose Reading Speed	Exp
		Snellen Ratio	Wpm	
P1	Retrolental Fibroplasia	20/300	35.3	1
P2	Macular Degeneration	20/80	60.7	1
P3	Uveitis	20/200	67.4	1
P4	Not diagnosed	Not diagnosed	98.3	1
P5	Nystagmus/Stephylomis	20/400	31.1	1+2
P6	Corneal Opacification	20/960	48.2	1+2
P7	Glaucoma	20/400	63.0	1+2
P8	Congenital Cataracts	20/250	93.0	1+2
P9	Optic Neuropathy	20/2000	20.6	2

A. Methods

Participants: Information retrieval performance was recorded for eight participants with low vision, who varied in visual disorder and age (Table 2). All participants used a computer (at least once a week) and were familiar with the Internet. A control group of six students with normal or corrected-to-normal vision participated in the experiment. Informed consent was obtained from all participants. Low-vision participants were paid for their time, whereas participants in the control group volunteered.

Apparatus: Participants worked on a Pentium II computer with a 16-in monitor and a standard mouse. The desktop configuration was 256 colors and 1024 × 768 pixels. The browser used was Netscape 3.1 from which all default navigation buttons were removed. The experiment was run on a local network with an Apple IIcx as the server. This server recorded the sequence of nodes accessed and the time spent on each node.

Websites: Participants were tested on two websites matched as closely as possible for style of language and layout. One website contained information on low vision, the other on juggling. All the text on a given node could be contained on a single screen, eliminating the need to scroll. Both websites had a hierarchical nodal structure with 54 nodes and 53 hyperlinks (Fig. 1). There were two types of nodes; nodes that linked to other nodes (connecting nodes) and nodes on the end of the hierarchy (end nodes). Connecting nodes displayed on average 60 words with three to five hyperlinks. End nodes displayed on average 200 words across four paragraphs (no hyperlinks). All nodes displayed two navigation buttons on the bottom of the screen and a backward and a forward button. Text was black on a white background. Hyperlinks were colored blue and turned red once visited. A third website, with only 15 nodes, but a similar layout, was used to train participants on the experimental procedure.

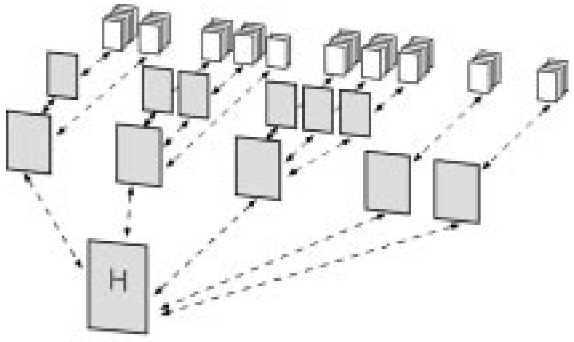
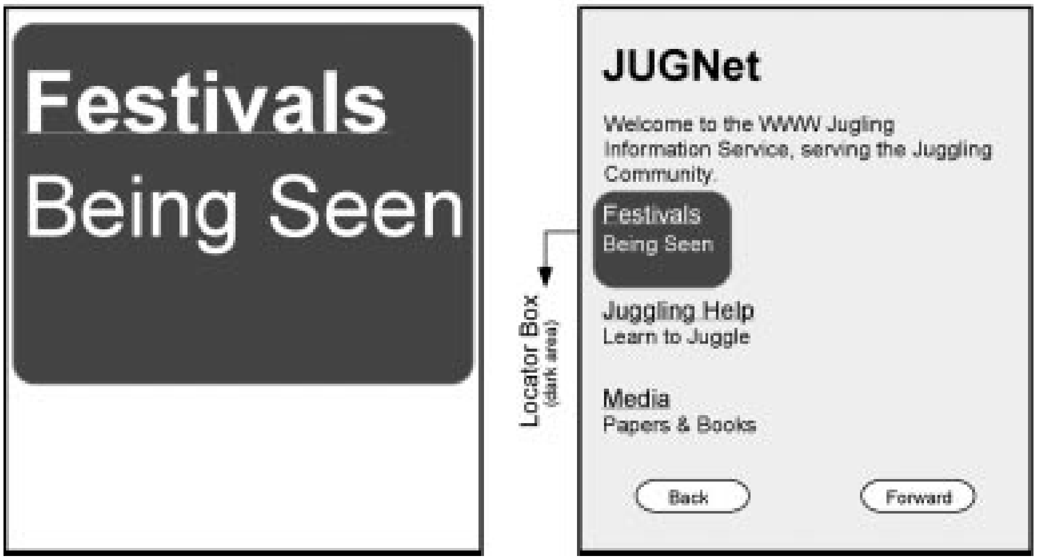


Fig. 1. Nodal structure of the websites in Experiments 1 and 2. Connecting nodes are colored gray, including the homepage (labeled "H"). End nodes are colored white and are stacked behind the referring connecting node.

Viewing Conditions: The program ZoomText5.1 (Ai Squared, Manchester Center, VT) was modified to create two viewing conditions: a magnifier mode and a magnifier-plus-overview mode. In the magnifier mode, only a portion of the total content of a node was displayed in a screen window at one time (magnified window) [see Fig. 2(a)]. To view the entire content of a node, a participant could use the mouse to move the magnified view over the node. The magnifier-plus-overview mode consisted of two windows



Welcome to the WWW Jugling Information Service, serving the Juggling Community.

(a) (b)

Fig. 2. Viewing conditions in Experiment 1. (a) Magnified window. (b) Overview window. In the magnifier mode, the participant sees a magnified window, which contains only a portion of the total content of a node at one time. In the magnifier-plus-overview mode, the participant can alternate between a magnified window and the overview window. Overview window displays the entire content of a node along with the locator box.

that could be viewed in alternation by using hot keys: the magnified window (described above) and a window showing an overview of the complete node [Fig. 2(b)]. This overview mode displayed the normal unmagnified node content along with a locator box indicating the portion of the node visible in the magnifier mode. This locator box was linked to the position of the mouse cursor and could be moved to any position on the screen.

The magnified window was always 12-characters wide. Low-vision subjects could choose between two character sizes, either 4-cm x-height (for which the magnified window was three lines high) or 2.2-cm x-height (for which the window was six lines high).

For the overview window, most low-vision participants used arial 11 point. Those subjects who had difficulty perceiving the location of hyperlinks used arial 12 point rounded bold. The overview window was 24-cm high and 20-cm wide.

The control group viewed a conventional screen that displayed one complete node at one time and was 24-cm high and 20-cm wide.

Procedure: Low-vision participants were placed at a viewing distance of 40 cm from the screen. Next, they made the display choices as described above: contrast polarity, color of hyperlinks, and size of characters in the magnified window. During the subsequent practice phase, participants familiarized themselves with: 1) the magnifier mode by reading paragraphs of text; 2) the magnifier-plus-overview mode by locating hyperlinks on a node; 3) the experimental procedure; and 4) the layout of the website by answering five questions in the practice website.

Next, participant's reading speed for sequential text (prose) was measured. Participants used the magnifier mode and were instructed to read three paragraphs of text (about 375 characters on six lines each) with both accuracy and speed. Reading speeds were calculated as the number of standard-length words read per minute (= total number of characters, including spaces and punctuation, divided by six) [17].

Next, hypertext information retrieval performance was measured. Participants had to answer four blocks of five questions each, two blocks for each of the two viewing conditions (magnifier mode and magnifier-plus-overview mode). Each block of questions required navigating the same number of nodes to find the answers (on average, 4.4 nodes per question). For the first question of each block, the search started at the home page of the website. Subsequent searches started at the node where the previous search terminated. The order of the websites, the order of the viewing conditions and the order of the search blocks were counter-balanced across the participants. The total time to complete the experiment varied from an 1 h 15 min to 2 h.

The procedure for the control group was similar, except that they only used the normal viewing condition.

Hypertext retrieval performance was measured as the time taken and the number of nodes traversed to answer a question. The total retrieval time was split into two components: the time it took to reach the correct node (browse time) and the time it took to find the answer on that node (skim time). The number of nodes traversed was calculated as the number of transitions between nodes. For each subject we calculated the total retrieval time, browse time, skim time, and number of nodes as the average over ten questions.

B. Results and Discussion

Because of the heterogeneity in the low-vision group, individual data are given in Table 2 (prose reading speed) and in Fig. 3 (hypertext performance).

