Virtual computer monitor for visually-impaired users

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ABSTRACT

Conventional computer display products for the visually impaired are limited by the amount of enlarged imagery that can be displayed at any one time, and by awkward methods for navigating about the scene. This paper describes a prototype system designed to address these problems by providing a head-mounted display interface which allows the user to position a cursor anywhere on an enlarged virtual page by turning to view that location in space. Also discussed are human subject trials underway at SRI International and the Veterans Administration under a US Department of Health and Human Service research grant, and technical issues requiring further investigation.

Keywords: low vision, adaptive devices, computer access, head-mounted displays, screen enlargers

1. BACKGROUND: THE FIELD NAVIGATION PROBLEM

Among the visually-impaired population, the most common approach to computer access is specialized software that magnifies the image on the computer monitor. This is because simpler solutions such as moving closer to the monitor, using a larger monitor, adding a screen magnifier, or using a spectacle-mounted telescopic system provide either limited magnification or a very limited viewing field.

These computer display magnification solutions operate by magnifying the original image of the computer screen to a "virtual screen" whose size is much larger than the physical monitor. The visually-impaired user then operates the computer by using a mouse, joystick, or cursor keys to control which portion of the virtual screen is shown on the physical monitor at any one time.

Unfortunately, there are two basic shortcomings to this approach. The first problem is spatial orientation, in that it is difficult to determine where on the page one's view is directed at any given time. At 15x magnification, a 15" monitor can only display about 1% of a standard 8.5"x11" page, making most computer work essentially impossible. The second problem is dynamic control, in that all of the various control schemes for navigating about the page are cumbersome, confusing, and slow. Together, these problems were termed the "field navigation" problem in the US National Advisory Eye Council's 1994-98 National Plan, in which the Low Vision and its Rehabilitation Panel identified "text navigation" as a particularly promising opportunity for new technologies (Legge et al, 1994).

2. VIRTUAL REALITY TECHNOLOGY APPLIED TO FIELD NAVIGATION

In response, the Virtual Computer Monitor (VCM) was conceived by General Reality, and a breadboard first constructed in mid-1994. This breadboard received an award as "Most Innovative New Device" at CSUN's Virtual Reality & Persons With Disabilities Conference in August 1995. Under a US National Eye Institute sponsored Phase I Small Business Innovation & Research project initiated during 1995, improved "proof-of-concept" prototypes were constructed from commercially-available virtual reality components.

As shown conceptually in Figure 1, the VCM operates by combining a head-mounted display (HMD), head tracker, and screen enlarger software to fix the enlarged virtual screen of data in space and scan the user's line of sight across the data, instead of scanning the virtual screen across the display device as done in conventional screen enlargement systems. By incorporating a cursor at a fixed position in the user's visual field, interaction with computer data is then possible by turning one's head to the desired insertion point and clicking a mouse button.

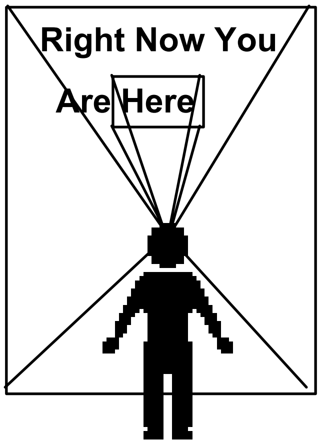

Figure 1: *VCM Concept*

The VCM approach represents an entirely new methodology for providing visually-impaired individuals with enhanced access to computer data and other visual content. The research team as well as others in the disabilities field hypothesize that this methodology can provide significant value for various populations of computer access-impaired users as a result of the following properties of the VCM approach:

1) An HMD-based display system can provide significantly greater instantaneous display field-of-view than a large conventional computer monitor, at lower system cost, and in a portable configuration.
2) An HMD-based display system can provide an unlimited field-of-regard, accessible merely by turning one's head. This should provide a more intuitive interface, since turning one's head instead of using a mouse provides natural proprioceptive feedback and frees the hands for input instead of navigation.
3) The VCM's ability to fix a computer control cursor at a user's preferred retinal locus can provide a significant enabling advantage to users with large central scotomata or smaller distributed scotomata, as well as to low vision quadriplegic users.
4) An HMD-based display system can be adjusted to any desired apparent display focus distance independently of instantaneous field-of-view, which may be more comfortable for some users and may help prevent the incidence of myopia caused by extended close viewing of conventional monitors.
5) HMD-based displays block undesirable external stimuli and remain fixed with respect to the user's visual field regardless of intentional or uncontrolled head motions, which can enable computer access for individuals with non-optically related computer visualization impairments.

