Quantitative assessment of visual acuity in projective head mounted displays

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Abstract

One issue of head mounted display design relates to the tradeoff between field of view (FOV) and resolution, which can lead to reduced visual acuity (VA). Essentially, an increase in FOV causes a decrease in visual acuity, for a given LCD display that has a fixed number of pixels. The effects of enhanced brightness on VA using two different types of retro-reflective material (cubed or beaded) were tested using a 52 deg. FOV projective helmet mounted display with VGA resolution. Three lighting conditions were also tested. Based on the display size, resolution, and FOV, we estimated a maximum visual acuity of 4.1 minutes of arc. In a counter-balanced between measures design, subjects' psychometric acuity functions were determined using a computer-generated 4AFC Landolt C test presented stereoscopically and probit analysis. The results confirmed that the maximum visual acuity possible within the setup was 4.1 arc minutes, the limit imposed by the microdisplay, and not the retroreflective material.

Keywords: visual acuity, resolution, FOV, head mounted display, Landolt C, ARC Display

1. INTRODUCTION

The potential utility of virtual and augmented reality simulations for medical, military, and educational applications has long been realized. One of the challenges in designing and implementing effective alternative reality environments is the integration of technology with the human user. Each has limitations, for example, there is trade off between field of view (FOV) of the head mounted display (HMD) and human visual acuity (VA). More specifically, as field of view in the HMD increases the limited number of pixels of the LCD displays reduces image resolution, thereby decreasing VA of the user. In this example of technology and user integration, the visual perception of the user is affected by a limitation in the display capabilities of the LCDs used in the HMD. Quantifying changes in visual acuity given normal use conditions allows one metric by which to judge the efficacy of any virtual environment setup. How to measure visual acuity using a user-centered approach is the subject of this paper. We use a computer generated Landolt C Visual Acuity Test (National Academy of Sciences, 1980)[1] in an augmented reality virtual environment. Visual acuity was determined using probit analysis (Finney, 1980; Pinkus & Task, 1998)[2,3].

1.1 Augmented Reality Visualization Center (ARC)

Our goal is to use a user centered approach to develop a methodology for systematically optimizing each aspect of the virtual environment (VE) from the HMD, computer graphics, to display components. The current work is an initial attempt at creating optimal conditions for visual perception within an augmented reality paradigm, although the methodology would apply to all types of VE setups. The VA experiments were conducted within a quasi-circular (4.57 m/15 ft.) diameter ARC display, a multi-modal Augmented Reality System with 3D visual, 3D audio and haptic capabilities (Davis et al., 2003)[4]. The display consisted of a curved wall of retroreflective material, a head-mounted projective display (HMPD), and a Linux-based PC. The optics of the HMPD, custom designed in the ODALab, were lightweight (6 g per eye) and projected images to the user in a binocular 52º field of view (Hua et al., 2003)[5]. Off-the-shelf miniature LCDs within the HMPD had a VGA resolution of 640 x 480, yielding a visual acuity of about 4.1 arc minutes (See figure 1)

Helmet- and Head-Mounted Displays VIII: Technologies and Applications,
Clarence E. