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The virtual retinal display as a low-vision computer interface: A pilot study

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Abstract—This pilot study examined the performance of an alternative computer visual interface, the Virtual Retinal Display (VRD), for low-vision use. The VRD scans laser light directly onto the retina, creating a virtual image. Since visually impaired individuals can have difficulty using computer displays, a matched comparison study was done between the VRD and the standard cathode ray tube (CRT) monitor. Reading speed and acuity tests were collected from 13 low-vision volunteers selected to represent the broad range of partially sighted individuals actively involved in the work force. Forty-six percent of subjects had highest visual acuity while viewing the VRD; 30% of subjects had highest acuity viewing the CRT; and 24% of subjects had equal acuity across the two displays. Although mean reading speed across all 13 subjects indicated no significant difference between displays, individual subjects with predominantly optical causes of low vision exhibited clinically important increases in reading speed versus the CRT. However, most subjects with predominantly retinal damage showed a slight disadvantage using the VRD. We give theoretical explanation to the bifurcated results and conclude that for a subset of low-vision users, the VRD technology is very promising as a basis for future low-vision aids.

Key words: *computer displays, low vision, reading, retinal scanning, visual disabilities, visual impairment, VRD.*

INTRODUCTION

In recent years, the use of personal computers in the workplace has become prevalent. This ubiquity is apparent in all age groups, even the older-aged ones. In fact, 50.7 percent of American workers aged 50–59 years old and 32.6 percent of American workers 60 years old and over use a computer at work (1). A small but significant portion of computer users in the workforce are individuals with low vision, many that are in these older age groups. It is estimated that over 14,000 low-vision individuals are actively working in Washington State alone (J. Olson, Washington State Department of Services for

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the Blind, personal communication). Individuals with low vision required to work with computers can find the current standard interface, a cathode ray tube (CRT) monitor, a hindrance to their productivity.

Adaptations made by low-vision individuals to the standard computer interface may have limited effectiveness and can even reduce job performance. For example, page navigation with the use of magnifiers can make screen navigation tedious, actually slowing reading speed and requiring a very large screen size (2). In addition, the common practice of increasing image size on the retina by moving the eyes closer to the display screen is a poor long-term solution, because of the induced visual and musculo-skeletal strain (3). An alternative approach to simple enlargement is a fundamentally different strategy that can provide increased visual acuity, hence requiring less magnification to read displayed text. A possible alternative visual interface is the Virtual Retinal Display (VRD), which is the first retinal light-scanning system specifically intended for use as a display. The purpose of this study is twofold: (1) to evaluate the VRD as an alternative low-vision computer interface and (2) to provide the theoretical motivation for implementing the VRD (a retinal light scanning device) in the low-vision population. We compare the VRD with the CRT by utilizing visual acuity and reading speed tests.

The Virtual Retinal Display

The VRD scans modulated, low-power laser light to form bright, high-contrast, and high-resolution images directly onto the retina. This technology is related to the technology underlying the scanning laser ophthalmoscope (SLO) (4) but with the sole intent of image display, not acquisition. The VRD accepts the standard (RGB color or monochrome) output of a computer and generates a raster-scanned image similar to the CRT monitor (**Figure 1**). The portable VRD used in this study converts the VGA (red only) video output of a computer into a signal that modulates the laser diode light source. The modulated beam of light (636 nm) is scanned horizontally (15.75 kHz) and vertically (60 Hz) by two mirrors. A lens system converges the raster-scanned beam to a 0.8-mm exit pupil. When the viewer aligns his or her eye at the exit pupil, the collimated beams of scanning light create a virtual image that appears in the distance. A detailed explanation of the VRD during early development at the University of Washington is found in Johnston and Willey (5).

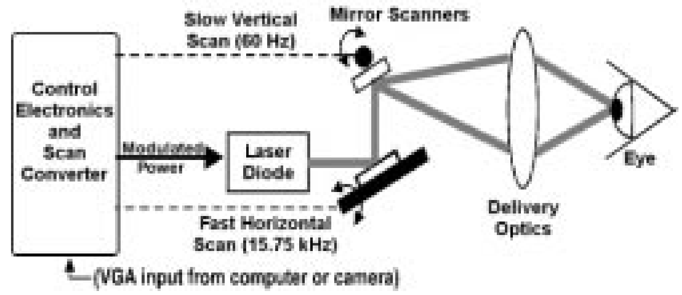

Figure 1.
Schematic diagram of the portable VRD used in this study. The directly modulated laser diode produced a monochrome red (636 nm) output. The video input was standard VGA (640×480) color video from a PC laptop computer.

Retinal Scanning Technology in Low Vision

Scanned laser light for use in low-vision research and rehabilitation has previously been considered advantageous by several authors (6–9). Laser sources, as used within the VRD, can produce images beyond the brightness and contrast of conventional displays, such as the CRT and liquid crystal display (LCD). For example, miniature LCD displays used for the purpose of a wearable low-vision aid, project inferior images in terms of contrast and brightness compared to the CRT (10). Since a scanned laser beam is capable of intensity beyond what is safe for the human eye, the VRD has been designed and shown (11) to produce images at safe levels, well below maximum permissible exposure levels as defined by ANSI- and FDA-regulated standards. The capacity of a display to produce bright images is important for low-vision use. Cornelissen et al. (12) tested partially sighted individuals with a wide range of maladies and found significant visual acuity improvement at higher illuminance levels. Specifically, higher illuminations have been suggested to improve reading speed for patients with macular degeneration (MD) (13).

Previous research with low-vision individuals viewing retinal scanned images has shown promising results in the clinic. Webb and Hughes (6) reported dramatic improvement in visual acuity (up to 20/70) for several patients who previously could only distinguish light from dark. Culham et al. (14) used a SLO in low-vision reading performance testing to both locate and display virtual images onto optimal retinal locations for reading. These authors suggest that their methods could be used to teach low-vision patients (e.g., with MD) how to more effectively use the remaining functional areas of their retina.

In addition, visual acuity and survey data from eight low-vision subjects comparing VRD and CRT images with the use of full-color display systems have been reported by Viirre, et al. (15). In all of these studies, the unique capabilities of retinal light scanning benefited individuals with low vision.

However, these studies used large, sophisticated lab systems, impractical for use as low-vision aids. Also, in the Viirre et al. (15) investigation, display brightness was optimized for each individual and was not matched in a controlled comparison. In our study, a portable, monochrome red version of the VRD is used to better simulate a low-vision aid. We also offer the first study to match luminance and field of view (FOV) between the VRD and the CRT. Our research goal was to conduct a controlled, quantitative performance comparison between the portable VRD and standard CRT in terms of visual acuity and reading speed for individuals in the work force over a wide range of low-vision conditions.

METHODS

Subjects

Our study included 13 individuals with low vision, and was conducted at the Washington State Department of Services for the Blind (WSDSB). All subjects gave approved, informed consent. The 13 low-vision volunteers were recruited by the WSDSB to comprise a variety of vision conditions (**Table 1**). All 13 individuals, except one, were either actively employed or in graduate school. The subjects ranged in age from 28 to 59 years old with a mean age of 41.2 years old (SD=10.3). Each subject was surveyed regarding his or her vision history and current eye condition, and each survey was verified from patient records at WSDSB.

Materials and Apparatus

We measured visual acuity using Landolt "C's," following the specification that the width of the "C" and the gap in the "C" are one-fifth the dimension of the height. The "C's" on the acuity chart had a range of sizes of 4.7º to 0.3º, corresponding to a 20/1130 to 20/70 visual acuity range. Acuity was measured while subjects viewed the CRT with white on black color contrast and the VRD with red on black color contrast. The VRD was set at its higher light output power level, matching the CRT in terms of retinal illuminance (see below).

A unique reading speed test based on the Minnesota Low-Vision Reading test (MNRead™) (16) was used to compare performance between the CRT and the VRD. Rather than implementing scrolled text or Rapid Serial Visual Presentation (RSVP) to overcome FOV constraints, we chose to design entire words that more closely simulated the selective reading involved in actual computing. The words were presented in an unrelated manner because Legge et al. (16) have shown that reading speed of unrelated words correlates directly with normal sentence reading. In testing, three words at a time were presented to the subject: one five-letter, one four-letter, and one three-letter word. The three words were on three separate lines within the display field. The order (3-, 4-, or 5-letter) and placement (top, middle, bottom) were randomized. For each subject, no group of three words appeared together more than once. Individual words appearing more than once was rare (frequency ≤1 percent). Lists of words were randomized with the four test conditions (see Procedure).

The portable VRD displayed the red component of a standard VGA (640×480) color video signal using a directly modulated laser diode (636 nm). A PC laptop computer produced the VGA output at 640×480 resolution. Sans serif Arial type font was chosen, because it allowed more letters to fit on the portable display, which had a measured FOV of 33º horizontal by 26º vertical. The VRD can have a much wider FOV, but this particular version was calibrated with those parameters. Subjects' heads were kept stationary during testing by using a chin rest constructed in the lab (**Figure 2**).

A 17-in. CRT (EIZ0 Flexscan TX-C7, Nanao Corp.) was used for the comparison testing. Its full white-screen luminance was 107 cd/m2. All illuminance and luminance levels were measured using a Spectrascan PR-650 spectrophotometer (Photo Research, Inc.). In addition, the spectrophotometer was used to measure the peak wavelength of the CRT red screen (628 nm) and the VRD (636 nm). The contrast and power levels for laser power were measured using a silicon diode optical meter (model 1835-C, Newport Corp.). The Michelson contrast, $(L_{max}-L_{min})/(L_{max}+L_{min})$, of both the VRD and CRT letters was 0.99. Two power levels of the VRD were used during the experiment, averaging 1.27 μW (SD=0.05), and 2.45 μW (SD=0.14). These two power levels were measured when the VRD was illuminating its entire FOV and was at maximum contrast. The higher power level (2.45 μW) was set to match the luminance value of the fully illuminated CRT screen when predicting a pupil size of 3.3 mm (2.43 μW, see below). The lower power level

Journal of Rehabilitation Research and Development Vol. 38 No. 4 2001

Table 1.
Subject characteristics.

Subject	Age	Diagnosis (of eye tested)	Classification
A5	58	Amblyopia, nystagmus	Ambloyopia/restricted
A6	39	Congenital cataracts, surgical aphakia, congenital glaucoma, retinal scars	Optical/restricted
A7	54	Severed blood vessel, glaucoma	Retinal/full
A8	59	Amblyopia, strabismus	Amblyopia/full
A9	30	Surface wrinkling retinopathy, retinal scars, astigmatism	Retinal/full
A10	28	Unknown	Full
A11	40	Retinal detachment, congenital cataracts, artificial IOL implant	Retinal/restricted
A12	36	Cataract, artificial IOL implant, floaters	Optical/restricted
A13	32	Congenital aniridia, cataracts, corneal ulcers	Optical/full
A15	45	Diabetic retinopathy, surgical aphakia	Retinal/restricted
A16	33	Diabetic retinopathy, retinal detachment and scarring	Retinal/restricted
A17	38	Glaucoma, congenital cataracts, surgical aphakia	Retinal/restricted
A18	43	Glaucoma, congenital cataracts, nystagmus	Retinal/full

Note: Both primary and any secondary (listed in such order) diagnoses are outlined for each subject. Subjects were classified by their primary eye condition into three categories: optical, retinal, or amblyopic. The subjects were further classified as having "full" or "restricted" field of view. Restricted field of view describes any occlusion or visual field degeneration.

(1.27 μW) was set at half the luminance level of the CRT screen (1.22 μW, see below), approximating the lower brightness red on black CRT display condition.

