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ORIGINAL ARTICLE

# Reading with a Head-Mounted Video Magnifier

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**ABSTRACT: *Purpose:* This study compared the effectiveness of a head-mounted video magnifier, low-vision enhancement system (LVES), with closed-circuit TV (CCTV) and large print as a device or means of improving reading performance in people with low vision. *Methods:* The reading performance of ten low-vision participants was assessed in two ways: (1) By measuring reading speed as a function of print size with LVES and without LVES, and (2) by comparing reading speed and comprehension of news articles using the LVES vs. a popular non–head-mounted video magnifier, the CCTV. *Results:* Maximum reading speeds with LVES matched the maximum reading speeds with unaided vision attained by enlarging print. The critical print size (the smallest print size that could be read at maximum reading speed) improved significantly for all participants using LVES compared with unaided vision. When comparing reading performance using LVES and CCTV, we found that reading speed and comprehension for the two conditions were equivalent. The two low-vision participants with lowest acuities (20/640 and 20/960) could not read the 10-point newspaper articles with LVES, even with an 8 D auxiliary reading lens that permitted a very close reading distance. *Conclusions:* Head-mounted video magnifiers, such as LVES, can support good low-vision reading performance, but the restricted range of magnification may limit the usefulness of the device as a reading magnifier for people with very low acuity. (Optom Vis Sci 1999;76:755–763)**

Key Words: low vision, head-mounted display, video, magnifiers, reading

Many reading magnifiers are available to people with low vision. These devices range from simple optical magnifiers of relatively low power to high-power video magnifiers. The most widely used of all of these devices are traditional optical magnifiers.[1–3] These magnifiers are popular because they are usually inexpensive and portable, and provide adequate magnification for many people with mild or moderate vision loss. But optical magnifiers have limitations that prevent them from being useful for some people with more severe forms of low vision. For example, the highest practical magnification of optical magnifiers is not sufficient for readers with very poor acuity. For readers suffering from severe light scatter (e.g., from cataract), reversing text contrast from black-on-white to white-on-black improves reading speed,[4, 5] but optical magnifiers are not capable of contrast reversal. Other problems with optical magnifiers include the need to position them at an appropriate distance from the page or to maintain appropriate eye-to-magnifier alignment and distance. Strong magnification also reduces the number of characters visible at any one time, which can hamper navigation through text.[6] In some cases, it can be difficult to obtain adequate illumination of the reading material because the head, hand, or magnifier may block the light.

Video magnifiers were designed to overcome the limitations of optical magnifiers.[7] The closed-circuit television (CCTV) consists of a large monitor and a video camera equipped with a zoom lens. The camera and lens are mounted above a movable platform. Printed material is placed on the platform and the reader views the magnified image on the monitor screen. The reader navigates through the text by moving the material through the camera's field of view. CCTV's are good reading magnifiers because they provide a large range of magnification levels, wide field of view, good illumination, freedom to vary head position, and control of contrast polarity. CCTV's can also be used for writing. The major limitation of CCTV's is that most of them are not portable.

Recently, head-mounted video magnifiers have been introduced to combine the advantages of the CCTV with the portability of optical magnifiers. Developers of the head-mounted magnifiers recommend them not only for reading but also for a number of activities such as knitting and watching TV.[8]

They are not recommended for walking or driving because the reduced field of view with increasing magnification adversely affects mobility. Although head-mounted video magnifiers are potentially useful aids for visually impaired people, there has been very little research on their functionality in daily activities. The general objective of the present study was to learn more about these systems by evaluating a commercial head-mounted video magnifier called low-vision enhancement system (LVES). LVES consists of a headset (weighing 2.6 pounds) containing a binocular, battery-powered, black and white, video display that is attached by a cord to a control box. It is equipped with two video cameras having fixed-focus unit magnification optics for orientation and a center-mounted camera with variable focus and variable magnification optics for performing near, intermediate, and distance tasks. LVES also incorporates a user-controlled electronic contrast enhancement feature and an automatic compensation of camera sensitivity for changing light levels.[8]

In the present study, we tested the usefulness of LVES as a reading aid. To date, studies of LVES have only investigated improvements in visual acuity and contrast sensitivity. The common finding is that visual acuity can improve by about 0.7 log units and contrast sensitivity can improve by about 0.4 log units.[9, 10] Because acuity and contrast sensitivity are poor predictors of reading speed,[11, 12] it remains unknown whether head-mounted video magnifiers are useful in improving reading performance.

Successful reading with magnifiers requires coordination of eye, hand, and head movements.[6, 7, 13] In the case of reading with a head-mounted display, head movements tend to play a more important role than manual movements. While the studies of Beckmann and Legge[6] and Harland et al.[13] have shown that sensory factors impose more limitations on low-vision reading speed than manual control of magnifiers, it remains unknown whether this is also true for head-mounted video magnifiers.

In this study, we addressed the following questions: (1) How much can the range of readable print sizes be extended with LVES? (2) Can maximum reading speed be attained with LVES? (3) How do reading speeds compare for LVES and a CCTV?

## METHODS

### Participants

Ten participants with low vision and two with normal vision were recruited for the study. The protocols for the experiment were reviewed by the University of Minnesota's internal review board for the Protection of Human Subjects, and written informed consent was obtained from all participants before data collection. All participants spoke English as their native language and were paid to participate in the study. We selected participants with a wide range of visual conditions. Snellen acuity for the low-vision readers ranged from 20/100 to 20/960 and contrast sensitivity ranged from 0.15 to 1.65 Pelli-Robson log contrast sensitivity. Normal-vision participants both had acuities of 20/16 and normal contrast sensitivities (1.95 and 2.10). Table 1 presents a summary of each low-vision participant's age, visual diagnosis, acuity, and contrast sensitivity. In addition, participants were chosen on the basis of being proficient CCTV users, which ensured that they would have some familiarity with video-based magnification devices. None of the participants had prior experience using LVES.

### Materials and Apparatus

In the first part of the study, we used the MNREAD Acuity Chart[14] to compare reading performance of the low-vision participants with and without LVES. Throughout the study, the luminance of the chart was maintained at 80 cd/m$^2$. The MNREAD Acuity Chart consists of 19 sentences and the print size of successive sentences differs in steps of 0.1 logarithm of the minimum angle of resolution (logMAR) (i.e., reduction to 80% of the print size of the previous sentence. When the chart is viewed at a reading distance of 40 cm, the largest sentence corresponds to 1.3 logMAR (20/400 Snellen equivalent) and the print size of the smallest sentence corresponds to −0.5 logMAR (20/6.3 Snellen equivalent). Each sentence consists of 60 characters (10 "standard-length words," defined as the number of characters divided by six)[15] printed on three lines. Reading times and the number of errors were scored for each sentence to calculate three parameters of reading performance: *reading acuity*, the smallest print size that can just be read; *maximum reading speed*, the reading speed when print size is not a limiting factor; and *critical print size*, the smallest print that can be read at the maximum reading speed (for a detailed description of the computation of the three parameters see Mansfield et al.[16]).

The maximum reading speed is an objective measure of the best reading performance attainable by the reader. The critical print size is the optimal print size for reading because it is the smallest print size at which participants read with their maximum rate.[14, 16] Statistical definitions of maximum reading speed and critical print size are given in the results sections of this article as well as the formula used to calculate reading acuity.

**TABLE 1.**
Age, visual diagnosis, visual acuity, and contrast sensitivity score of 10 low-vision participants.

| Participant | Age | Diagnosis | Snellen Distance Acuity | Pelli-Robson Contrast Sensitivity Score |
|---|---|---|---|---|
| A | 24 | Uveitis | 20/200 | 1.65 |
| B | 49 | Secondary corneal opacification | 20/960 | 0.15 |
| C | 25 | Glaucoma | 20/400 | 0.3 |
| D | 48 | Optic neuritis | 20/125 | 1.05 |
| E | 74 | Optic neuritis | 20/320 | 1.35 |
| F | 58 | Viral infection causing retinal damage | 20/640 | 0.15 |
| G | 79 | Macular degeneration | 20/100 | 1.2 |
| H | 47 | Macular degeneration | 20/200 | 0.9 |
| I | 39 | Posterior staphyloma | 20/250 | 0.9 |
| J | 25 | Retrolental fibroplasia | 20/400 | 0.6 |

Typically, reading speed remains constant over a wide range of print sizes, but when print size is smaller than the critical print size, reading speed slows down until the acuity limit is reached. Fig. 1 shows the MNREAD plots of a person with low vision and a person with normal vision. The MNREAD plots of persons with low vision are usually shifted downward and to the right of the MNREAD plots of people with normal vision. This means that people with low vision read slower and require larger print to read.

In the second part of the study, news articles were used to assess reading performance. Forty-five news articles were obtained from the electronic version of the UPI/Reuters news reader and participants reported not having previous knowledge of the news stories used in the study. The articles were chosen so that the difficulty of the text was well below the participants' reading level, ensuring that reading rate was not limited by text difficulty.[17, 18] The news articles had a ninth-grade level of difficulty (Flesch-Kincaid Grade Level score) and all participants had completed at least the 12th grade. All articles contained at least 100 words, and some articles contained two or three additional words to complete the meaning of the final sentence. Text was printed in 10-point Times Roman font because this is a typical typeface used in newspapers. Text was left-justified, and three asterisks were placed at the end of the last word of each article to signify the end of the article. The maximum number of characters per line was 40 characters, and the articles were an average of 15 lines long. Each article was printed on a separate sheet of paper using a 600 × 600 dpi laser printer. Fig. 2 shows a sample article used in the study.

The LVES system was equipped with three cameras. Only the centrally mounted zoom camera was used in the study. This camera provided the same video image to both eyes. Fig. 3 shows a picture of a participant reading the MNREAD Acuity Chart with LVES.

LVES offered a range of magnification between 1× and 9×. The camera could be tilted down by as much as 45° for a "down gaze" while reading. An auxiliary lens, with dioptric power 2, 4, or 8 D, could be inserted in front of the zoom camera so that the LVES could focus at a closer working distance and thus increase

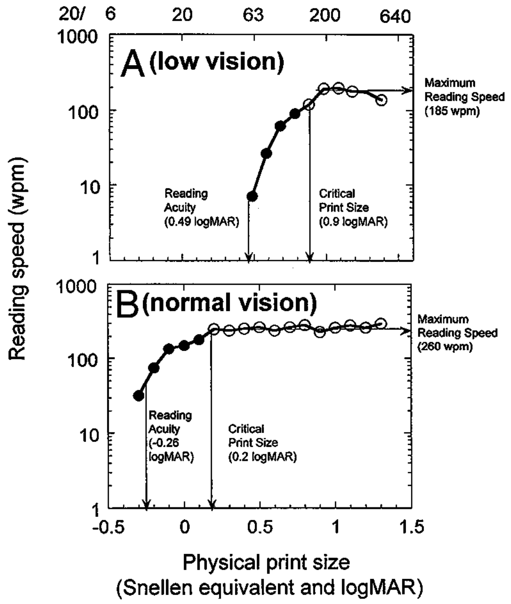


**FIGURE 1.**

Normal and low-vision sample MNREAD plots showing reading speed as a function of print size for (A) low-vision and (B) normal vision participant. In each plot, unfilled symbols represent the reading speeds that were taken into account for the computation of the maximum reading speed.

Passage 3

British scientists say they have discovered the possibility of increasing people's intelligence by adjusting the level of chemical acidity in the brain. A team of scientists at Oxford said intelligence could be directly linked to pH level. They reached the conclusion after conducting an experiment which measured the acid content in the brains of 42 boys aged between six and thirteen years. Their findings indicate a link between IQ and pH in the brain's cortex, so that a higher or more alkaline brain pH is likely to be associated with a higher IQ. For those whose pH levels exceeded 7.0, their IQ levels almost doubled.***

*The passage indicates that the more alkaline in your brain*

*a) the more drugs you take.*
*b) the less likely you are to get Alzheimer's disease.*
*c) the less aggressive you are.*
*d) the higher your IQ.*

*ANSWER: d*

**FIGURE 2.**

Sample news article used in the study. The comprehension question was included at the end of the article. In the actual experiment, comprehension questions (in italic) were not included in the printed pages of the articles, but were asked verbally by the experimenter.

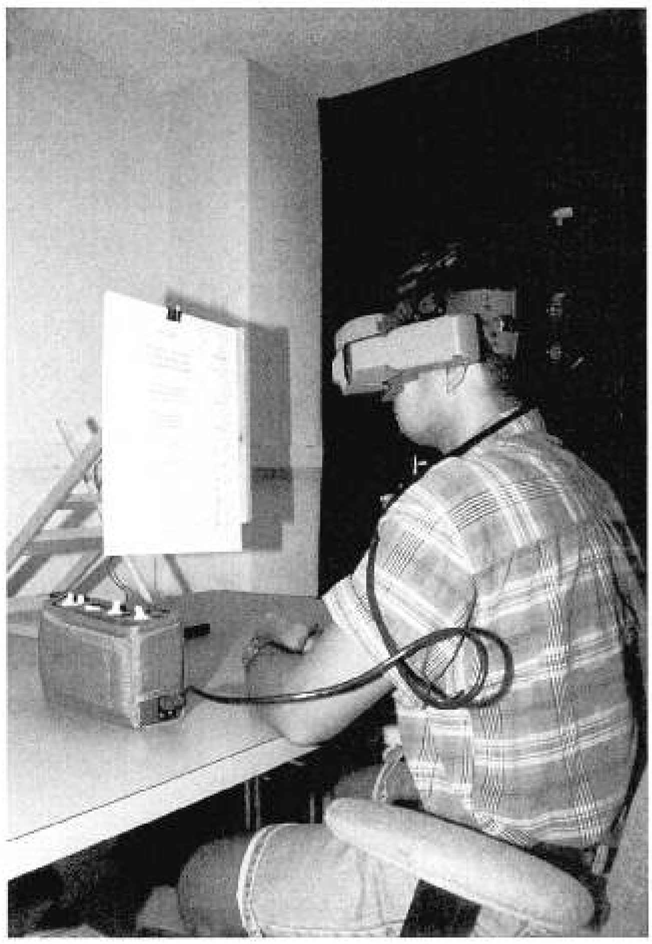

**FIGURE 3.**

A photograph of a participant using LVES and the experimental set up.

the overall magnification. Participants could not wear glasses while wearing the LVES, but optical correction for the participants' refractive errors could be incorporated into the headset. While wearing the headset, each of the user's eyes viewed a CRT video display with a resolution of about 350 TV lines. This was the only visual input they had. When looking at a white surface illuminated by conventional room lighting, the luminance of the LVES display was 30 cd/m$^2$.

