Subjective Image Quality Assessment of a Wide-view Head Mounted Projective Display with a Semi-transparent Retro-reflective Screen

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ABSTRACT

This paper reports on a wearable Hyperboloidal Head Mounted Projective Display (HHMPD) and two user studies on the evaluation of visual quality of a wearable HHMPD. Using a hyperboloidal mirror, an HHMPD can provide a wide field-of-view (FOV), a large observational pupil, and optical see-through capability. We propose a simple head attached screen that is both retro-reflective and semi transparent thereby allowing the HHMPD to be used in a wearable situation. The two user studies have shown that our wearable HHMPD provides a virtual image with a visual acuity of around 20/200 at perceptually 2 to 3 meters away from the user.

KEYWORDS: wide view head mounted display, retro-reflective semi-transparent screens, wearable computing

1 INTRODUCTION

Our research goal is to realize a wearable computing system with a more intuitive and flexible information display by employing a wide FOV video display. An optical see-through head mounted display (HMD) is commonly used in a wearable computing system to enjoy a variety of IT services. With a see-through HMD, a computer can be used without interrupting the work at hand. Augmented reality (AR), that superimposes computational information onto the real objects, can also be realized with a see-through HMD. However, there is a major problem in most existing see-through HMDs; they can provide a very limited field of view (a horizontal viewing angle of 30-60 degrees) near the central visual field [1]. Sensics's piSight HMD provides 180 degrees of horizontal field of view, but is a closed HMD. To our knowledge, LinkSim. Train's optical see-through HMD, A-HMD, provides the largest horizontal field of view (110 degrees) in an optical see-through fashion.

Originally, human vision has a very wide field of view of 200 degrees horizontal and 125 degrees vertical. Peripheral vision plays an important role in determining situational awareness and action [2]. In a wearable environment, various advantages are obtained if a display device can present information to the peripheral visual field. For example, information can be superimposed by AR to the entire field of view. This can improve the efficiency and safety of the real-world tasks such as driving directions and monitoring. Moreover, considering the sensitivity of visual receptors, information can be presented more flexibly, e.g. to display critical information in the central view, and noncritical information in the periphery.

We have previously proposed a variation of a head mounted projective display (HMPD) that provides both a wide field-of-view and see-through capability, using a hyperboloidal half mirror (Hyperboloidal Head Mounted Projective Display, HHMPD) [3]. The original HHMPD requires a retro-reflective screen placed in the real environment and is unable to be used in a wearable environment. In order to make the HHMPD usable in a wearable environment, we have been building a prototype system with simple semi-transparent screens that combines semi-transparent and retro-reflective [4]. In this paper, we integrate an actually semi-transparent retro-reflective screen into the HHMPD, and report on subjective evaluation experiments conducted on visual acuity and perceptual distance of the projected image.

In the following, Section 2 briefly summarizes basic characteristics of a HHMPD design and its prototype [3]. Section 3 introduces a number of design considerations for a semi-transparent retro-reflective screen [4]. Sections 4 and 5 describe the conducted subjective experiments and Section 6 gives conclusions and future directions.

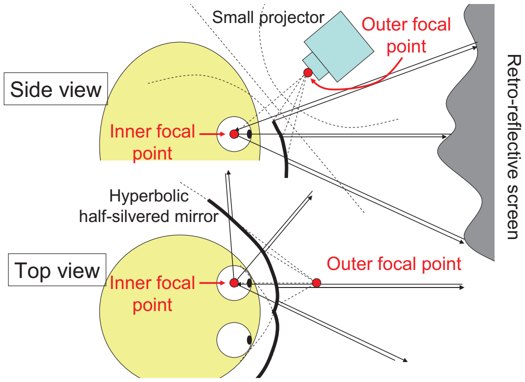

Figure 1. Schematic diagram of a HHMPD

2 CHARACTERISTICS OF HHMPD

The basic concept of the HHMPD is to employ a curved combiner rather than a planar combiner to diverge light rays to acquire a wider FOV. Every light ray reflected on the combiner should eventually travel back toward a single point, the user's eye. This constraint indicates that the combiner should be a hyperboloidal surface. Hyperboloidal mirrors have been widely used in computer vision [5]. However, our HMPD is thought to be the first display device to utilize a semi-transparent hyperboloidal mirror.

Figure 1 shows an overview of the design of the HHMPD. Projectors are placed at the outer focal points of the hyperboloidal semi-transparent mirrors, and the viewer observes stereo imagery from the mirrors' inner focal points. The axes of the hyperboloids are inclined to achieve a wide FOV without occlusion from the projectors. As described later in detail, an HHMPD can provide a

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very wide FOV with a normal projector that has a moderate projection angle.

A head mounted stereo prototype HHMPD was built using a pair of custom-made mirrors (see Figure 2) and two pocket projectors (3M MPro110, VGA, 17.7 by 14.4 degrees). It provides a 109.5-degree horizontal view angle and a 66.6-degree vertical view angle. As reported in [3], note that the HHMPD's optical design is theoretically capable of providing a horizontal field of view wider than 180 degrees, if appropriate mirror parameters and wider horizontal projection angles (~50 degrees) are given.

The primary advantages of the HHMPD include:

- Large observational pupil: As in the case of the conventional HMPD, a user observes a projected image on a retro-reflective screen a few meters away from the eyes. With an appropriately reflective screen, the observational pupil can be very large, making image visibility robust to eye rotation. This is important because eye rotation is likely to occur more frequently with a wide FOV image.
- Large binocular overlap: Owing to the curved shape, the HHMPD can provide a large binocular overlap, up to approximately 120 degrees, which is larger than that of a conventional HMPD.
- Small mirror size: Owing to the curved shape, the HHMPD can be much smaller for the same FOV with a more natural glasses-like appearance, compared to a conventional HMPD with a planar mirror.
- Wide range of applications: The HHMPD can be used, e.g., as an alternative to immersive projection technology (IPT) displays and for multi-user collaboration that requires wide FOV images. By adding a camera at the position of the projector using another optical combiner, taking wide FOV pictures from the user's viewpoint becomes possible [6], which is otherwise very difficult. The last example is useful for human activity analysis and attentive interfaces, for instance.

The main disadvantages of the HHMPD include:

- Low resolution: Since the entire FOV is covered by a single projector, the angular pixel resolution is decreased accordingly.
- Image distortion: Projected imagery has distortion caused by the curved mirror. However, this can easily be compensated by pre-distorting the rendering image.
- Defocus: The HHMPD, as well as a conventional HMPD, must project an image onto a retro-reflective screen without defocusing. Unlike a conventional HMPD, the basal plane of the projection frustum in the HHMPD is no longer planar, but is rather a curved surface. This means that keeping the entire projected image in focus is difficult. Dedicated projector optics, special screen geometry, or an anti-defocus projection is required to alleviate this problem.
- Last but not least, as in the case of a conventional HMPD, the HHMPD requires a retro-reflective screen, making it difficult to use in a wearable environment.

Figure 2. A stereo prototype of HHMPD

3 SEMI-TRANSPARENT RETRO-REFLECTIVE SCREEN

In principle, a retro-reflective screen has no transparency. In order to make a retro-reflective screen semi-transparent, many techniques have been proposed such as using an optical combiner [7], a rotational time division screen [8], or applying different optical principles [9]. We propose a simple pupil division screen and a vibrating screen. In the following, an overview and characteristics of each screen are described.

3.1 Pupil division screen

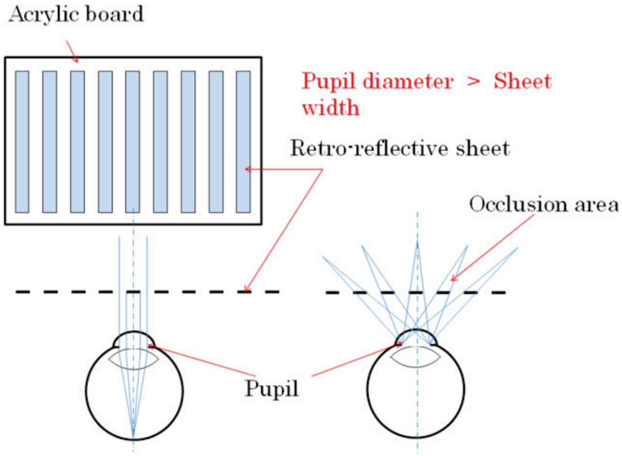

Figure 3. Pupil division screen

A pupil division screen is composed of many thin strips of retro-reflective material in a stripe whose width are smaller than a pupil diameter attached on a transparent substrate (such as an acrylic plate) to achieve both transparency and retro-reflection. This method does not need to move the screen so it is inexpensive and safe for the user. With a pupil division screen, the transparent part of the screen allows for viewing the real world, but there is a problem that the projected image on the transparent part is not retro-reflected and is missing. However, if the virtual image is distant from the screen, there will be no missing region in the observed image (Figure 3).