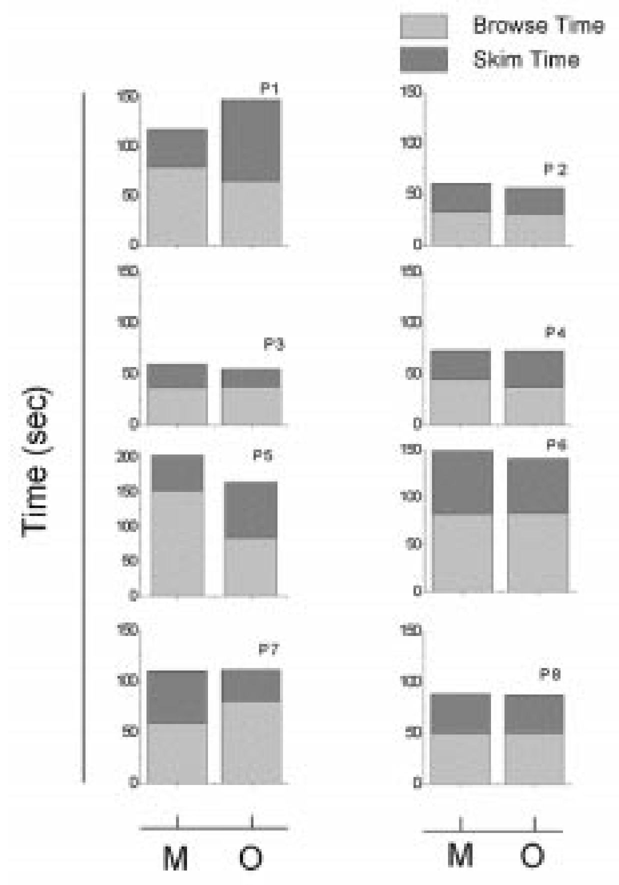


Fig. 3. Results of Experiment 1 for both the magnifier mode (M) and the magnifier-plus-overview mode (O). Total retrieval time is split into browse time and skim time. Data are shown separately for participant P1–P8, described in Table 2.

Prose Reading Speed: The low-vision group read with an average speed of 61 Wpm (magnifier mode) whereas the control group read with an average speed of 201 Wpm. Low-vision sequential reading speeds ranged from 35 to 98 Wpm. Such reading rates are similar to data measured by Harland *et al.* [12].

Total Retrieval Time: Low-vision participants took an average of 108 s to find the answer to a question (magnifier mode) whereas the control group averaged 34 s.

Browse Time: For the magnifier mode, the low-vision group averaged 67 s per question to browse the website and find the correct node, compared with 26 s for the control group

Skim Time: For the magnifier mode, low-vision participants took an average of 41 s per question to skim for the correct answer on an end node, whereas the control group took an average of 8 s.

Number of Nodes: The search strategy was evaluated by counting the number of nodes traversed to answer a question. On average, the minimum path length was 4.4. Low-vision participants traversed 4.9 nodes on average (magnifier mode), not significantly different from the 4.7 nodes for the control group. From this we infer that people with low vision used browse strategies that are similar to normal-vision participants in this experiment.

Magnifier-Plus-Overview Mode: To evaluate the use of the overview mode, the time the overview window was used was expressed as a percentage of the total browse time and skim time. There were large individual differences in these percentages which ranged from 13% to 87% for the browse time and from 0% to 34% for the skim time. Yet the low-vision group did not show any significant improvement in hypertext retrieval time when provided with the overview mode. This was even true for those participants who used the overview window extensively.

Speed Comparisons: The low-vision group averaged 30% of the prose reading speed of the normal group (61 Wpm versus 201 Wpm). Overall, the low-vision hypertext information retrieval time was 3.2 times longer than the total retrieval time of the normal-vision group. Converting these values to the speed of hypertext retrieval, the low-vision group averaged 32% of the normal-vision control group, close to the 30% value for sequential reading. Thus, for the low-vision group in this experiment, the reduction in hypertext information retrieval performance is equivalent to the reduction for reading prose.

The low-vision browse time was more then twice as long as the browse time for the normal-vision group. In terms of speed, the performance of the low-vision group averaged about 40% of the normal group. Compared to sequential reading, the low-vision group was slightly faster. Thus, the low-vision group did not encounter additional difficulties in locating hyperlinks.

Analyses of the skim time revealed a much larger difference between the low- and normal-vision participants. A five-fold difference was found between their times to find the correct answer on an end node. In terms of speed, the performance of the low-vision group was about 20% of the normal group.

We predicted that low-vision hypertext reading performance would be more adversely affected than reading sequential text. The data of Experiment 1 did not reveal such an effect for the overall performance (total retrieval time) nor for the browse time. However, the low-vision group was at a greater deficit for skimming text.

