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Development and evaluation of vision rehabilitation devices

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***Abstract*—We have developed a range of vision rehabilitation devices and techniques for people with impaired vision due to either central vision loss or severely restricted peripheral visual field. We have conducted evaluation studies with patients to test the utilities of these techniques in an effort to document their advantages as well as their limitations. Here we describe our work on a visual field expander based on a head mounted display (HMD) for tunnel vision, a vision enhancement device for central vision loss, and a frequency domain JPEG/MPEG based image enhancement technique. All the evaluation studies included visual search paradigms that are suitable for conducting indoor controllable experiments.**

I. Introduction

As one of the complex sensory systems, the visual system plays an important role in daily activities. Loss of vision affects the quality of life in millions of people [1]. Central and peripheral vision loss are the two common types of visual impairment. Central vision loss (typically due to macular degeneration) affects high resolution central vision resulting in loss of detail, while peripheral vision loss (commonly caused by glaucoma and retinitis pigmentosa) mainly restricts the peripheral field impacting mobility. Both types of vision loss greatly affect quality of life by limiting reading, watching TV, driving and walking. While therapeutic treatments for these eye diseases are still limited in effect, vision rehabilitation techniques may help patients to better cope with their disabilities.

Over the past decade, we have developed a range of vision rehabilitation devices and techniques for people with impaired vision. Our main approach has been to provide supplemental visual information for the lost visual functions while allowing maintenance of residual (central or peripheral) vision. Besides the difficulties in technical development, documentation of their potential benefit for the targeted population is also a key challenge. We have used visual search testing in controlled laboratory environments to evaluate the devices and technologies. Visual search tasks resemble some of the visual demands of daily life, such as navigation, scanning the environment, and finding objects of interest. In this paper, we review the development and evaluation of two vision rehabilitation devices and a JPEG image enhancement technique.

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II. Development and Evaluation of Vision Assistive Devices

A. Augmented vision field expansion device

Visual field (VF) is an important aspect of visual function. When the field size is restricted below a certain level, it is strongly associated with a reduction in the ability to perform activities of daily living [2]. Patients with severely restricted peripheral field (known as tunnel vision), frequently have collisions, stumbles, and failures to find objects.

To address the tunnel vision problem, various field expanders based on the principle of minification have been developed, but none has succeeded in evaluations, mainly because of resolution loss and change in perceived visual direction resulting from the minification [3-6].

We have developed an augmented-vision field expander based on an optical see-through Head Mounted Display (HMD) that implements a spatial vision multiplexing concept [7, 8]. The system superimposes minified (~5×) edge images of the ambient scene over the wearer's see-through natural vision (Figure 1). Because the edge pixels in the display only occupy a very small portion of the field of view, they do not substantially occlude the wearer's natural see-through view. For instance, the door knob in Figure 1 is still easily visible.

Figure 1. The augmented-vision field expander superimposes a minified outline of the ambient scene over the wearer's see-through natural vision. This is a picture taken behind the device. The highlighted area represents a typical field of view of patients with tunnel vision. With such a device a patient should be able to maintain central resolution while detecting objects outside his/her residual visual field.

To test whether the device can improve patients' performance of finding targets outside their residual field of view (VF: 7-16º), we conducted a visual search experiment [9]. The patients' gaze points were tracked during the search. According to the gaze paths shown in Figure 2, the patients were able to find targets much more directly with the device than without. In addition, their search time performance improved with the device (Figure 3). It can also be seen from Figure 3 that patients were able to find targets much faster even without the device when given a smaller search area (66º×54º) compared with a larger search area (90º×74º). These evaluation results suggest that the device may help with difficult search tasks, but patients have adapted well for relatively easy tasks and the room for further improvement is limited.

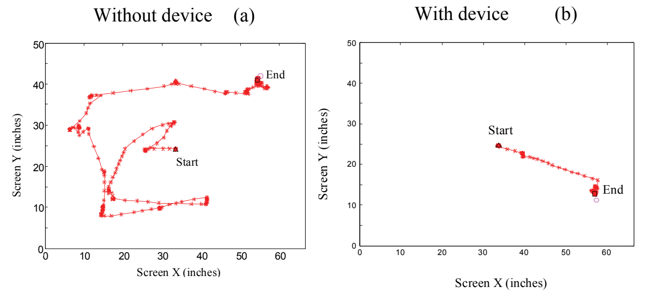

Figure 2. Examples of gaze path during search by a patient with tunnel vision. (a) without the augmented vision device, and (b) with the device.

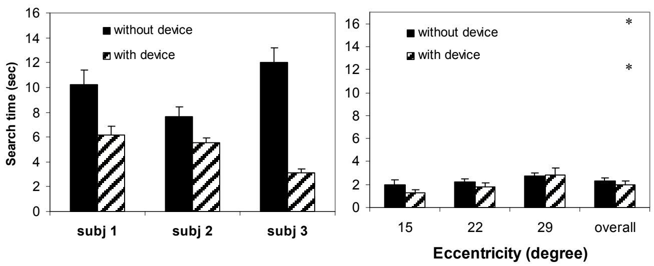

Figure 3. Search time performance with and without HMD field expander. The left graph is for a larger search area (90º×74º, 3 patients were tested). The right graph is for a smaller search area (66º×54º, collapsed across 9 patients). Stars denote for two outliers who had very low contrast sensitivity. Comparing to the larger area search, there was a limited room for improvement in the smaller area search.

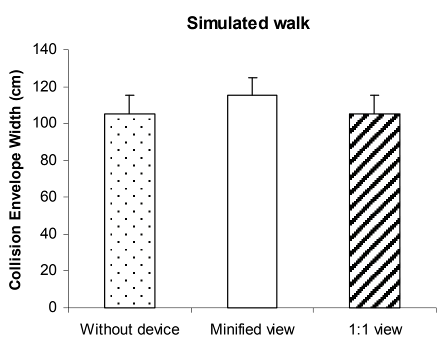

Figure 4. Patients' collision estimation quantified as collision envelope (a space in which obstacles are perceived to be likely to cause collisions) did not significantly change whether they directly looked at the obstacles or viewed through the device in minified scale or at full scale.

We also studied whether the highly minified images would cause patients to overestimate collision risk because objects seen in the minified display appear much closer to the heading direction than they really are [10]. The experiment was conducted in a virtual walking environment that simulates walking in a shopping mall corridor. Human-sized obstacles appeared at different offsets from the patient's moving trajectory for one second, and the patients (n=7) judged if they would collide with the obstacle. Their judgment was quantified as collision envelope — a space in which obstacles are perceived to be likely to cause collisions. It was computed by fitting a Gaussian psychometric function on patients' responses. Three conditions were tested- without the device (directly viewing), with the device using a full scale, and 5× minified edge images with see-through view blocked. We did not find using the device nor did the image minification significantly affect their collision judgment (Figure 4).

B. *Hybrid vision enhancement device*

Central visual impairment can be alleviated by magnification and contrast enhancement. Optical devices are widely used in rehabilitation because they are relatively inexpensive and portable. However, they have limited magnification and lack contrast enhancement functionality. Electronic magnification systems, including stationary and portable closed circuit televisions and HMD systems, were designed to overcome the limitations of optical devices and provide high magnification with enhanced contrast [11]. Several HMD devices have been developed over the years, including the Low Vision Enhancement System (LVES) [12], Jordy, Flipperport and NuVision. These HMD devices have been shown to be helpful to patients with low vision improving their visual acuity [13]. Although the HMD magnifiers are designed to be portable and versatile for multiple tasks, none of these HMD products is suitable for mobile use because: (1) magnified images make it very difficult to walk, and (2) the limited field of view of the opaque display in these products restricts the peripheral vision that is important for safe mobility (The field of view of HMDs are usually smaller than 40º). Consequently, users can't wear these devices when moving around.