3.2 Vibrating screen

A vibrating screen is a type of moving screen. An example is shown in Figure 4. In this example, the screen is configured to move in a direction parallel to the transparent plate, and perpendicular to the stripe of the retro-reflective material. To accommodate a wide FOV, a cylindrical screen can be moved along the arc as shown in Figure 4(c) or multiple screens can be used as shown in Figure 4(b).

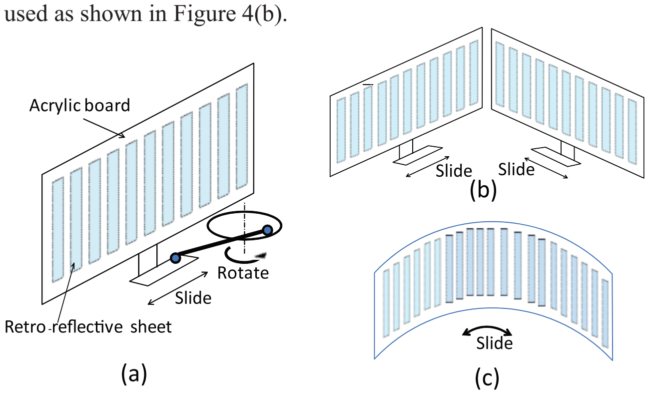

Figure 4. Vibrating screen

3.3 Prototype of semi-transparent retro-reflective screen

A vibrating screen and a pupil division screen were prototyped by attaching a retro-reflective sheet (3M Scotchlite High Gain Retro-reflective Sheeting 7610) cut into strips at a regular interval on an acrylic plate. The strip width and spacing between the strips are about 0.35mm for the pupil division screen and about 1.0mm for the vibrating screen. In addition, the base mechanism for vibration of the screen was produced by modifying a commercial CD drive unit. The vibration stroke of the screen is 36mm and the oscillation frequency is 5.5Hz. Thus, the average switching frequency between semi-transparency and retro-reflection is about 100Hz.

Photos were taken by a digital camera Sanyo Xacti HD1010 from an inner focal point of the HHMPD to verify that the prototype screens have characteristics of both retro-reflection and semi-transparency (see Figure 5). Figure 6 shows the captured pictures. Distance between the camera and the prototype screen is 15cm. The projected image is configured to focus on the screen. Distance between a reference real object (checkerboard) and the camera is 250cm. Focus *F* of the camera is set to 250cm and 15cm, and the shutter speed *S* is set to 1/8s considering the temporal characteristics of human motion perception [12]. The effective diameter of the lens is 3.5mm, close to the human pupil diameter under normal conditions. White fluorescent lights were used in the darkroom. In this experiment, a planar half mirror was used instead of a hyperboloidal half mirror.

As shown in Figure 6, it is clear that the virtual image (alphabet letters and numbers) and the reference real image (checkerboard) can be observed simultaneously. That is, it is confirmed that the prototype screens work as a semi-transparent retro-reflective screen that has both retro-reflective and transparent properties. With the pupil division screen, visibility of the real world is very poor when the focus *F* is near. And when *F* is far enough, the real images are able to be observed without missing regions. In addition, when *F* is near the screen gaps are apparent. When *F* is far the screen gaps are much less noticeable. In the latter case, the alphabet letters in the third row from the top can be recognized. The size of these letters is about 5mm by 3mm on the physical screens that is equivalent to visual acuity of around 0.07 or 14 minarc. Note that the visual field of each picture is about 30 x 20 degrees.

With the vibrating screen, when the focus *F* is far then the results are almost the same as those with the pupil division screen. On the other hand, when *F* is near, the visual quality significantly improves compared to that of the pupil division screen.