To match the VRD with the CRT, the luminance of the fully illuminated CRT ($\mathbf{L}_{CRT}$=107 cd/m^2) was converted to the lumens captured by the eye, then converted to watts (W_{VRD}) by the following relation (where 1 cd=1 lm * sr^{-1}) (17):

Figure 2.
Picture showing author demonstrating experimental setup, viewing the VRD with his left eye. Subjects held their head in the chin rest as shown and viewed either the VRD or the CRT screen. The CRT screen shown in author's line of sight was covered during actual testing. The laptop shown in the foreground was the device subjects used to manually advance through the reading speed test.

$$W_{VRD}(\text{watts})=[L(\text{cd/m}^2{}_{CRT}*A(\text{m}^2)*\rho(\text{sr})]/\sigma(\text{lm/watt})=2.43\mu W \quad [1]$$

In this equation, A is the area of the CRT screen (0.070 m^2), ρ is the steradian measurement (4.6 * 10^{-5}) for a viewing distance of 432 mm and pupil diameter of 3.3 mm, and ?σ is the radiometric conversion, assuming a photopic curve (142 lm/W at 636 nm) (17). A pupil diameter of 3.3 mm was estimated using the empirical equation of pupil size as a function of luminance and FOV reported by Stanley and Davies (18). This estimate of pupil size was confirmed by taking measurements of each subject's pupil using a semi-circular pupil diameter gauge, which resulted in finding an average pupil diameter of 3.2 mm, (SD=0.72). To calculate the lumens captured by the eye viewing the CRT screen as an extended source, the assumption was made that the 3.3-mm diameter pupil captures the same solid angle from each pixel point source. Retinal illuminance was equivalent between the CRT and the VRD because we matched fields of view for each display during the calibrations and subsequent testing.

PROCEDURE

Testing was conducted in a naturally lighted room. Ambient illumination in the testing room was controlled by measuring the luminance from a covered CRT screen before each subject test (53.10 cd/m², SD=3.93). Mylar shades were adjusted at these times to keep conditions constant for all subjects. The vision testing was done monocularly; each subject was asked to choose his or her preferred eye. The same eye was used for both the acuity tests and the reading speed tests. Throughout testing, subjects wore their own optical correction (contact lenses or eyeglasses) according to what they would normally wear when viewing a CRT screen at a distance of 17 in.

Visual acuity testing was always completed before the reading speed tests. The order of acuity testing, in terms of viewing the CRT or VRD first, was randomized. Each subject's acuity was scored at the last line at which he or she correctly identified at least 3 of the 5 Landolt "C's."

Subsequently, each subject was given a reading speed test comprised of four different test conditions: (1) viewing a CRT with white letters on a black background, (2) viewing a CRT with red letters on a black background, and (3) viewing a VRD image with a lower power setting (1.27 μW), and (4) viewing a VRD image with a higher power setting (2.45 μW). The CRT red-on-black contrast condition was used to more closely match the CRT wavelength with the monochrome red VRD. The two power settings of the VRD were used to determine if there was an effect of retinal illuminance. The order of test condition was randomized.

Each reading speed test (at each of the four test conditions) included four character sizes, 3.15º, 1.88º, 1.22º, and 0.74º, measured using a lower case "x" as reference. These four values were selected to comprise the midrange sizes between the intended subjects' predicted lower reading threshold and their predicted upper plateau of reading speed. Reading speed, with respect to character size, has been empirically shown to start at a certain value, increase, then plateau, and then finally decrease, as characters become impracticably large, for both normal and low-vision subjects (19). We targeted the midrange between the subjects' visual acuity threshold and plateau, predicting that reading rate would be most sensitive to this range of character size. The character size range was selected so as to encompass the predicted visual acuity limits of our subjects. This prediction was based on subjects' records at the WSDSB.

At the start of each reading test, subjects read at the largest character size, then at successively decreased sizes. For each character size, three (20-s) trials were conducted consecutively. The subject manually advanced through the three-word presentations by clicking the mouse button on the laptop and reading the words aloud. The number of correctly read words per 20-s trial was recorded; the subjects were allowed a brief rest in between each trial. In the few cases where the subject reported fatigue, trial number was reduced from 3 to 2, since the subject's first two scores were similar. At the conclusion of the reading tests, we asked subjects to rate the VRD as "better, the same, or worse than the CRT'' in terms of perceived brightness and perceived clarity.

RESULTS

The results for 13 of 15 low-vision volunteers are reported here. Subject A4 requested to be withdrawn from the testing because of fatigue. Subject A14 was unable to locate the VRD exit pupil and maintain a stable image on the small functional portions of peripheral retina. Therefore, we removed these two subjects from the study.

Forty-six percent of subjects had highest visual acuity while viewing the VRD (at the increased power); 30 percent of subjects had highest acuity viewing the CRT (white-on-black contrast); and 24 percent of subjects had equal acuity across the two displays (**Table 2**). However, a repeated-measures t-test showed no significant difference between the two displays across all subjects ($p=0.24$). A Pearson correlation test showed no significant correlation between improved acuity and improved reading speed ($r=0.26$; $p>0.05$).

Individual reading performances are summarized and listed in **Table 2**. Reading speed columns contain the mean reading rates in words per minute (wpm) averaged over trial and the two respective VRD or CRT conditions. The fourth column over from the left shows both the subjects' minimum angle of resolution (MAR) and the one testing character size that was chosen to average across for each subject. This character size was one of the four sizes used in the testing (3.15º, 1.88º, 1.22º, and 0.74º) and was determined by multiplying their measured CRT MAR by five and then selecting the character size that was the next largest. For example, subject A5 had a MAR of 0.24º (visual acuity=20/290), therefore the 1.22º character size was chosen. The factor of five derives from

Journal of Rehabilitation Research and Development Vol. 38 No. 4 2001

Table 2.
Summary of individual performances.