Adjustments to the image could be made using the control box that was linked to the headset by a cord. This control box contained switches that were used to adjust magnification, contrast enhancement, and contrast polarity of the reading material. It also had a "focus mode" switch, which allowed participants the ability to choose between the manual or automatic-focusing mode.

Participants A, B, C, D, and E were tested with an LVES model that had a zoom camera with a resolution of 492 × 512 pixels (model LC10B), and participants F, G, H, I, and J were tested with an LVES with a higher resolution camera (492 × 768 pixels, model LC10C).

CCTV reading was evaluated with a VTEK Voyager XL CCTV. The resolution of the CCTV monitor is standard television format (about 500 TV lines). The luminance of the display was 450 cd/m$^2$.

## Procedures

Before the experiment, an experienced representative from LVES's manufacturer (Visionics Inc., Minneapolis, MN) performed the fitting of LVES for each participant. Fitting involved positioning the video displays to match the participant's interpupillary distance, incorporating their optical correction into the system, and adjusting the comfort level of the headset. During testing, LVES was connected to an external TV monitor to provide the experimenters with a view of what the participant was seeing.

## MNREAD Testing

Participants were tested on the MNREAD Acuity Chart with and without the LVES. Participants sat at a viewing distance of 25 cm from the chart when using LVES. To ensure that each sentence was seen clearly by the participant, they were first shown a sheet of paper with the phrase "focus here" printed at print sizes ranging between 1.3 and −0.5 logMAR, corresponding to the range of print size used on the MNREAD Acuity Chart. Participants were asked to make the necessary adjustments to the LVES settings so that the phrase "focus here" that shared the same print size as the upcoming MNREAD sentence was seen most clearly. Four different kinds of adjustments were made to the LVES settings to maximize the clarity of the characters. The order in which these adjustments were made was the same for all participants:

1. The participant selected the preferred contrast polarity, white-on-black or black-on-white text. Contrast polarity remained the same throughout testing.
2. The magnification was adjusted until the participant indicated that the image was at a comfortable reading size. The magnification factor was read from a digital display attached to the LVES control box and recorded for each participant. The magnification factor display was not a regular feature of the LVES and was provided by the manufacturer at our request. The accuracy of the display readings was confirmed by our independent measurements of the image size using an optical bench.
3. Focus adjustments were made to the image.
4. The contrast level of the image was adjusted until the participant found a comfortable setting. To ensure that the image seen through LVES was at its optimum for the participant, adjustments to the contrast, magnification, and focus were sometimes made by the experimenter (but guided by the participant). These adjustments were usually made before the participants read the next sentence on the MNREAD Acuity Chart.

For most participants and print sizes, less than a full line of text was visible on the LVES screen at any one time. To scan the lines of text while maintaining the viewing distance, a participant turned his or her head while keeping the chin in a chin rest. Participants were allowed to take breaks between sentences.

## News Articles Reading

Participants were asked to read seven news articles using the LVES and seven news articles using a CCTV. Articles were chosen randomly from our pool of 45 news articles. The order of testing with LVES and CCTV was counterbalanced across participants. To read the articles using LVES, participants sat at 25 cm from the text, which was printed on a piece of paper and positioned on an easel. A chin rest was used to help the participants maintain the distance from the text. Most participants were presented with 10-point text; however, for the two participants with the lowest visual acuity (participant F, 20/640, and participant B, 20/960), 10-point print was too small so they were presented with 16-point text instead. Additional magnification was provided for these two participants by inserting the 8 D auxiliary lens in front of the LVES zoom lens. Consequently, the reading distance was changed to 12.5 cm for these two participants so that the overall nominal magnification was increased to 18×.

At the beginning of this part of the study the participants were presented with a sample news article and were instructed to adjust the LVES settings to get the best possible image. The order in which these adjustments were made was the same as before (contrast polarity, magnification, focus, and contrast level). Once the participants made all the necessary adjustments, they were asked to read a few more sample news articles. Because all the articles were of the same size, the LVES settings did not change during this part of the study. After practice trials, the participants were instructed to read seven test news articles silently and as quickly as possible. They were informed that they were going to be asked a multiple-choice question about the article's content. The questions were designed so that they could be answered easily only if the article was read accurately. During practice trials, participants were also presented with a sample question after each article to give them an idea of the kind of questions they were going to be asked. The magnification factors used by the participants were recorded. None of the articles was read more than once. During testing, the time taken for the participants to finish reading until the last word of each article was measured using a stop watch and reading speed was calculated in words per minute using the following formula:

Reading speed (wpm) = number of standard-length words divided by time, where standard-length words refers to total number of characters divided by 6 and time was measured in minutes.[16]

Participants selected their own viewing distance for the CCTV reading measurements. The CCTV settings were then adjusted to obtain the best possible image on the monitor according to the participant's preferences. Contrast polarity, magnification, focus, and contrast level were adjusted by the participant. The physical x-height of the letters on the screen was measured as well as the distance of the participant from the CCTV monitor.