The overall goal of the VCM effort is to demonstrate the benefits of these conceptual advantages sufficiently to justify commercial introduction of the system.

3. PHASE I PROTOTYPE DEVELOPMENT AND CONFIGURATION

3.1 Target Platform Scope

The Phase I prototype development resulted in VCM systems designed and constructed for both Macintosh and PC platforms. The completed systems function similarly, and are shown in block diagram form in Figure 2. The Macintosh system is shown photographically in Figure 3, which demonstrates the portability of the VCM system.

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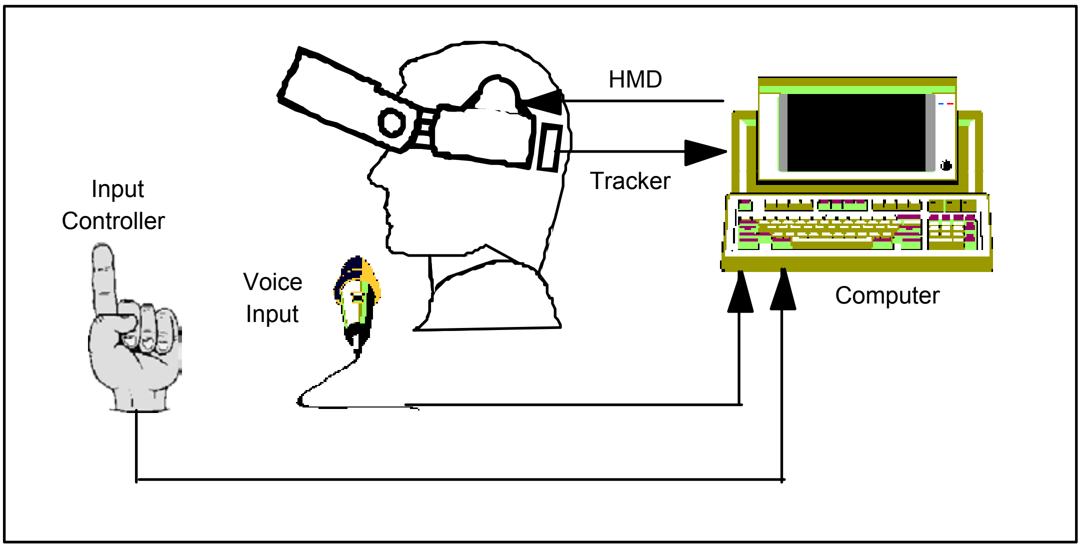

Figure 2: *Virtual Computer Monitor Block Diagram*

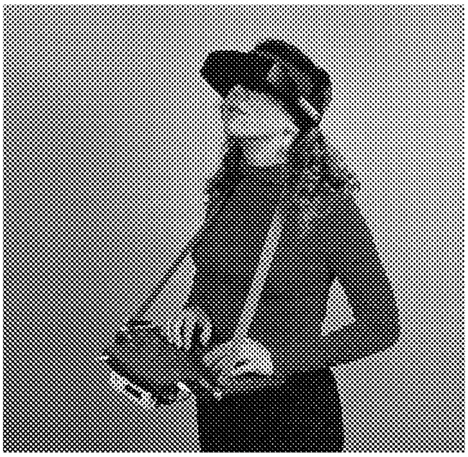

Figure 3: *Virtual Computer Monitor Macintosh Prototype*

3.2 Tracking System Design

In an ideal VCM system, the head tracker senses every rotational head movement with perfect accuracy, and the viewport location is changed instantaneously in response. The result would be an enlarged document that appears to float at a fixed position in front of the user, and which remains fixed in space as the user turns to look at various portions of it. Unfortunately, neither perfect accuracy nor instantaneous response can be achieved in a real system. The resulting imperfections and delays can cause the document to appear to jitter or move in various ways unintended by the user. This can be frustrating, and is believed to be a major cause of vertigo, dizziness, and other short-term symptoms often termed "simulator sickness".