Unlike the websites used in Experiment 1, many websites on the Internet do not have a predictable columnar arrangement of hyperlinks. Experiment 2 was designed to investigate the effect of reducing the predictability of the layout of hyperlinks on low-vision performance.

IV. Experiment 2—Comparing Low-Vision Retrieval for Predictable and Unpredictable Layouts of Hyperlinks

In this experiment, only subjects with low vision participated. Hypertext retrieval performance was tested for two types of webpage layout: one with a predictable columnar arrangement of hyperlinks and the other with an unpredictable arrangement of hyperlinks. Once again, we tested performance for two viewing conditions: magnifier mode and magnifier-plus-overview mode.

LOVNet

LOVNet (Low Vision Network) is the WWW-interface for the Low Vision Research Group.

Low Vision
Vision Rescources

Research
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Low Vision Aides

JUGNet

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Festivals
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Juggling Help
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Papers & Books

(a) (b)

Fig. 4. Nodal layouts in Experiment 2. Two layouts were used: (a) left-justified hyperlinks and (b) distributed hyperlinks.

We predicted that: 1) hypertext reading performance would be slower for text with hyperlinks in unpredictable locations compared to text with predictable hyperlinks and 2) the magnifier-plus-overview mode would improve hypertext retrieval performance for unpredictable layouts.

A. Methods

Participants: There were five participants with low vision (see Table 2.). Four of them also participated in Experiment 1. Although they had worked with the websites before, we did not expect them to remember these in detail, since Experiment 2 was conducted 1.5 years after Experiment 1. Furthermore, different questions were asked. Informed consent was obtained from all participants and they were paid for their time.

Apparatus: The apparatus was identical to that used for Experiment 1.

Websites: Participants were tested on two websites that were similar to those used in Experiment 1. For each website, two types of layout were developed (Fig. 4). One layout had all hyperlinks placed in one left-justified column as in Experiment 1 [see Fig. 4(a)]. The other had hyperlinks distributed across three columns: a left-justified column, a centered column, and a right-justified column [see Fig. 4(b)]. Compared to the left-justified column, such an arrangement of hyperlinks made the locations of hyperlinks unpredictable for magnifier users. To locate hyperlinks, they had to search with the magnified window to find the hyperlinks.

Viewing Conditions: Like Experiment 1, there were two viewing conditions: the magnifier mode and the magnifier-plus-overview mode. In contrast to Experiment 1, the magnifier-plus-overview mode in Experiment 2 was displayed as a second window on the same screen as the magnifier window (Fig. 5). The screen was divided horizontally, creating an upper half displaying the overview window and a lower half displaying the magnified window. This design eliminated the need to press hot keys.

JUGNet

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Being Seen

Juggling Help

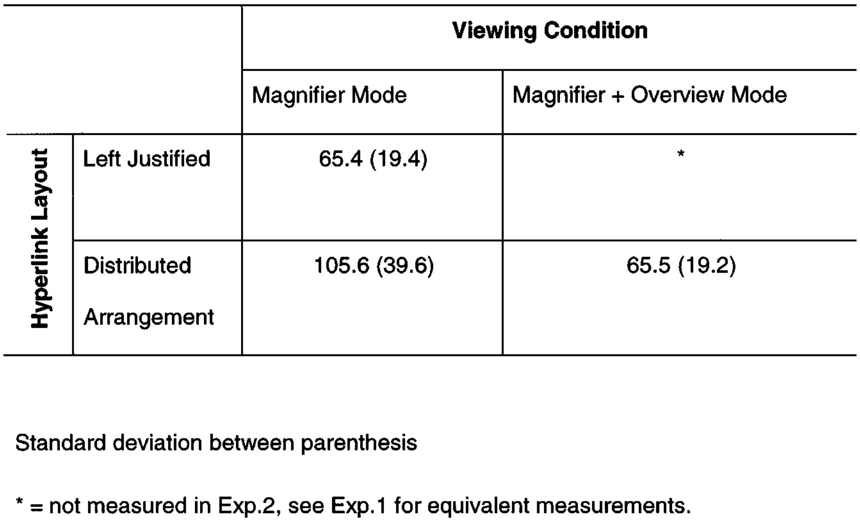
Festivals
Being Seen

Fig. 5. Magnifier-plus-overview mode in Experiment 2. Magnified window (bottom) and the overview window (top) are displayed on the same screen.

The magnified window was 14-cm high and 30-cm wide, displaying two lines of text each 12-characters wide. The overview window was 14-cm high and 20-cm wide.

Procedure: Measurements were taken in two sessions. Session 1 started with participants making display choices as in Experiment 1. The viewing distance was 40 cm from the screen. The subsequent practice phase was the same as Experiment 1. Next, hypertext information retrieval performance was measured using the magnifier mode. Participants were instructed to answer two blocks of six questions, one block for the layout with left-justified hyperlinks and

Table 3
Mean Browse Times as Measured for Two Different Types of Hyperlink Layout and Two Different Viewing Conditions (Experiment 2)



		Viewing Condition	
		Magnifier Mode	Magnifier + Overview Mode
Hyperlink Layout	Left Justified	65.4 (19.4)	*
	Distributed Arrangement	105.6 (39.6)	65.5 (19.2)

Standard deviation between parenthesis

* = not measured in Exp.2, see Exp.1 for equivalent measurements.

another block for the layout with a distributed arrangement of hyperlinks. Session 1 finished with the introduction of the magnifier-plus-overview mode. Participants made themselves familiar with this mode by solving 25 visual search tasks that required access to page layout using the overview window. Session 2 started with repeating these visual search tasks until the participant felt comfortable using this viewing mode. The subsequent test phase measured low-vision hypertext information retrieval performance using the magnifier-plus-overview mode. Participants were asked to answer two blocks of six questions for a layout with a distributed arrangement of hyperlinks. Sessions 1 and 2 were conducted on different websites. The order of the websites and the order of the question blocks were counterbalanced across the participants. Since we were interested in the effect of the layout of hyperlinks (predictable versus unpredictable), with primary impact on the browse time, only browse time was recorded. All data were analyzed with paired sample t-tests.

B. Results and Discussion

Browse Time: Group averages are listed in Table 3. For individual data, see Fig. 6. For the magnifier mode, participants spend an average of 65 s browsing a website with all hyperlinks arranged in the left-justified column. When the location of hyperlinks was changed to the distributed arrangement, participants needed significantly more time (average of 106 s of browse time) (one-tail: $t = 2.77$, 4 df, $p < 0.05$). This increase in browse time reflected the efforts of participants to locate the appropriate hyperlinks.

For the magnifier-plus-overview mode, participants spend an average of 65 s browsing a website with the distributed arrangement of hyperlinks, almost identical to the average for the magnifier mode with left-justified links. This value was significantly shorter than their time with the magnifier mode for a distributed arrangement of hyperlinks (mean of 106 s; one-tail: $t = 2.66$, 4 df, $p < 0.05$). Observations by the experimenter revealed that participants changed back and forth between the magnified and overview window when exploring a node. They placed the locator box on a hyperlink of interest, read its name and content using the magnified

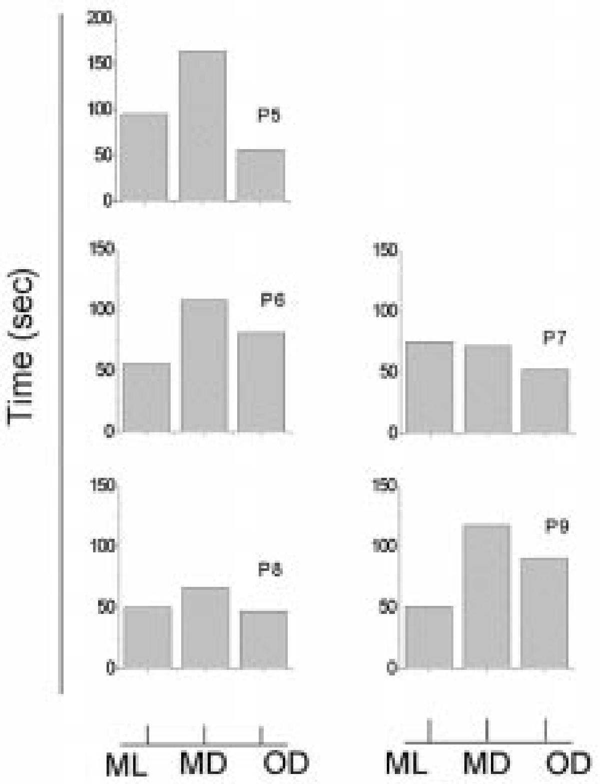


Fig. 6. Results of Experiment 2. Browse times are shown for the three combinations of viewing condition and nodal layout: magnifier mode with left-justified hyperlinks (ML), magnifier mode distributed hyperlinks (MD), magnifier-plus-overview mode for layout with distributed hyperlinks (OD). Data are shown separately for participant P5–P9, described in Table 2.

window, and changed back to the overview window to locate a subsequent hyperlink.