## RESULTS

## MNREAD Testing with and without LVES

Fig. 4 shows reading speed (in words per minute) as a function of print size obtained with and without LVES for each of the low-vision participants. A visual examination of the plots shows that in all cases, the curve obtained with LVES is shifted to the left of the curve obtained without LVES. This implies that participants were able to read text of smaller physical size when using LVES. In most cases, both curves reach similar maximum reading speeds, indicating that maximum reading speeds with LVES are similar to maximum reading speeds without LVES.

To quantify the reading performance, reading speeds and print sizes of each participant were entered into the computer program MNREAD ANALYSIS 0.3 to compute two parameters of reading performance[16]: the maximum reading speed and the critical print size. The algorithm used by the analysis program first identifies the reading speed plateau of the data set. The reading speed plateau refers to the range of print sizes over which reading speeds are within 2 standard deviations of the iterated maximum reading speed. Maximum reading speed is defined as the geometric mean of the reading speed across the plateau. Critical print size is defined as the smallest print size included in the plateau.

The third parameter, reading acuity, was calculated using the following formula[16]:

logMAR reading acuity = 1.4 − (number of sentences read × 0.1) + (number of words read incorrectly × 0.01).

It is important to point out that participants B, C, G and J do not show a well-defined reading speed plateau when reading without LVES. These participants were able to read only three to five MNREAD sentences (even when all of them read the chart at a viewing distance closer than 40 cm). These participants also presented the largest variability in reading speeds. Because of this variability and the few sentences read by these participants, the MNREAD ANALYSIS program was unable to accurately estimate critical print size and reading speed. For these participants, maximum reading speed was defined as the fastest reading speed achieved and critical print size was defined as the smallest print size at which the fastest speed was obtained.

Table 2 presents the computed maximum reading speed, critical print size, and reading acuity for the ten low-vision participants. Fig. 5 shows a graphical representation of Table 2. On each scatter plot in Fig. 5, the data obtained with LVES were plotted on the y axis and the data obtained without LVES were plotted on the x axis. Any data point that lies on the diagonal of each scatter plot indicates equality.

The maximum reading speeds, critical print sizes, and reading acuities obtained with and without LVES (shown in Table 2) were