To prevent simulator sickness issues, a design goal of 40msec maximum lag between head movement and updated display video was set. Recent work (Azuma, 1994) has shown that total system lags of this magnitude are required for augmented reality applications (in which virtual objects are visually overlaid on physical objects using a see-through HMD), and it was postulated that a similar performance requirement applies to the VCM application. Additional criteria for the tracking system included low cost and portability, to support near-term commercialization. An analysis of available tracking technologies was performed, and is summarized in Table 1. Based on this analysis, prototypes were designed and constructed using two alternative technologies, magnetic/gravitational and gyroscopic.

Table 1: *Available Tracking Technologies*

Technology	Benefits	Drawbacks
AC/DC Electromagnetic	• Low Latency • Familiarity	• Bulky Transmitter • High Cost • Metallic Interference
EM Compass + Gravitational	• Small & Sourceless • Low Cost/Available	• Ambient Jitter (Floor) • Settling Time
Solid-State Gyroscope and/or Accelerometer	• Small & Sourceless • Very Low Latency • Potential Low Cost	• Drift • Dynamic Range • Commercial Availability
Optical	• Low Latency • High Accuracy • Low Interference	• Bulky Transmitter • Occlusion Problem • Cost
Ultrasonic	• Low Latency • High Accuracy	• Line-of-sight • Bulky Electronics • Interference
Image-Based Analysis	• Least Encumbering • Most Flexible	• Compute-Intensive • Availability/Cost • Occlusion Problem

3.2.1 Magnetic/Gravitational Tracking Results. This device operates by sensing the earth's magnetic and gravitational fields, and reporting changes in the sensed data that result from orientation changes of the tracker with respect to those fields. The highest performance magnetic/gravitational tracker available commercially was used.

Upon testing, it was found that the magnetic/gravitational tracking approach provided insufficient performance for the VCM application. The primary problem was jitter, wherein the imagery jumps randomly by a small amount one or more times per second. In addition, the interface device used to combine tracker output with mouse output added latency to the image updates, which caused the movement of the viewpoint to lag head movements. As a result, selecting objects on the screen was found to be difficult, since overlaying the cursor over the imagery often required several attempts. The only feasible approach to solving the jitter problem was determined to be averaging data over several samples prior to output, which would have exacerbated the lag problem.

3.2.2 Gyroscopic Tracking Results. The gyroscopic approach uses two tiny solid-state gyroscopes, each of which senses accelerations about one rotational axis. In theory, such devices can provide extremely rapid response to head motions (below 10msec), with essentially no ambient jitter. However, limitations to the gyroscopic approach include drift (which results in the imagery within the VCM moving steadily in one direction even when the user's head is still) and dynamic range (wherein very slow or very fast orientation changes are not properly tracked).

Two gyroscope suppliers were considered. The first, VR Systems, is based in the United Kingdom, and markets a $1,700 gyroscopic tracker for use as a cursor control device for the motor-impaired. The second, Gyration, is based in Mountain View, CA, and markets a $129 gyroscopic mouse used for stand-up computer-based presentations. The Gyration unit was selected for Phase I testing as it is much less costly and available more quickly in the US. It was incorporated in the VCM by means of sorting through six Gyropoint mice from Gyration to find the two units exhibiting the lowest ambient drift. The selected mice were then modified to serve as trackers and mounted on head-mounted displays. This implementation was found to provide extremely rapid, responsive tracking with insignificant jitter, and was used in the human subject trials. However, periodic manual recalibration to manage the drift is still necessary.

For future implementations, the project team plans to eliminate the drift issue by developing a hybrid tracker using a combination of gyroscopes or accelerometers for rapid response and magnetometers to periodically correct drift.