We are developing a hybrid vision enhancement device based on an optical see-through HMD (Figure 5). The open design see-through display allows the users to look through the HMD with minimal peripheral restriction, like regular spectacles. The device has two modes: magnification and wideband enhancement. The magnification option can be activated on demand to see fine details (the see-through view is occluded by LCD shutters in this mode to improve contrast). When wide field of view and unaffected visual-motor coordination are needed for mobility tasks, the device can provide a wideband enhanced view, which is the natural see-through view superimposed with bright outlines of the ambient scenes [14]. This wideband enhancement method has been shown to be preferred by patients for TV images [15, 16]. We are now implementing the enhancement for the real world scenes.

A portable prototype device that implements the on-demand magnification function has been developed [17, 18]. Visual function testing showed that patients' visual acuity and contrast sensitivity were greatly improved when using the device (Figure 7). While visual acuity improvement by magnification is obviously expected, our dynamic image enhancing algorithms [17] could improve patients' contrast sensitivity by properly enhancing a range of contrast levels. This result is in contrast with the previous clinical findings that several commercially available HMD magnification devices (Jordy, Flipperport and NuVision) actually reduce contrast sensitivity [13], although they are able to further enhance images with moderately high contrast that patients are already able to see.

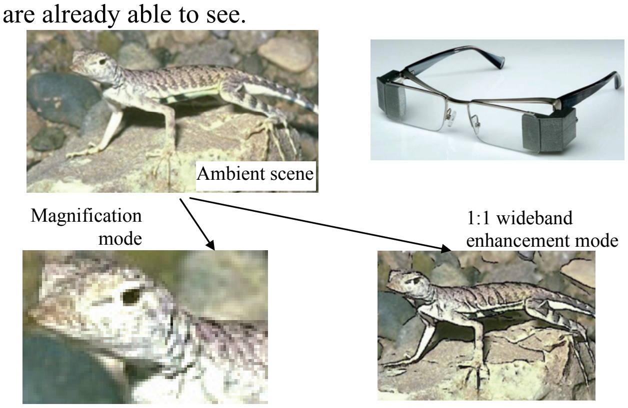

Figure 5. Concept of hybrid vision enhancement device based on an optical see-through HMD. The device works in two alternative modes – magnification and 1:1 scaled wideband enhancement, in which outline images of the scenes are superimposed over the see-through natural view. Magnification is suitable for discerning fine detail while the wideband mode is suitable for situations requiring visual motor coordination and peripheral vision.

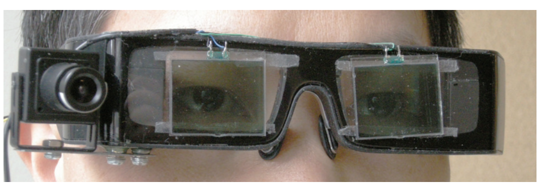

Figure 6. A portable prototype device that implements the on-demand magnification function. Magnified images are presented in the display when the LCD shutter is activated to occlude the see-through view. When the shutter is clear, users have a minimally restricted field of view.

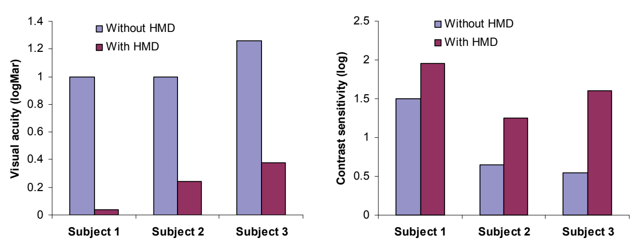

Figure 7. The magnification HMD device improved visual acuity and contrast sensitivity for people with central vision loss. Typical normal vision has 0 log acuity and 1.7 log contrast sensitivity.

In addition to visual function testing, we also conducted a preliminary mobile search test, in which 3 patients searched for and walked to targets posted on the walls in a large (17' by 27') empty room (Figure 8). Without the device, they had to walk very close to objects one by one before giving confirmative responses regarding the identity of the object. When wearing the device the patients were able to walk as they normally do, with the see-through view enabled. With magnification toggled on, they were able to identify targets from a much farther distance. The device reduced the number of attempts of walking to target for all 3 patients (4.3 to 1.6 on average) [18]. Search time was reduced only for one subject (51 to 33 sec), but not for the other two (30 to 47 sec, 72 to 104 sec, respectively). Although the two patients were able to see targets with the device from the start point in many trials, they spent a long time carefully examining them with the device before giving responses. This suggests that the targets might happen to be near the discrimination limits for them even with the device.

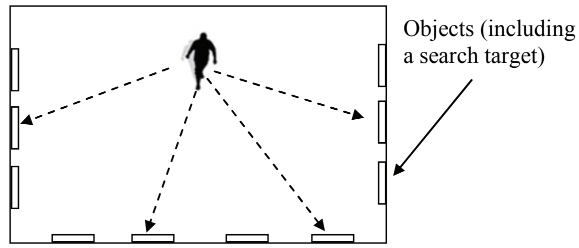

Figure 8. Search and walk to target experiment. From a fixed start point, patients had to identify and walk to a given target. If the target they walked to was incorrect, they returned to start point and repeated attempts until the correct target was found. Objects were shuffled in each trial.

C. *JPEG image enhancement*

Increasing contrast using image processing approaches can be an alternative or a supplement to the magnification function to help the patients see details (i.e. the high frequency content in images). Based on the JPEG format, in which image data are saved in a form of frequency, we have proposed an image enhancement method that directly boosts the high frequency bands of the quantization table in the JPEG or MPEG decoder [19, 20] (Figure 9). This technique does not add any extra computation load to enhance images and videos beyond the decoding. A number of image rating studies have shown that patients prefer images enhanced using this method [16, 21, 22]. We are currently conducting a visual search study with visually impaired people to evaluate whether the enhancement also results in any performance improvement in terms of search time and error rate. The same visual search test is being used to evaluate other image enhancement techniques that are under development.

1.0	1.2	2.0	3.3	4.0	3.3	2.0	1.2
1.2	1.5	2.3	3.5	4.0	3.1	1.9	1.2
2.0	2.3	3.0	3.9	3.8	2.7	1.7	1.1
3.3	3.5	3.9	4.0	3.3	2.2	1.4	1.1
4.0	4.0	3.8	3.3	2.4	1.6	1.2	1.0
3.3	3.1	2.7	2.2	1.6	1.2	1.1	1.0
2.0	1.9	1.7	1.4	1.2	1.1	1.0	1.0
1.2	1.2	1.1	1.1	1.0	1.0	1.0	1.0

Figure 9. The mid frequency bands in the JPEG quantization table are boosted directly in the JPEG decoder (shown as scale coefficients larger than 1). The resultant enhancement is shown on the left side of the image.

Our visual search evaluation tool includes 360 real world pictures in 3 categories - human group photos (Faces), indoor scenes (Indoor), and collections of similar objects

(Collection). An object in each picture is selected manually as the search target (Figure 10). In a randomized and balanced order, a picture is presented in either an unenhanced or enhanced form (possibly at different enhancement levels) to the subjects in each trial. Each subject sees a picture only once.

Our pilot experiment with 5 visually impaired patients (visual acuity: 20/50 - 200) has found that their search time reduced significantly with enhancement for Faces (from 12.2 to 9s) and Collection (from 6.5 to 5.8), but not for Indoor images (from 7.1 to 8.3s, not significant). The overall error rate with and without enhancement was not significantly different (20% and 23% respectively). The preliminary findings might suggest a possible benefit to the visually impaired from image enhancement.

Figure 10. An image from our visual search evaluation tool. An image patch pertaining to an object is manually selected from the image, and presented as the search target to the subjects.

III. Discussion and Conclusion

The ultimate standard for evaluating the utility of vision rehabilitation devices should be the actual long term use by the targeted patients. However, this is a very time consuming and costly procedure. Before a technique is put into such a long term trial, its potential utility and limitations should be objectively evaluated in a laboratory environment through repeatable and controlled experiments. Visual search is a type of testing paradigm that is suitable for this purpose; it closely resembles some visual demands of daily life, and it can be designed to test different visual functions, such as visual field extent, contrast perception, and object recognition. We have also added a mobility component into the search experiment for the evaluation of the hybrid vision enhancement device, in order to make the controllable lab experiment more closely resemble real world activities.

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