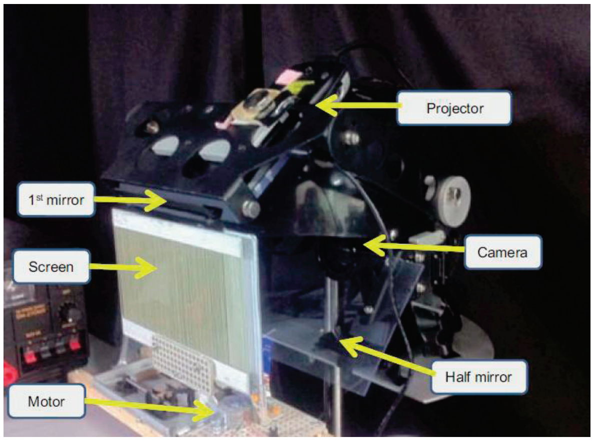

Figure 5. Vibrating screen with HHMPD

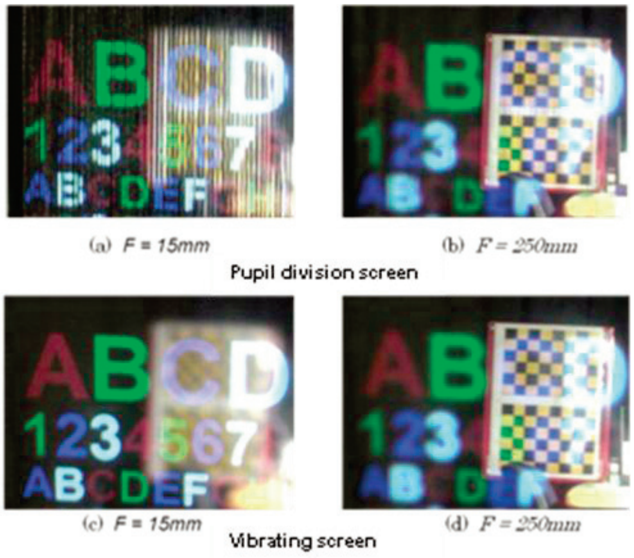

Figure 6. Photos taken through prototype screens

4 EXPERIMENT 1: SUBJECTIVE EVALUATION ON PERCEPTUAL DISTANCE

4.1 Objective

The purpose of this experiment is to investigate the relationship between the physical observation distance in the real world and the perceived distance of the projected image using the HHMPD with a curved semi-transparent retro-reflective screen (hereinafter referred to as a wearable HHMPD, shown in Figure 7). In AR applications, it is very important to be able to simultaneously observe virtual information and the real environment that the virtual information is referring to. It is also often desirable that those two types of visual stimuli are observed perceptually at the same distance. However, it is unclear if this simultaneous observation is comfortably possible because the perceived distance of a projected image on the semi-transparent retro-reflective screen, that is only 15cm in front of the user's eye, is expected to be very short. Note that this problem cannot be solved by a pin-hole projector or a laser-projector as the image is formed near the screen distance whereas the user needs to see further real objects. Stereoscopic viewing will help the user observe the projected image at an intended distance. However it is of our interest to investigate the fundamental properties in a monocular setup as a first step. Using a monocular setup, Zhang et al. [10] report that a perceived distance of the projected image is generally influenced by both the distance between the projector and the screen and the projector's focal length. In other words, a perceived distance of the projected image can be larger than the distance between the projector and the screen. However, such configurations require special retro-reflective materials such as high precision corner cubes that the current system does not have. Thus, the experiment is configured to use the projection distance consistent with the screen distance to investigate whether the projected image is perceived at a similar distance as the real environment that the projection is superimposed onto.

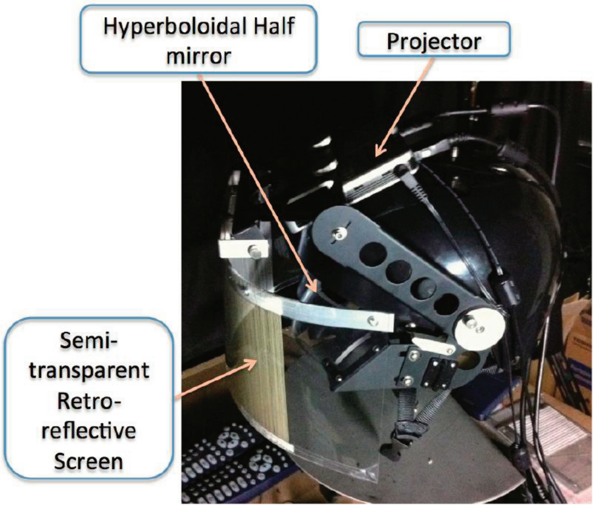

Figure 7. Wearable HHMPD

4.2 Procedure

Figure 8 shows the configuration of the experiment 1. Figure 9 shows visual stimuli presented to subjects (top) and the experiment environment (bottom). Each subject's head was fixed and equipped with the wearable HHMPD. Subjects observed the image with their dominant eye. The right half of the physical board presented a radial pattern, and the virtual image was superimposed in the left half. The degree of perceptual distance between the virtual and real images was subjectively evaluated in a five-step Likert scale (see Table 1). After exposing the subjects to the real pattern once at a distance of 1.0m and 4.0m, they were asked to indicate the level of agreement in perceptual distance between the virtual and real images by changing the position of the physical board. The board was placed at seven positions with 0.5m intervals, from 1.0m up to 4.0m. The experiment was then continued with the board being moved closer to the subject (in a reverse order, from 4.0m to 1.0m with 0.5m intervals). This procedure obtained ratings for 7 positions twice for each subject. Subjects could see the physical board being moved back and forth but had no information as to the actual distance it was placed at.

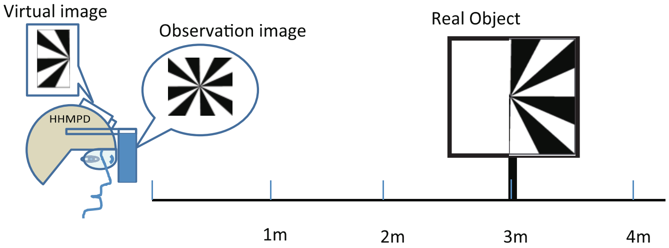

Figure 8. Configuration of experiment 1

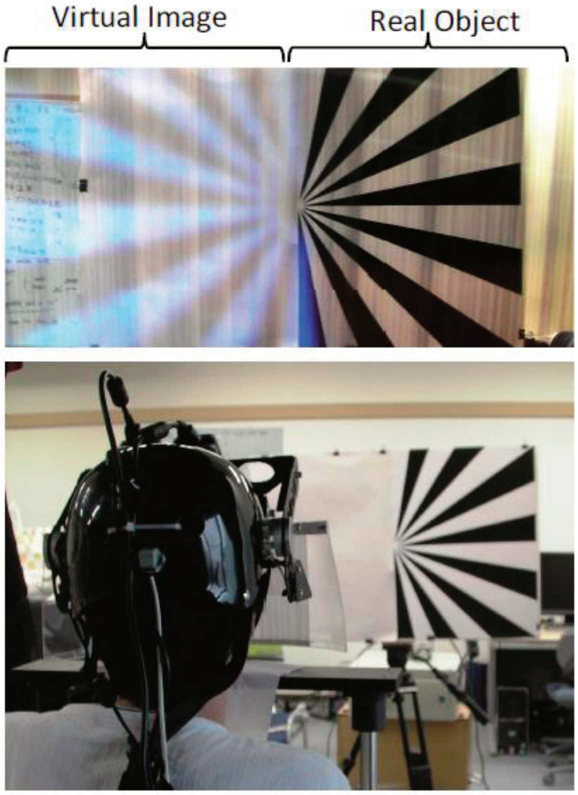

Figure 9. Experiment 1: example of visual stimuli (top) and experimental environment (bottom)

Table 1. Rating criteria in experiment 1

Does the real image appear to be at the same distance with the projected image?	Rating
Strongly agree	5
Agree	4
Neither agree nor disagree	3
Disagree	2
Strongly disagree	1

4.3 Result and discussion

We conducted this experiment with 10 test subjects (graduate and undergraduate students). Figure 10 shows the result including the averages and standard errors of the rating obtained from 20 samples for each distance. As shown in Figure 10, the level of agreement in perceptual distance between the virtual and real images is decreased rapidly with increasing observation distance.

This result shows that in this experimental configuration the virtual image is perceived at a similar distance as the real image only when the observation distance is within 2m. At the same time, this result also shows that subjects felt noticeable inconsistency between the virtual and real images only when the observation distance is beyond 3m. This result indicates that our simple prototype display is applicable to indoor and tabletop AR applications where the observation distance is relatively small.

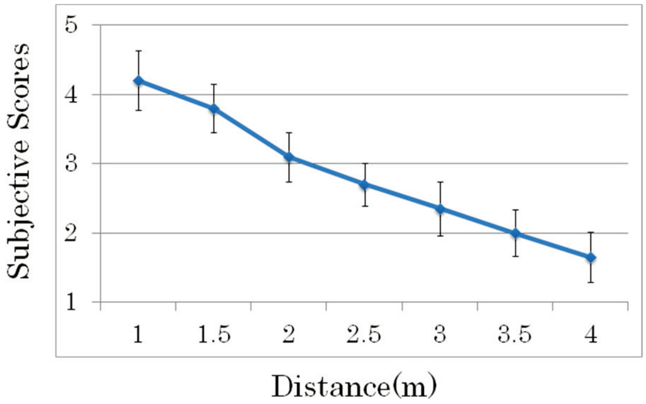

Figure 10. Results of experiment 1

5 EXPERIMENT 2: SUBJECTIVE EVALUATION ON VISUAL ACUITY

5.1 Objective

The purpose of this experiment is to investigate the perceived visual resolution of the projected image when a user sees it while observing the real environment at the same time using the wearable HHMPD. It is expected to be able to observe the projected image in its highest resolution determined by angular resolution of the projected image and slit intervals of the screen, when focusing on the retro-reflective screen that is 15cm in front of a user. However, as described in the previous section, virtual and real images often need to be observed at the same time in many AR applications. The projected image will get blurred when focusing on the real environment and the real environment will get blurred when focusing on the projected image. The two types of visual stimuli will appear perceptually at different distances. Therefore it is practically of high importance to investigate how detail the projected image can be observed when focusing on the real environment. In this experiment, we use Landolt rings, commonly used for visual acuity test, as visual stimuli and investigate the minimum apparent size of the virtual and real Landolt rings that are presented in a short period of time and yet simultaneously observable.

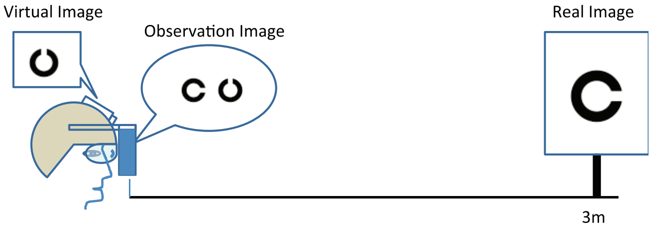

Figure 11. Configuration of experiment 2

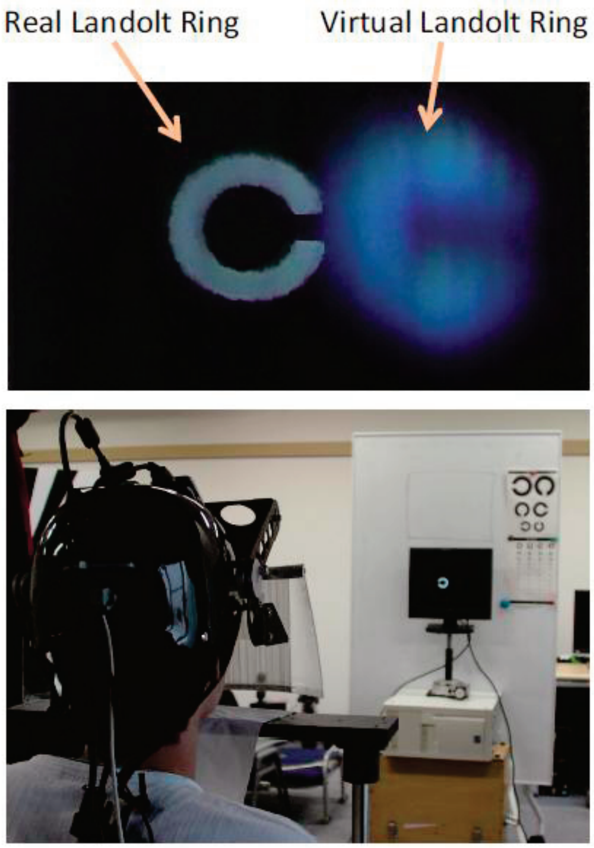

Figure 12. Experiment 2: example of visual stimuli (top) and experimental environment (bottom)

5.2 Procedure

Figure 11 shows the configuration of the experiment 2 while Figure 12 shows the entire environment of the experiment and an example of visual stimuli. Each subject's head was fixed and equipped with the wearable HHMPD. Subjects observed the stimuli with their dominant eye. The visual stimuli presented to the subjects at the same time are two Landolt rings. One is virtual, presented by the HHMPD and the other is real, displayed on an LCD monitor. The semi-transparent retro-reflective screen used in the experiment 2 is a pupil division screen same as the experiment 1, however this time is fixed on the vibrating mechanism. In this case the HHMPD is not wearable as the resulting vibrating screen is not fixed to it.