3.3 Display System Design

The baseline prototypes utilize a standard CyberEye Model CE-100 HMD. This device is designed for professional virtual reality and data display applications, and provides 420x230 display pixels over a 22.5 by 16.9 degree field-of-view, focused at near-infinity. This results in individual RGB pixels which subtend about 3.2 arc-minutes as seen by the user. The display uses one 0.7" diagonal full-color active matrix liquid crystal display (AMLCD) for each eye, with optics that provide the equivalent of a 19" viewing monitor.

3.4 Software Design

3.4.1 Pointer Control Software. The pointer control software is a device driver that accepts input from the head tracker and mouse, and interprets that data to control the screen pointer. Conceptually, this software must support gross positioning on the magnified page using head tracker input, fine positioning using mouse input, and selection of screen objects based on input of mouse "clicks".

The pointer control software problem was simplified on the Macintosh platform due to the Apple Desktop Bus (ADB), which supports daisy-chaining of multiple input peripherals. Since the Gyropoint connects directly to the ADB, no special software was required to combine tracker and mouse inputs on the Macintosh. Instead, the standard Macintosh mouse driver software was used.

On the PC platform, providing for dual-input control devices was more challenging since the PC architecture does not include an analog of the ADB. Therefore, combining the data from two control devices to control the screen pointer was found to require either an external interface device or a customized controller driver capable of combining inputs from the mouse port and the serial port. Initially, the external interface device approach was attempted and ruled out due to lag, while development of a customized driver was ruled out due to budgetary constraints. In response to this barrier, a dialog was initiated with Microsoft, who provided a software driver capable of providing this functionality. This driver has been found adequate for human subject trials.

For future implementations of the VCM, the project team intends to incorporate the following features in the tracking driver:

1) Drift Correction: The first processing stage of the software will use output from the magnetic/gravitational tracker to correct drift in the gyroscopic tracker.
2) Prediction: To maximize tracking performance, predictive algorithms such as Kalman filtering will be applied to the drift-corrected tracking output. Such algorithms have been demonstrated to provide major reductions in perceived lag, with corresponding reductions in simulator sickness symptoms (Emura and Tachi, 1994; Foxlin, 1996).
3) Field-of-Regard Selection: This software will modify tracking sensitivity based on user input, which provides the user with the ability to manage the overall field-of-regard in the VCM system. This is required in order to limit the amount of head rotation to a comfortable range.

3.4.2 Screen Magnifier. The second software component required for the VCM is a screen magnifier capable of magnifying application output and delivering the appropriate portion of the magnified image to the display buffer. Commercially-available screen magnifiers were used to limit project cost and to allow side-by-side comparison between the VCM and conventional screen enlargement approaches using the same user interface software.

On the Macintosh platform, the only commercially available screen enlarger is inLARGE, by Berkeley Systems (Berkeley, CA). The latest (unreleased) version was used to ensure compatibility with late-model Macintosh systems and with the VGA/NTSC converters selected for the project.

On the PC platform, a large number of commercially available screen magnifiers exist, including LP-DOS (VisionWare Software, Boston MA), Vista (Telesensory, Inc., Mountain View, CA), Magic (Microsystems Software, Inc., Framingham, MA), Zoomtext (Ai Squared, Manchester Ctr., VT), and Magnum GT (Artic Technologies International, Inc.). Each was tested to evaluate performance within the VCM regime. In the case of LP-DOS, an unreleased new version was obtained. This version provided faster screen updating, which reduced overall perceived tracking lag.

While all of the PC platform enlargers function in the VCM regime, the Macintosh inLARGE product contains a beneficial feature which could not be found in any Windows product. This feature maintains the cursor in the center of the viewport even when the user tries to move beyond the edge of the magnified desktop. In the Windows enlargers, moving to the edge of the desktop unfreezes the cursor from the center of the viewport and moves it to the edge of the desktop. This is suboptimal, but was unavoidable for initial human subject trials.

While no Windows product provides this constant centering feature, LP-DOS does provide it when used under the DOS operating system. In addition, LP-DOS provides the ability to maintain the screen pointer at locations other than the center of the screen. It is believed that this feature can be important for users with central vision obstructions such as might occur in macular degeneration. However, evaluation of the benefit of non-central screen pointer positions has not been performed due to the lack of suitable DOS applications. A future release of LP-DOS for Windows will be available in late 1996, and is expected to provide both constant centering and selectable pointer positions in the Windows environment.

4. PHASE I RESULTS FEEDBACK

4.1 Informal Results

The VCM prototypes have been demonstrated at three virtual reality conferences, where several hundred normally-sighted individuals used the system to navigate about a typical computer desktop after only one sentence of instruction. While no formal data was taken, it is clear that the interface functions intuitively, since productive interaction with the desktop folders was instantaneously achieved even among those unfamiliar with virtual reality concepts. This is supported by the observation that a very high percentage of trade show attendees immediately navigated to the "games" folder, where they booted "Wolfenstein 3D".

4.2 Safety Evaluation

Long-term physiological effects of VCM use are a major concern that must be addressed as early as possible in the product development cycle, and are being evaluated by SRI International, one of the world's leading research institutions in the area of HMD safety. The safety evaluation is being performed in three stages:

1) Compile Research On HMD Safety: SRI has updated its database, focusing on physiological effects of HMD use. This search included a review of physiological effects of liquid crystal display (LCD) and other visual display systems, physiological effects of inadequate ergonomic design of HMDs, and visual stimuli that can induce epilepsy.
2) Evaluate Subjective User Reactions: SRI is conducting a series of tests on user acceptance and ease of adjustment of HMD designs for head size, interpupillary distance, and vertical phoria (differences in the vertical position of the two eye's images). In these tests, subjects don a VCM, adjust the HMD for their head and eyes, and are asked to comment on 1) the comfort of the HMD after adjustment, 2) any difficulties they had in making adjustments, and 3) whether they were able to see clear, single, fused images prior to making adjustments for the eyes, 4) whether they were able to see single, fused images after making any necessary adjustments for interpupillary distance or vertical phoria, and 5) whether they experienced any vertigo or eye, face, neck, headache, or bodily discomfort.
3) Establish Guidelines For Extended Use Of HMDs: SRI has developed and is performing a set of standard visual and vestibular tests aimed at determining whether an upper limit should be imposed on use of the VCM. In these tests, subjects access the computer while wearing the VCM for periods between 15 minutes and 2 hours. The access tasks consist of a simple game involving 2-dimensional localization and identification of objects, repositioning those objects in valid places within the scene, and cancellation of occasional dialog windows that pop up when non-valid positions are selected. A scoring system is kept to encourage active participation of the subjects.

Tests are administered before and after use to measure visual modulation transfer function (detection threshold criterion), visual acuity, near and far phorias (vertical and horizontal), near point of accommodation, near point of convergence, and stereo disparity sensitivity. These vision tests are used to determine whether the subject has: 1) developed eye strain, 2) experienced a loss in either far or near visual acuity, 3) had a change in ocular alignment or 4) a reduction in depth perception. Routine vestibular tests of balance and locomotion are also administered to subjects. The entire test procedure is repeated using a conventional screen enlarger to enable detection of differential effects between the VCM and conventional monitors.

While the SRI safety evaluation is not complete, no results indicating fundamental safety problems in the VCM approach have been identified. A minority of users have noted vertigo, dizziness, and analogous symptoms known to occur in virtual reality simulations when the delay between head motion and display regeneration is appreciable. These results are attributed to tracking errors and artifacts in the prototype VCM system used in the prototype, and solutions have been identified.

Interestingly, a growing body of research suggests that extended close work such as reading or computer use may be a major cause of myopia (short-sightedness), which affects nearly 50% of pre-high-school children in the US (Seachrist, 1995). Given these findings, it is logical to assume that users with visual impairments unrelated to emmetropy (accurate eye focal length) may develop myopia as a result of working extremely close to conventional computer monitors. This has not been researched, but if confirmed, it may be the case that HMD use can prevent this problem. This is because the HMD can be focused at any arbitrary distance from the user, which can optically eliminate extended close viewing. If this is found true, it may be the case that for some individuals and some tasks, HMDs may actually prove safer than conventional displays.

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4.3 Performance Evaluation

The Phase I performance evaluation effort is using one of the Western Blind Rehabilitation Center's low vision computer training workstations. These workstation are used on a regular basis to provide computer access training to 30-35 legally blind veterans annually out of the center's 180 annual students. As such, these workstations are outfitted with "the latest" available low vision access tools, including a wide range of screen enlargement software, large monitors, and other specialized hardware.

As of this date, experimentation has begun using professional staff and students of the Western Blind Rehabilitation Center as subjects. The vision of these subjects ranges from fully-sighted to legally blind. Each subject is given an overview presentation regarding the virtual monitor concept and the purpose of the study, then provided with a VCM training and practice session. While this is sufficient to allow use of the system, it does not overcome potential bias against the VCM caused by familiarity with only the conventional enlarger solutions. Each subject is then tested for computer access capability on the VCM, and on standard (13"-14") and large (20"-23") monitors, using identical software with all display devices. Magnification is adjusted to provide the same apparent text size on all monitor devices to control for the acuity variable.

While the evaluation at the VA Blind Rehabilitation Center is not complete, every user tested has provided strongly positive feedback about the VCM's promise, and praised the virtual desktop concept. Several stated that "it is fun to use". Most users provided suggestions and requests for further development, with individual requests including wider FOV, monocular operation, monochrome operation, increased contrast, reduced brightness, disabling tracking during typing, accommodation for smaller head sizes, increased resolution, and larger icon sizes. As some of these suggestions conflict, all will be evaluated further and implemented as necessary during the Phase II effort.

5. SERENDIPITOUS DISCOVERIES

The project team strongly believes that one of the major benefits of applying leading edge technologies such as virtual reality to a driving problem such as low-vision computer access is serendipity, meaning unexpected discoveries. Several such serendipitous results were found during the Phase I effort, and will be more fully explored during Phase II.

5.1 Real-Time Video Magnification

The first serendipitous result occurred via realization that the VCM can be modified in a straightforward manner to magnify live video, and present it in a virtual monitor approach. This approach was conceived in response to the problems visually-impaired students face in classroom lecture environments such as mathematics courses.

As shown in Figure 4, a VCM for real-time video use requires addition of a camera and video capture board to the baseline VCM. By positioning the camera to view the entire blackboard (or overhead projector screen), an image of the scene is captured into memory, and can be enlarged and displayed using the VCM. The student can then easily turn to look around the enlarged virtual blackboard, thus facilitating visual access. A second benefit can be achieved by incorporating a command which captures the image for later viewing, thus allowing the student to concentrate on learning instead of note taking.

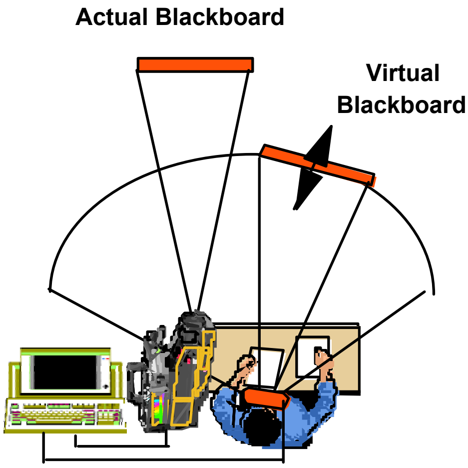

Figure 4: *Real-Time Video Magnification Application*

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It is noted that this approach is expected to provide superior access performance for real-time images than alternative devices such as the Low Vision Enhancement System (LVES) developed at Johns Hopkins University. This is because the LVES system mounts the camera on the user's head, so any jitter in the user's head is magnified to the same degree as the viewed image (just as is the case when using binoculars). In contrast, the VCM configured for live video uses a fixed camera, so jitter in the user's head position is unmagnified.