Subject	Acuity VRD	Acuity CRD	MAR/Char (°)	Speed VRD (wpm)	Speed CRT (wpm)	Percent difference	Better display (for reading)	Apparently clearer	Apparently brighter
A5	20/200	20/290	0.24/1.22	51.5	22.5	129	VRD	VRD	VRD
A6	20/100	20/100	0.083/0.74	95.5	67.0	43	VRD	VRD	VRD
A7	20/100	20/290	0.24/1.22	64.0	73.5	–13	CRT	VRD	VRD
A8	20/70	20/70	0.058/0.74	111	114	–3	CRT	VRD	VRD
A9	20/360	20/200	0.17/1.22	38.5	54.0	–29	CRT	CRT	VRD
A10	20/140	20/200	0.17/1.22	57.0	56.0	2	VRD	Same	Same
A11	20/140	20/200	0.17/1.22	18.0	11.5	57	VRD	VRD	VRD
A12	20/100	20/70	0.058/0.74	94.3	113.5	–17	CRT	VRD	VRD
A13	20/430	20/700	0.58/3.15	73.0	8.00	813	VRD	VRD	VRD
A15	20/140	20/100	0.083/0.74	43.3	74.0	–42	CRT	CRT	VRD
A16	20/200	20/290	0.24/1.22	68.0	101	–33	CRT	Same	Same
A17	20/140	20/100	0.083/0.74	32.0	36.0	–11	CRT	VRD	CRT
A18	20/100	20/100	0.083/0.74	74.5	86.0	–13	CRT	VRD	VRD
Average				**63.1**	**62.8**				

VRD and CRT reading speeds, listed in words per minute (wpm), are averaged over trial, character size and respective viewing condition (VRD or CRT). MAR refers to minimum angle of resolution for the CRT acuity test, and Char(°) refers to the next largest character size after five times the CRT MAR. Percent difference was calculated as (SpeedVRD–SpeedCRT)/SpeedCRT. Apparently clearer and apparently brighter columns correspond to results of subject survey.

Snellen letter specifications, which require the smallest detail in a Snellen letter be one-fifth the size of the overall letter. The Arial font we used displayed characters with details that averaged 0.22 times the size of the overall letter, thus approximating the Snellen specification. In this way, reading performance could be evaluated across subjects relative to their own acuity limitations.

Five subjects read faster while viewing the VRD, and eight subjects read faster viewing the CRT at their respective selected character size. Individual reading speed averages ranged from +813 (A13), to −42 percent (A15), when the VRD was compared to the CRT (**Table 2**). However, when averaging across all subjects, the two displays were almost equal in performance at 63.1 wpm for the VRD *versus* 62.8 wpm for the CRT. A repeated-measures t-test showed that when all four font sizes were included in the averaging, there was no significant difference across all subjects ($p>0.5$), which is shown graphically in **Figure 3**. Similarly, no significant difference was found (again using a repeated-measures t-test) in reading performance between the two displays ($p>0.5$) when using only the selected character sizes.

A summary histogram of the pilot data is shown in **Figure 4**. The average reading speeds at the selected character size for the 12 subjects categorized by their low-vision condition (subject A10 had an unknown eye condition) is graphed. We classified these 12 subjects into the following four categories as shown in **Table 1**: optical causes (A6, A12, A13), amblyopia (A5, A8), retinal causes with full FOV (A7, A9, A18), and retinal causes with restricted FOV (A11, A15–17). A restricted FOV is defined here as a visual field with occlusion or visual field degeneration. For the optical cause and the amblyopia groups, the VRD (averaged over power levels) provided increases in reading speed of 39.4 percent and 19.0 percent, respectively, over the CRT (averaged over color contrast). Subjects with retinal causes plus restricted fields of view, and subjects with retinal causes plus full fields of view had greater reading speeds when viewing the CRT than when reading the VRD (27.5 percent and 17.1 percent, respectively). A two-way analysis of variance (ANOVA) of low-vision category and display condition reading speeds showed no significant main effect for category ($F=1.7$, $p>0.05$), or for display condition ($F=0.24$, $p>0.05$), and no significant interaction ($F=0.41$, $p>0.05$). However, given the low sample size, analysis showed that the power was extremely low in the different treatments (less than 0.3 at $\alpha=0.05$). Based on the power analysis results, we would have needed about 20 subjects per category in our study to achieve a significant power level (e.g. 0.8) when comparing the low-vision categories.

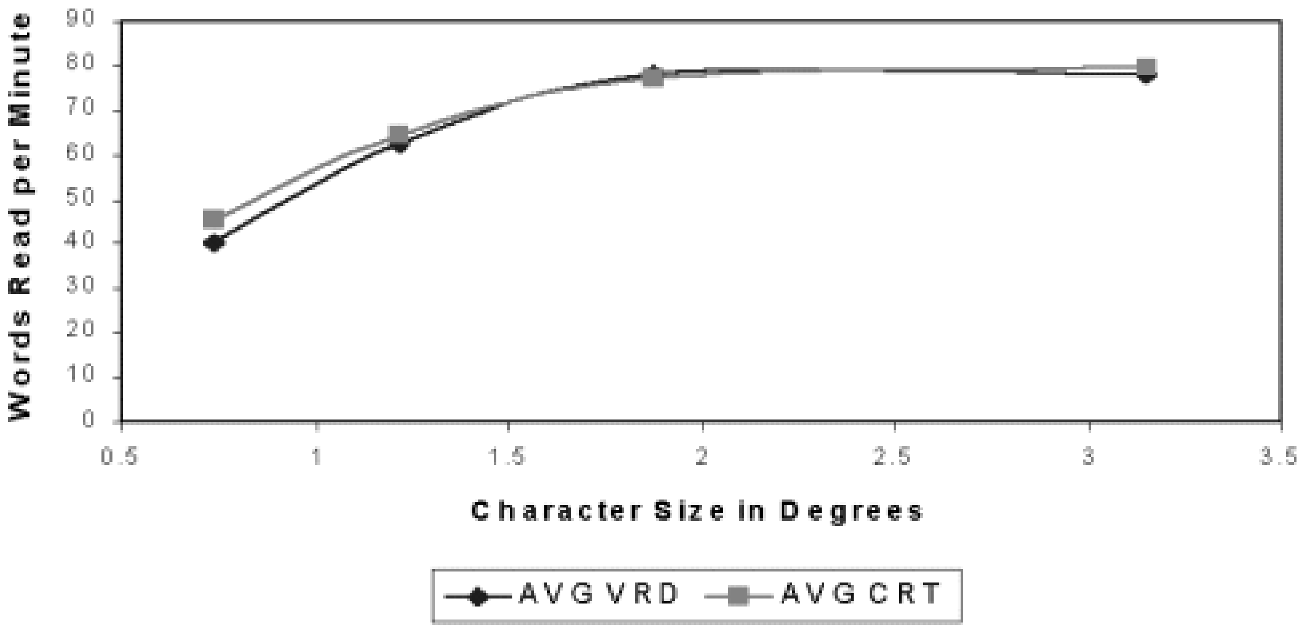

Figure 3.
Average reading speeds for all 13 subjects. Reading speed scores are averaged across trial, type of display (VRD or CRT), and across subject. After averaging the reading speeds for the entire study, no significant difference is found between viewing VRD and viewing CRT.

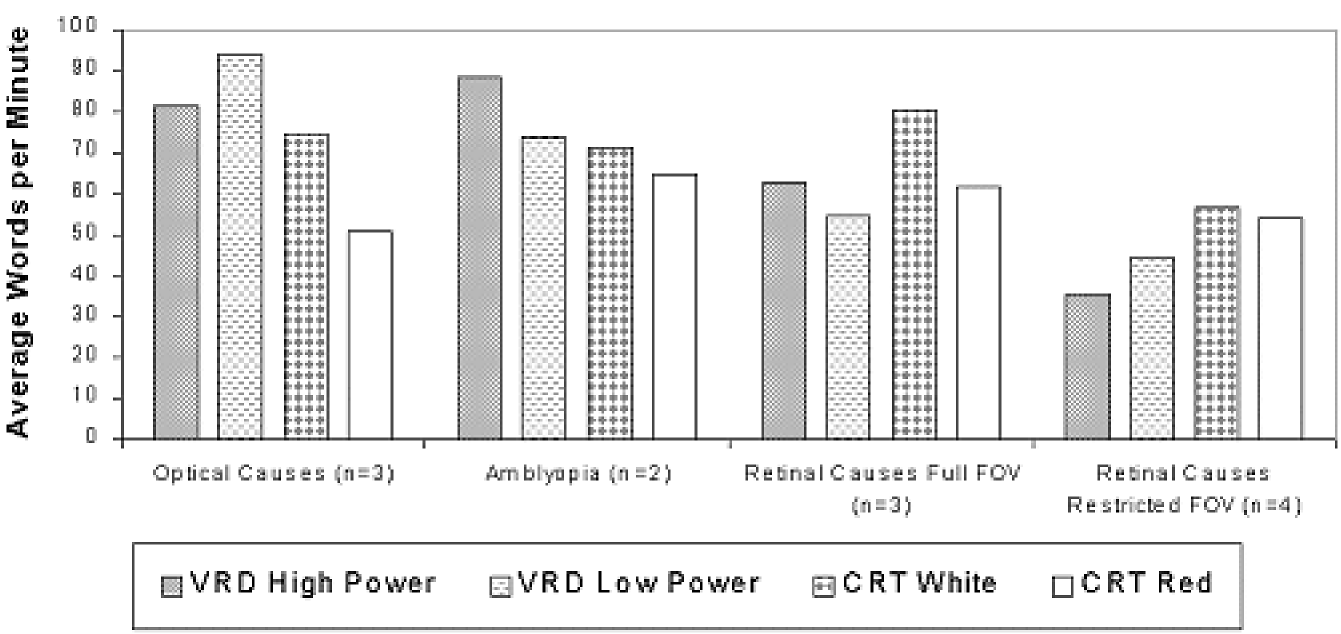

Figure 4.
Reading speed summary for subject groups classified by eye condition (see **Table 1** for classifications). Reading speeds are averaged over respective viewing condition (VRD or CRT). Subjects with optical causes of low vision showed greatest increases in reading speed (39.4%), and amblyopia subjects had a 19.0% increase in reading speed when viewing the VRD compared to the CRT. For subjects with retinal causes of low vision, decreases in reading speed while viewing the VRD were found for both full FOV subjects (17.1%), and restricted FOV subjects (27.5%).

Averaging across all subjects or within designated categories does not reveal the large differences in reading performance between the displays that are apparent for individual subjects. Seven subjects (A5, A6, A9, A11, A13, A15, and A16) demonstrated clinically important reading speed differences between the two displays (define clinical importance as ±25-percent difference, E. Peli, personal communication). The reading speeds are plotted for four of these seven subjects (A13, A5, A9, and A16) at the four viewing conditions, each one representing one of the four low-vision categories (**Figure 5**). Subject A13 (optical causes, **Figure 5A**) had an 813-percent increase in reading speed viewing the VRD at the selected character size of 3.15º. Note that this was the only size where this subject was able to practically read CRT images and only in the white-on-black contrast. Subject A5 (amblyopia, **Figure 5B**) read 129 percent faster with the VRD at the selected character size. In contrast, subject A9 (retinal full FOV, **Figure 5C**) had a 29 percent decrease in reading speed when viewing the VRD compared to viewing the CRT, while subject A16 read CRT words 33 percent faster than VRD words (retinal restricted FOV, **Figure 5D**). The remaining six subjects (out of the 13 total) showed comparable reading speeds between the VRD and the CRT throughout the four categories (≤25-percent difference).

All subjects were surveyed with results listed in **Table 2**. Survey questions had the subjects compare the two displays in terms of the overall apparent brightness and clarity of images. Nine of 13 subjects found VRD images as clearer, while 2 of 13 found CRT images as clearer, and another 2 subjects rated both displays as equivalent in image clarity. In terms of brightness, 10 subjects reported the VRD as having brighter images, 1 subject found the CRT to be brighter, and another 2 subjects rated both displays as equal in apparent brightness. A noteworthy result of the survey revealed that 12 of 13 subjects expressed a difficulty or a specific dislike of red on black contrast. Statistical analysis demonstrated that the red on black color contrast had a significant detri-

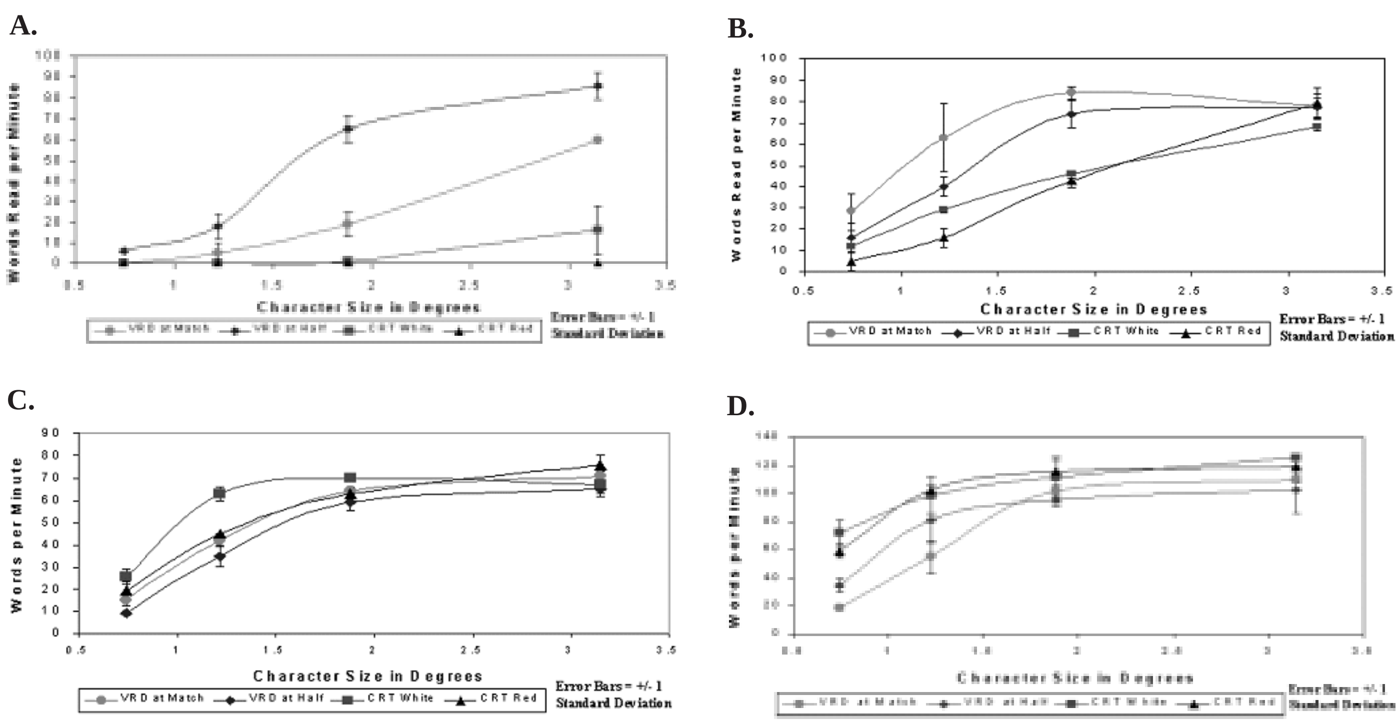

Figure 5.
Average reading speed scores with respect to character size for subjects A13, A5, A9, and A16. In each graph, data points are connected by a best-fit smoothed line. **A:** Reading speeds for subject A13. Individual had an 813% increase in reading speed when viewing VRD compared to viewing CRT at selected 3.15º character size. **B:** Reading speeds for subject A5. Subject had a 129% increase in reading speed when viewing VRD compared to viewing CRT at selected 1.22º character size. **C:** Reading speeds for subject A9. Subject had a 29% decrease in reading speed when viewing VRD compared to viewing CRT at selected 1.22º character size. **D:** Reading speeds for subject A16. Subject had a 33% decrease in reading speed when viewing VRD compared to viewing CRT at selected 1.22º character size.

mental effect on reading speed within the two CRT display conditions when averaged across all subjects ($p=0.035$).

DISCUSSION

Visual Acuity

Although visual acuity can be a poor predictor of reading speed (20), it can be a measure of nonreading performance; for example, improved acuity may allow for faster and more accurate recognition of graphical user interface icons. The increase in acuity shown by 6 of 13 subjects may be attributed to the VRD's narrow exit pupil, which has two effects. The first is that the collimated light at the exit pupil produces a large depth of focus. The extended depth of focus allows retinal scanned displays like the SLO and VRD to remain unaffected by moderate refractive errors in the eye, and in some low-vision cases delivering an image of higher quality than the naturally apertured eye. The ≤0.8 mm diameter beam from the VRD is assumed to be diffraction limited at the retina. Thus, depth of focus is calculated for a perfectly spherical wavefront (21) at 3 diopters, *versus* ≤0.2 diopters for viewing the CRT. Interestingly, empirical results (not reported) have demonstrated that persons viewing the VRD do not notice refractive errors ranging up to a maximum of 6 to 12 diopters.

The second effect of having the small exit pupil is higher contrast because of less dispersive scattering by the optical media (6). Damaged or abnormal media such as the cornea, lens, or vitreous greatly add to the scattering of incident light and hence decrease visual contrast as the individual perceives the scatter as glare. Standard displays such as the CRT illuminate all optical media allowed by pupil size, including the abnormal media that cause scatter. The very narrow directed beam of scanned light allows for less diffuse scatter and possibly less interception of scatter-causing media, producing a higher contrast retinal image. Furthermore, a low-vision individual can strategically orient his/her eye with respect to the narrow laser beam to minimize the glare from specific scattering points (e.g., corneal scars) to optimize image quality. These two effects may also explain why 69 percent of subjects reported that the VRD displayed clearer images.