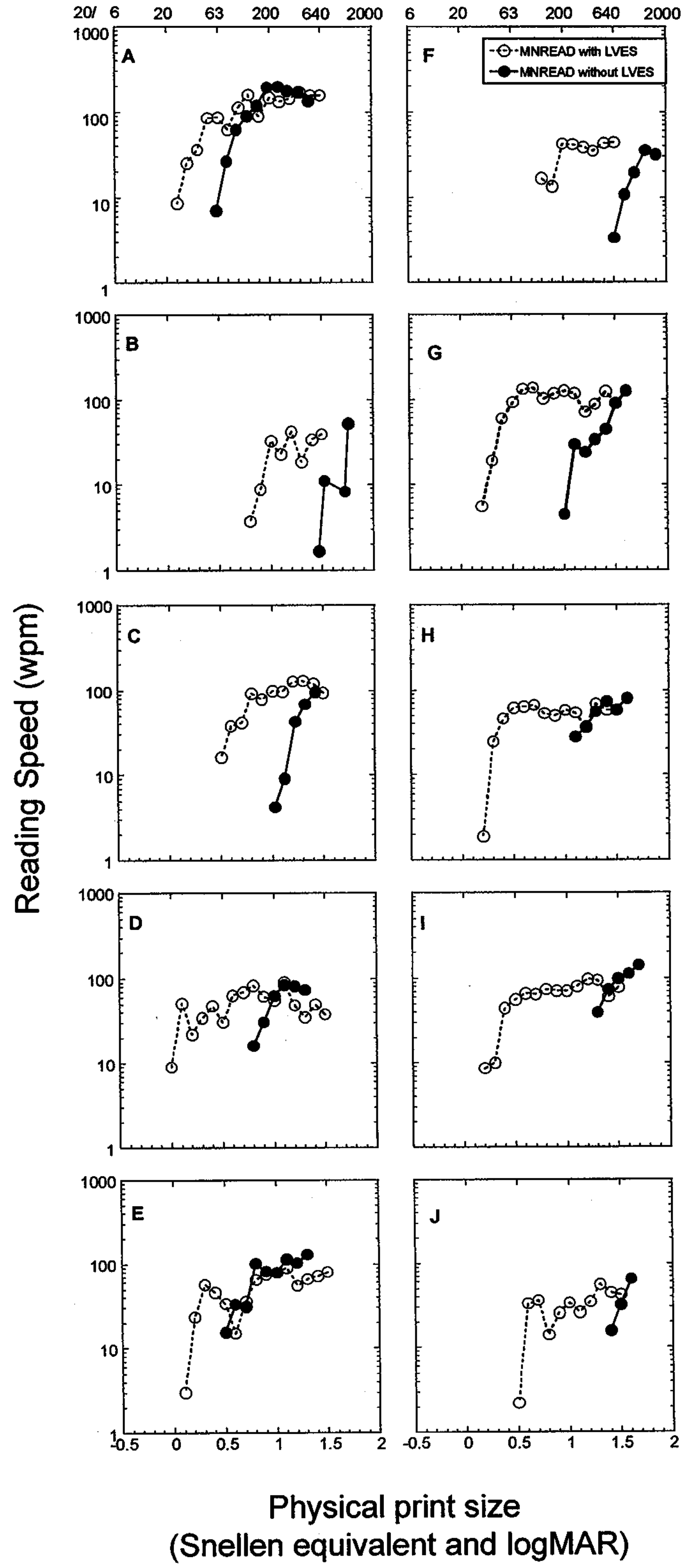


**FIGURE 4.**

Reading speed as a function of print size with and without LVES for participants A through J.

compared using paired-samples t-tests. In terms of reading speed, the 10 participants on average read 5.7 wpm faster without LVES than with LVES. This difference did not reach statistical significance [t(9) = −0.482, p = 0.641]. An additional power analysis

**TABLE 2.**
Summary of maximum reading speeds, critical print sizes, and reading acuities obtained with and without LVES measured with the MNREAD Acuity Chart for 10 low-vision participants.

| Participants | LVES | | | No LVES | | |
|---|---|---|---|---|---|---|
| | Maximum Reading speed (wpm) | Critical print size (logMAR) [Snellen] | Reading Acuity (logMAR) [Snellen] | Maximum Reading speed (wpm) | Critical Print size (logMAR) [Snellen] | Reading Acuity (logMAR) [Snellen] |
| A | 139.62 | 0.7 [20/100] | 0.18 [20/30] | 184.5 | 0.9 [20/159] | 0.49 [20/62] |
| B | 30.6 | 1.0 [20/200] | 0.9 [20/159] | 16.95 | 1.5 [20/640] | 1.5 [20/640] |
| C | 103.56 | 0.8 [20/125] | 0.53 [20/68] | 65.2 | 1.2 [20/317] | 1.1 [20/250] |
| D | 49.56 | 0.1 [20/25] | 0.04 [20/22] | 80.09 | 1.1 [20/250] | 0.82 [20/133] |
| E | 48.71 | 0.1 [20/25] | 0.1 [20/25] | 99.7 | 0.8 [20/125] | 0.53 [20/68] |
| F | 40.23 | 1.0 [20/200] | 0.82 [20/133] | 27.7 | 1.7 [20/1016] | 1.6 [20/806] |
| G | 106.98 | 0.5 [20/63] | 0.26 [20/36] | 47.81 | 1.5 [20/640] | 1.1 [20/250] |
| H | 55.46 | 0.4 [20/50] | 0.3 [20/40] | 65.98 | 1.3 [20/400] | 1.1 [20/250] |
| I | 72.64 | 0.5 [20/63] | 0.26 [20/63] | 116.52 | 1.5 [20/640] | 1.3 [20/400] |
| J | 32.78 | 0.6 [20/80] | 0.6 [20/80] | 32.37 | 1.4 [20/508] | 1.4 [20/508] |
| Means | 59.97 (geometric mean) | 0.57 [20/74] | 0.4 [20/50] | 59.28 (geometric mean) | 1.29 [20/392] | 1.1 [20/250] |

revealed that given the estimates on variability (SD = 37.41) a group size of 338 participants would be required before a 5.7 wpm difference would reach significance at the 0.05 alpha level (beta = 20%).

The t-test conducted on the critical print sizes revealed a significant difference between reading with LVES and reading without LVES [$t(9) = -8.219$, $p < 0.001$]. The improvement in critical print size was on average about 0.68 log units when using LVES. Reading acuities were also significantly different between reading with LVES and reading without LVES [$t(9) = -10.178$, $p < 0.001$]. The average improvement in reading acuity was about 0.7 log units.