5.2 New VCM Applications

A key serendipitous result achieved during the Phase I effort was discovery of several new classes of computer access impairments that can be addressed through variants of the VCM. These include Dystonia, Parkinson's Disease, Cerebral Palsy, Autism, Attention Deficit Disorder, Dyslexia, and mobility impairments. In some of these cases, it is believed that benefits can be achieved simply because the HMD blocks undesirable external distractions, forcing the user to focus on the computer-based task at hand. In other cases, the benefits are achieved because wearing an HMD causes the display to remain in view despite uncontrolled head motions.

Exploring these benefits was outside the scope of the Phase I effort, however, one human subject was tested outside of the formal study, and the following case summary was provided by the clinicians involved:

> "15 years ago, Richard had a stroke resulting in Dystonia. The resulting head jerks and twists left him unable to continue in his work as a professional proofreader and narrator. He could not read because of the involuntary head jerks which would jerk his gaze away from the text. By the time the muscle contraction subsided and he had relocated his reading place, it would happen again.
>
> Over the years, many potential solutions were examined and tested without success. Various drugs were used to control the involuntary muscle movements, some of which had side effects worse than the Dystonia. Botulism was even injected into the muscles to partially paralyze them. Many avenues of technology were explored. The CyberEye head-mounted display was a last ditch attempt to meet his need. Because the display moves with his head jerks whenever they occur, it was reasoned he could maintain a constant gaze on the screen.
>
> Initially, we were concerned about possible torsional problems with the headset. Would it cause discomfort or shift position during his involuntary head jerks? Our evaluation revealed this was not a problem. Screen enlargement software was necessary because of a slight amount of "text blur" which still occurred due to the limited resolution of current-generation head-mounted displays. There were some initial compatibility problems between the screen enlargement software and word processing software in "panning" mode, but these were resolved.
>
> Using a computer with screen enlargement software and the VR headset, a scanner, fax/modem, a modified mouse with a large cursor and recording equipment, Richard is able once again to pursue a job he loves. For the first time in 15 years, he is able to read paragraph after paragraph of text without stopping and to narrate non-stop!
>
> Although it was never designed to help a person with Richard's condition, the CyberEye proved to be the missing link in his long odyssey to rehabilitation. What for many is used as a gaming device, became for Richard, a life changing device. A solution which more than meets the eye."

[Note: Researchers Rita Howells and Garry Bowman work for the Bureau of Blind Services, Illinois Dept. of Rehabilitation Services, State of Illinois.]

6. PHASE II RESEARCH PLAN

The VCM research to date can be considered exploratory research, as it leveraged commercially available components to construct and subjectively evaluate the VCM concept. In contrast, the planned Phase II research and development effort will be a focused technology development effort with a clear goal: design a VCM system meeting a specific set of user requirements.

The planned Phase II effort will initiate by answering key open questions regarding technical requirements for an optimized VCM product, especially in the area of display brightness/contrast/FOV/color depth. The results of the Phase I and initial Phase II work will then be used to develop an optimized HMD/tracker/enlarger combination designed specifically for the VCM application. In addition, the prototype VCM systems will be enhanced to improve performance in the baseline low-vision computer access application, and add capabilities for new applications such as classroom lecture access. Finally, this optimized prototype will be evaluated in an extensive series of user studies to validate the VCM system and improvements.

7. SUMMARY AND CONCLUSIONS

The project team believes the Phase I results to date are valuable and important for the following reasons:

1) Extensive progress towards determination of user requirements for a commercially-viable VCM system design has been achieved. Most of the detailed requirements for an optimized Phase II prototype have been generated.
2) The first VCM functioning in the PC environment has been designed, constructed, debugged, and demonstrated.
3) Professional computer trainers for the visually-impaired (including visually-impaired trainers) have used the prototype VCM system, and strongly praised the approach.
4) The existing body of HMD safety and performance research has been extended, and the first hypothesis that HMDs can actually be safer than conventional monitors has been generated.
5) Additional benefits of the VCM for unexpected populations have been discovered.
6) Significant momentum has been generated for further development and commercialization throughout the technology and disabilities field. This momentum includes technical support from industry leaders ranging from Apple and Microsoft to screen enlarger developers, plus an extensive list of clinicians, resellers, and consultants interested in patient evaluations following release of a pre-production version to beta test.

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