There was no significant difference in browse time between using the magnifier mode with predictable links and using the magnifier-plus-overview mode with unpredictable links ($t = 0.20$, 4 df, $p = 0.849$). This finding implies that access to the global layout is valuable in offsetting the problems associated with finding hyperlinks in unpredictable locations.

Number of Nodes: The minimum number of nodes transitions in order to answer a question averaged 4.0. When using the magnifier mode, the mean number of nodes traversed was 5.3 for the left-justified hyperlinks and 5.2 for the distributed hyperlinks, an insignificant difference. Fewer nodes, 4.7, were traversed on average for the distributed links when using the magnifier-plus-overview mode, a difference in modes that approached significance ($t = 2.722$, 4df, $p = 0.053$).

The results of Experiment 2 showed that low-vision hypertext search is much slower for unpredictable layouts of hyperlinks compared with a predictable columnar arrangement. Fortunately, however, access to global layout results in a reduction in search time that offsets the extra time associated with unpredictable layouts.

V. General Discussion

In Section II, we identified two problems that low-vision readers confront when retrieving information from hypertext. If they use a screen magnifier to compensate for reduced visual acuity, they lose access to global layout information. As a result, they may have difficulty in: 1) finding hyperlinks while browsing and 2) skimming text to find specific information.

The main finding of Experiment 1 was that for text-based websites with simple, columnar arrangements of hyperlinks, the extra time required for low-vision subjects to solve hypertext retrieval tasks is predictable from their deficits in prose reading speed. A subsidiary finding was that low-vision participants encounter difficulties when they attempt to skim text for specific information.

Experiment 2 showed that magnifier users encounter problems locating hyperlinks when they are placed at unpredictable locations (true for most websites on the Internet). The problem of locating hyperlinks can be solved in two ways: 1) reform at hyperlinks into predictable locations or 2) provide low-vision users with the magnifier-plus-overview mode so they can access node layout to find hyperlinks. This latter result is consistent with den Brinker's [16] finding of the importance of access to global page layout described in the Introduction.

Generalizing our findings to the accessibility of Internet websites for people with low vision, one could argue in favor of websites with predictable arrangements of hyperlinks. One might also plead for websites with a highly standardized layout. The argument is that for a standardized layout, important parts of the text can be found at predictable locations, facilitating performance with a magnified window. Some commercial software programs such as IBM Home Page Reader (IBM Corporation) and Jaws for Windows Screen Reader (Henter-Joyce, FL) work like this. These programs can rearrange all hyperlinks from a node into a column of hyperlinks.

Reformatting nodal layout for sequential reading with a magnified window forecloses any possible advantages of having direct access to the original page layout. The layout of information on a node provides a graphical structure that sometimes carries important information. With a tool such as the overview window plus locator box, low-vision users are able to perceive the layout and access such information. Some commercial screen magnification software packages, such as ZoomText provide such an overview mode.

In conclusion, low-vision users of hypertext benefit from simultaneous access to two types of information display: a magnified view of local information such as individual letters or words and an overview of the global characteristics of page layout.

Appendix
Psychophysics of Reading—Normal and Low Vision

This series of papers describes research on the psychophysics of reading conducted at the Minnesota Laboratory for Low-Vision Research by Gordon E. Legge and his colleagues. The research was funded by the National Institutes of Health.

I) G. E. Legge, D. G. Pelli, G. S. Rubin, and M. M. Schleske, "Psychophysics of reading. I. Normal vision," *Vis. Res.*, vol. 25, no. 2, pp. 239–252, 1985.

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XIII) S. J. Ahn and G. E. Legge, “Psychophysics of reading. XIII. Predictors of magnifier-aided reading speed in low vision,” *Vis. Res.*, vol. 35, no. 13, pp. 1931–1938, July 1995.

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XV) J. S. Mansfield, G. E. Legge, and M. C. Bane, “Psychophysics of reading. XV. Font effects in normal and low vision,” *Invest. Ophthalmol. Vis. Sci.*, vol. 37, no. 8, pp. 1492–1501, July 1996.

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