There was a discrepancy between the nominal magnification factor and the improvement in the participants' reading acuity and critical print size. We found that the improvement in reading acuity with LVES was on average about 0.22 log units less than expected from the nominal magnification factor used by the participants. This result was statistically significant [$t(9) = 3.160$, $p = 0.012$]. An additional analysis was conducted to investigate whether this discrepancy was smaller with the higher resolution camera (model LC10C) than the lower resolution camera (model LC10B). It was found that the difference between the observed and the expected improvement was on average about 0.37 log units for the LVES with the lower resolution zoom camera. A paired-samples t-test found that this difference was statistically significant [$t(4) = 5.660$, $p = 0.005$]. On the other hand, it was found that the discrepancy was on average only about 0.056 log units for the five participants who used the LVES with the higher resolution zoom camera. This difference was not statistically significant [$t(4) = 0.905$, $p = 0.416$]. An additional power analysis revealed that given the estimates on variability (SD = 0.14), a group size of 62 participants would be required before a 0.056 log units difference would reach significance at the 0.05 alpha level (beta = 20%).

We conducted an analysis that suggested that the discrepancy between the expected and the observed improvement in reading acuity could be attributed to the poor spatial resolution of the LVES zoom cameras (see Appendix).

## News Article Reading (LVES vs. CCTV)

We compared participants' reading speeds obtained with LVES and with the CCTV. Table 3 shows the calculated retinal image size and reading speed for news-article reading using the LVES and the CCTV for the ten low-vision participants. Retinal image size refers to the visual angle subtended by the magnified image on the retina and was calculated based on the magnification provided by the LVES or the CCTV. For reading with the CCTV, the viewing distance was also taken into account to derive the retinal image size. Fig. 6 is a scatter plot comparing reading speeds obtained with the LVES and the CCTV. Most of the data points lie close to the diagonal, showing that reading speeds obtained with LVES are very similar to those obtained with CCTV. The 10 participants on average read 5.33 wpm faster with CCTV than with LVES. This difference did not reach statistical significance difference [t(9) =

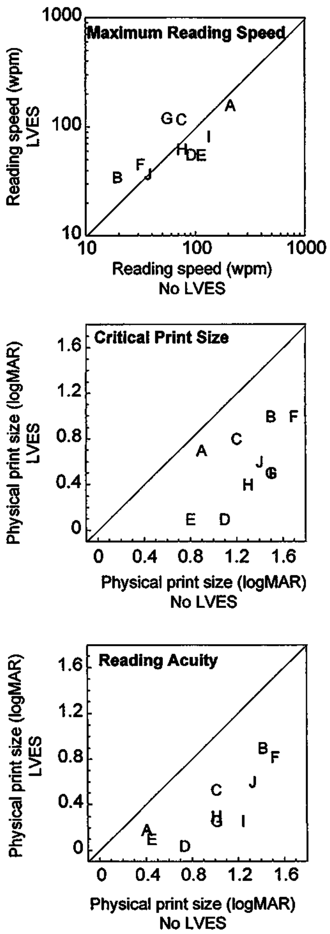


**FIGURE 5.**
Scatter plots of the maximum reading speeds, critical print sizes, and reading acuities obtained with and without LVES for 10 low-vision participants. For the plot of critical print size, data points for participants G and I are identical and thus are superimposed on each other.

1.509, p = 0.166]. An additional power analysis revealed that given the estimates on variability (SD = 11.15), a group size of 37 participants would be required before a 5.33 wpm difference would reach significance at the 0.05 alpha level (beta = 20%).

To ascertain that the participants were reading at their maximum reading speed when they read the news articles, we used a paired-samples t-test to compare the maximum reading speed obtained with the MNREAD Acuity Chart when using LVES, with the reading speed obtained for the news articles when using LVES. The 10 participants' maximum reading speed obtained with the MNREAD Acuity Chart was on average 6.73 wpm faster than the reading speed measured with the news articles. This difference did not reach statistical significance [t(9) = 1.029, p = 3.30]. An additional power analysis revealed that given the estimates on variability (SD = 20.65), a group size of 76 participants would be required before a 6.73 wpm difference would reach significance at the 0.05 alpha level (beta = 20%). The fact that maximum reading speed with LVES and the reading speed for the news articles using LVES were not statistically different supports the idea that participants read the news articles at their maximum reading speed.

To assess the possibility of a practice effect, we compared the average reading speeds between the first three and the last three news articles. No practice effects were found. The participants' accuracy in answering the comprehension questions when reading with the LVES and when reading with the CCTV exceeded 90% in both conditions, indicating good reading comprehension.