Reading Performance

Figure 3 shows the average reading speeds for all subjects when viewing the VRD (averaged over both power levels) compared to viewing the CRT (averaged over both color contrast settings). This figure demonstrates that mean reading speeds across all 13 subjects indicated no significant difference between the displays when averaged over all font sizes. However, our subject population consisted of persons with varied vision conditions and acuity limitations. Thus, selecting the most appropriate character size for each subject as described in the Results section allowed for a more reasonable comparison across subjects. Within each of the four low-vision categories, case-study analyses of subjects who showed clinically important differences in reading speed between displays (at the selected character size) provide insight into the performance of the VRD versus the CRT. The selected character size for each subject appears to have been in their own midrange of reading speed, based on individual plots of reading speed *versus* character size.

Subject A13, who was employed as a computer programmer, showed drastic improvement in acuity and reading speed while viewing the VRD compared to the CRT (**Table 2**, **Figure 5A**). This subject suffered from low vision due entirely to optical causes (aniridia, cataracts, and corneal ulcers) and evidences the finding that, in general, individuals with optically-based maladies exhibited the greatest improvement in reading speed when using the VRD (39.4 percent, **Figure 4**). Analogous to improving acuity, we attribute this finding to the VRD's narrow exit pupil and great depth of focus, as discussed earlier.

Subject A5, who suffered primarily from amblyopia, showed higher acuity and an increase in reading speed viewing the VRD (**Table 2**, **Figure 5B**). The other subject with amblyopia (A8) demonstrated equal acuity and comparable reading speed between displays. Both subjects' results indicate that the VRD may offer a viable alternative for individuals suffering from this condition (**Figure 4**).

In contrast, subjects with retinal disorders showed higher average reading performance viewing the CRT (**Figure 4**). For example, subject A9, who suffered from surface wrinkling retinopathy and retinal scarring, had a 29 percent decrease in reading speed (**Table 2**, **Figure 5C**) while viewing the VRD compared to the CRT. Although this subject's macula was intact, she still indicated that the VRD was “difficult to see into'' because of being unaccustomed to restricting head movements. (Head-mounting the VRD may alleviate this problem for similar individuals, see below.)

The VRD seemed to be even more problematic for subjects with retinal causes and restricted fields of view.

For example, subject A16 had a 33-percent decrease in reading speed at the selected 1.22º when viewing the VRD (**Table 2**, **Figure 5D**). This subject suffered from diabetic retinopathy, partial retinal detachment and retinal scarring because of retinal burns from previous laser treatments. The subject's significant reading-speed decrease may be explained by visual field defects since he reported that he lost speed viewing the VRD because of losing the words in his visual field. Thus, a limitation in the effectiveness of scanning light technology may be found in individuals with retinal disorders that reduce their FOV.

Most subjects (77 percent) perceived brighter images when viewing the VRD. The VRD's apparent brightness may be due, in part, to the Stiles-Crawford Effect (SCE) (22). The SCE describes the phenomenon that light sensitivity is optimal for light entering the eye near the center of the pupil and diminishes for light rays at the periphery of the pupil. Apparent brightness (luminous efficiency), based on the SCE, can be quantified by considering a ratio in luminous efficiency of light with respect to that at the optimal entry point (optimal varies slightly per individual). Stiles and Crawford (22) presented the following empirical formula to define η where p is a coefficient slightly dependent on wavelength (assume p=0.05) and r is the radial distance from the center of the pupil.

$$\eta=10^{-pr^2} \qquad [2]$$

Thus, the average luminous efficiency over a given pupil diameter is calculated by integrating the function in two dimensions, producing a three-dimensional luminous efficiency volume. For a calculated 3.3-mm pupil viewing the CRT (see Methods), the luminous efficiency is calculated to be 86 percent. A reasonable pupil diameter of 5 mm (the largest pupil size we measured) yields an average luminous efficiency of 71 percent. These values are to be compared to the smaller VRD exit pupil, where luminous efficiency is 99 percent. The ratio of VRD efficiency to natural pupil efficiency (when viewing a CRT display, for example) corresponds to a luminous efficiency increase of 15 percent (3.3 mm) to 40 percent (5 mm). The higher efficiency of the VRD's 0.8-mm exit pupil because of the SCE is supported by our empirical comparison data on perceived image brightness, as most subjects perceived the VRD as brighter than the CRT under matched luminous conditions.

There was no significant effect on reading speed between the two VRD power levels, which may be attributable to the wide variance of the optimum luminance level among individuals (12). The VRD can retain sufficient contrast and resolution in images at lower brightness levels for those individuals highly sensitive to light or glare. Some subjects (e.g., A13, **Figure 5A**) benefited more from the VRD lower power setting, a luminance half that of the white-on-black CRT.

Most low-vision subjects (e.g., A9) reported difficulty keeping their eyes aligned with the VRD's 0.8-mm diameter exit pupil. The problem of losing alignment can occur when head position moves relative to the display and/or the eye scans within a wide field of view VRD. Recent studies with the portable VRD configured as a head-mounted, augmented display has reduced exit pupil misalignment during performance evaluations (23). Future research will attempt to alleviate the alignment problem in wider FOV retinal displays by adjusting the method by which the beam enters the pupil. Thus, the prototype VRD using the disliked red on black color contrast and the experimental design of not configuring the VRD as head-mounted, produced an obvious performance bias against the VRD *versus* the CRT. Furthermore, recent research has confirmed that the red on black color contrast is not only least preferred but has reduced reading rates versus green-, blue-, or white-on-black color contrasts (24).

Another anticipated disadvantage of retinal light scanning technology could be the appearance of flicker in scanned optical images. Retinal light scanning produces a pixel of essentially no persistence time versus the well-known persistence of the CRT phosphor emission. However, research has indicated that human subjects do not detect flicker in the VRD any more than a CRT (25).