The real Landolt ring is presented on a 15-inch LCD monitor located at 3m from the HHMPD. The virtual Landolt ring is presented as a virtual image having the same apparent size as the real Landolt ring to its right. Each Landolt ring was presented in one of four orientations (up, down, left and right) randomly and the subjects had to answer as to whether or not the rings had the same orientation. The visual acuities corresponding to the apparent sizes of Landolt rings are 0.05, 0.075, 0.1 and 0.2 and were presented in this order. These parameters are chosen because of the fact that the visual acuity calculated from the angular resolution of the projection image is around 0.2, and that given by the slit intervals of the pupil division screen (0.35mm) and the screen distance from the eye (15cm) is around 0.25. We determine that a subject could observe Landolt rings in their size when three or more answers are correct out of five trials. During the experiment subjects were not told if their answers were correct or not.

In this way, we determine the visual acuity of the projected image for each subject for each size. In each trial, the Landolt rings are presented to the subjects for approximately 400ms [10], to avoid observation of the two rings sequentially by changing their focus.

5.3 Result and discussion

We conducted this experiment with 8 test subjects (graduate and undergraduate students). Six of eight subjects joined the experiment 1. The results are shown in Table 2 and Figure 13. Table 2 shows the normal visual acuity of each subject measured just before the experiment. These results show the visual acuity of the projected image is in the range between 0.05 and 0.1 for all subjects and conditions. It also shows that the visual acuity is higher with the vibrating screen than with the static pupil division screen. In addition, there is a positive correlation between the visual acuity of the projected image with the vibrating screen and the subjects' natural visual acuity (r = 0.76) but no correlation was found when the static pupil division screen was used (r = 0.23). These results are comparable to the visual acuity of the projected image estimated from captured pictures (approximately 0.07) as written in Section 3.3. Through this experiment, it was confirmed that the wearable HHMPD is applicable to indoor AR applications if coarse resolution suffices.

Table 2. Subjects' visual acuity

	S1	S2	S3	S4	S5	S6	S7	S8
Normal	0.4	0.7	0.7	0.8	1.2	1.2	1.5	1.5
Pupil	0.05	0.05	0.075	0.05	0.075	0.1	0.075	0.1
Vibrating	0.1	0.1	0.1	0.075	0.1	0.1	0.1	0.075

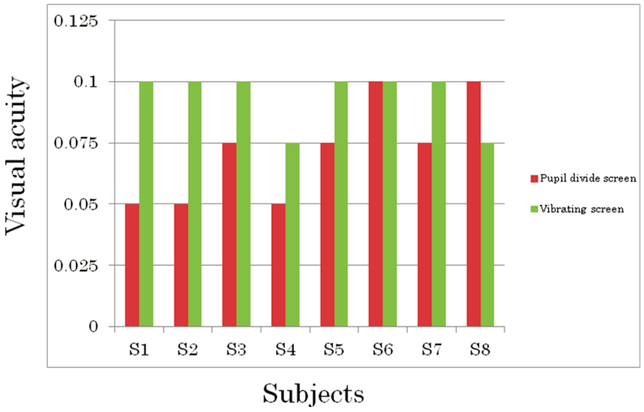

Figure 13. Result of experiment 2

6 CONCLUSION

In this paper, we reported a simple semi-transparent retro-reflective screen for a Hyperboloidal Head Mounted Projective Display (HHMPD) to be usable in a wearable scenario. A wearable HHMPD with the semi-transparent retro-reflective screen was built and the visual quality of the projected image was studied through subjective evaluation experiments. The experimental results show that subjects did not feel inconsistency in the perceived distance between the real environment and the superimposed projected image. The projected image was observable with the visual acuity of 0.05 to 0.1 when focusing on the real object at a distance of 3m. The visual acuity of the projected image estimated from captured pictures is around 0.07, and comparable results were acquired by the user studies. So these will be the upper bound of the visual acuity of the projected image observed by a human eye with the configuration of the prototype used. As future work we plan to improve the display in terms of visual quality, size and weight, and to investigate applicability of the wearable HHMPD in a wide mobile environment.

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