**TABLE 3.**
A comparison of the retinal image size and reading speed for news-article reading using CCTV and LVES.

| Participant | CCTV Retinal Image Size (logMAR) | CCTV Reading Speed (wpm) | LVES Retinal Image Size (logMAR) | LVES Reading Speed (wpm) |
|---|---|---|---|---|
| A | 1.6 | 89.50 | 1.44 | 93.45 |
| B | 2 | 50.41 | 1.9 | 43.83 |
| C | 1.77 | 129.97 | 1.7 | 115.00 |
| D | 1.2 | 41.71 | 1.4 | 47.37 |
| E | 1.24 | 61.18 | 1.39 | 57.43 |
| F | 2.01 | 38.89 | 2.1 | 24.12 |
| G | 1.41 | 96.34 | 1.64 | 86.19 |
| H | 1.39 | 40.32 | 1.48 | 56.76 |
| I | 1.63 | 51.48 | 1.65 | 42.45 |
| J | 1.66 | 65.93 | 1.6 | 45.89 |

## DISCUSSION

The primary goal of this study was to address three questions: (1) How much can the range of readable print sizes be extended with LVES? (2) Can maximum reading speed be attained with LVES? (3) How do reading speeds compare for LVES and a CCTV? With respect to these questions, we found that LVES could extend the range of legible print sizes between 0.3 and 1.04 log units. The maximum reading speed attainable with LVES is comparable with that obtained using enlarged print or with a CCTV, supporting the notion that LVES users can read at their maximum reading speed when using the device.

Despite the potential benefits as a reading device, LVES imposed some limitations on reading. Our two participants with acuities of 20/640 and 20/960 could not read the conventional 10-point print newspaper articles with LVES, but could read them with the CCTV. This indicated that the limited range of magnification available with LVES was insufficient to make 10-point print legible to those with very low acuity.

In addition, LVES has a floor effect. The maximum resolution

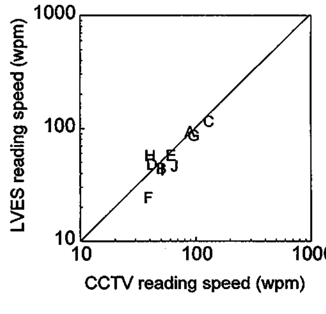


**FIGURE 6.**
Scatter plot of reading speeds obtained with LVES and with CCTV for 10 low-vision participants.

of the LVES display is approximately 20/100, so people with acuity better than 20/100 might not benefit from using LVES. This estimate of the maximum resolution of the LVES was confirmed by measuring the visual acuity of a normal-vision participant who used the LVES with the better resolution camera at unit magnification. These boundary conditions suggest that only low-vision patients whose acuities are within the range of 20/100 to 20/400 may benefit from using LVES as a reading device.

The range of magnification offered by LVES was also limited. One limiting factor was the spatial resolution of the video system. There are a few pieces of evidence that support this argument. First, for all our low-vision participants, the observed improvement in reading acuity is always less than the expected improvement. Second, the maximum magnification attainable with LVES was closer to the nominal 9× for the higher-resolution zoom camera but much lower than 9× for the lower-resolution zoom camera. Third, for both normal-vision participants, reading acuities were worse with LVES than without LVES. The worsening of reading acuity was smaller for the normal-vision participant who used the higher-resolution zoom camera than the one who used the lower-resolution zoom camera.

Another practical factor limiting the viability of head-mounted magnifiers for reading is the focusing feature. LVES can increase its effective magnification by adding auxiliary "reading lenses" to allow for near viewing of text (as close as 12.5 cm). In the present study, the two participants with the lowest acuity had to use these "reading lenses." In addition, LVES has an auto-focusing system; however, the auto-focus feature is too slow to compensate for defocus associated with small dynamic changes in head-to-text distance. In our study, we finessed this problem by stabilizing reading distance with a chin rest and reading stand. If head-mounted video magnifiers are to combine the advantages of optical magnifiers and desktop video magnifiers (CCTVs), they will have to enlarge their range of magnification and solve the problem of rapid autofocusing. An additional limitation of head-mounted video magnifiers might be their cost. For example, the cost of the LVES system ranged between $4000 and $5000.[a]

To increase their effectiveness as reading devices, future designs of head-mounted video magnifiers should incorporate systems that have high spatial resolution, a good range of magnification, as well as fast and accurate autofocusing.

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[a] The LVES is no longer available on the market. The quoted price was based upon the sales price when LVES was on the market.

## APPENDIX

To confirm whether the discrepancy between the expected and the observed improvement in reading acuity was caused by poor spatial resolution of the LVES zoom cameras, we tested two participants with normal vision on the MNREAD chart without LVES and with LVES set to unit magnification. If reading acuity measured with LVES at unit magnification is identical to that measured without LVES, then the idea that the difference between the expected and the observed improvement in reading acuity was due to poor spatial resolution of the LVES zoom cameras would not be supported. The results show that reading acuity was 0.9 log units worse with LVES than without LVES for the normal-vision participant who used the lower-resolution LVES camera. For the other normal-vision participant who used the higher-resolution LVES camera, reading acuity was 0.6 log units worse with LVES than without LVES. These results suggest that there is a limitation to the image quality provided by LVES and that this factor is likely to limit the smallest print size resolvable when using LVES.

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