Although we attempted to recruit subjects who were actively employed and who encompassed a wide range of vision maladies (**Table 1**), further research will be needed to address subjects with MD. An indication of the effectiveness of retinal light scanning with MD subjects is found in an earlier study by Viirre et al. (15). The full-color VRD demonstrated improved acuity in two of three MD subjects *versus* the CRT, which was attributed to the brighter, full-color VRD.

In addition, retinal light scanning can be made both small and inexpensive by the advent of new MEMS (microelectromechanical systems) optical scanners, miniature video cameras, and LED-based monochrome or multisource white light LEDs. A future display may be worn as a pair of oversized glasses or goggles to possibly eliminate pupil alignment problems and alleviate the poor ergonomics of holding the head at a fixed position. These studies are being carried out under the Universal Access and Research to Aid Persons with Disabilities Programs of the National Science Foundation (NSF) to understand the full potential of retinal light-scanning technologies for improving computer accessibility and navigational ability of all categories of low-vision users.

CONCLUSION

We compared the visual performance of low-vision subjects when using a standard desktop CRT and a portable, monochrome red VRD. Most subjects showed equivalent or improved visual acuity when viewing the VRD compared to the CRT. A reading performance test at controlled luminance levels matched to the CRT showed that on average, the VRD proved to be a comparable display. The greatest individual improvements in reading speed with the VRD were recorded with subjects having optical causes of low vision. Retinal light-scanning displays such as the VRD offer a safe visual interface to computers and are anticipated to improve computer accessibility because of greater apparent brightness, contrast, and depth of focus compared to standard CRT monitors.

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REFERENCES

1. US Census Bureau. Statistical abstract of the United States of America. Washington DC: US Census Bureau; 1999. p. 442.
2. Beckmann PJ, Legge GE. Psychophysics of reading XIV. The page navigation problem in using magnifiers. Vision Res 1996;36(22):3723–33.
3. Jaschinski W, Heuer H, Kylian H. A procedure to determine the individually comfortable position of visual displays relative to the eyes. Ergonomics 1999;42(4):535–49.
4. Webb RH, Hughes GW, Pomerantzeff O. Flying spot ophthalmoscope. Applied Optics 1980;19:2991–7.
5. Johnston RS, Willey SR. Development of a commercial retinal scanning display. Helmet- and head-mounted displays and symbology design requirements II. Proc of the SPIE 1995; 2465:2–13.
6. Webb RH, Hughes GW. Scanning laser ophthalmoscope. IEEE Trans Biomed Eng 1981;28:488–92.
7. Mainster MA, Timberlake GT, Webb RH, Hughes GW. Scanning laser ophthalmoscopy. Ophthalmology 1982;89:852–7.
8. Timberlake GT, Peli E, Essock EA, Augliere RA. Reading with a macular scotoma II. Invest Ophthalmol Vis Sci 1987;28:1268–74.
9. Schuchard RA, Fletcher DC, Maino JM. A scanning laser ophthalmoscope (SLO) low-vision rehabilitation system. Clin Eye Vision Care 1994;6(3):101–7.
10. Massof RW. Electro-optical head-mounted low vision enhancement. Pract Opt 1998;9(6):214–20.
11. Viirre E, Johnston R, Pryor H, Nagata S. Laser safety analysis of a retinal scanning display system. J Laser Appl 1997;9:253–60.
12. Cornelissen FW, Kooijman AC, Dumbar G, Van der Wildt G, Nijland R. Illumination research as part of a visual assessment of visually impaired individuals. Ophthalomologica 1991;78:195–203.
13. Eldred KB. Optimal illumination for reading in patients with age-related maculopathy. Optom Vis Sci 1992;69(1):46–50.
14. Culham LE, Fitzke RW, Timberlake GT, Marshall J. Use of scrolled text in a scanning laser ophthalmoscope to assess reading performance at different retinal locations. Ophthalmic Physiol Opt 1992;12:281–6.
15. Viirre E, Pryor H, Nagata S, Furness TA. The Virtual Retinal Display: a new technology for virtual reality and augmented vision in medicine. In: Proceedings of medicine meets virtual reality VI, studies in health technology and informatics. 1998;50:252–7.
16. Legge GE, Ross JA, Luebker A. Psychophysics of reading VIII. The Minnesota low-vision reading test. Optom Vis Sci 1989;66(12):843–53.
17. Wyszecki G, Stiles WS. Color science: concepts and methods, quantitative data and formulae. (2nd ed.) John Wiley and Sons, Inc; 1982. p. 256–8, 265, 731.
18. Stanley SA, Davies KA. The effect of field of view size on steady-state pupil diameter. Ophthalmic Physiol Opt 1995;15(6):601–3.
19. Legge GE, Rubin GS, Pelli DG, Schleske MM. Psychophysics of reading II. Low vision. Vision Res 1985;25(2):253–66.
20. Legge GE, Ross JA, Isenberg LM, LaMay JM. Psychophysics of reading: clinical predictors of low-vision reading speed. Invest Ophthalmol Vis Sci 1992;33(3):677–87.
21. Hopkins RE, Stephenson D. Optical systems for laser scanners. In: Marshall GF, editor. Optical scanning. New York, NY: Marcel Dekker; 1991. p. 38.
22. Stiles WS, Crawford BH. The luminous efficiency of rays entering the eye pupil at different points. Proc R Soc Lond 1933;B112:428–50.

23. Lin S-K V, Seibel EJ, Furness TA. (accepted). Testing visual search performance using retinal light scanning as a future wearable low vision aid. Int J Human-Computer Interact, two-volume Special Issue on Mediated Reality.
24. Seibel EJ, Gau CC, McQuaide S, Weghorst SJ, Kelly JP, Furness TA. Augmented retinal light scanning display for the low vision: effect of text color and background on reading performance. Vision Science and Its Applications, OSA Technical Digest (Optical Society of America, Washington DC, 2001); 51–4.
25. Kelly JP, Turner S, Pryor HL, Viirre ES, Seibel EJ, Furness III TA. Vision with a scanning laser display: comparison of flicker sensitivity to a CRT “Displays” (Submitted).

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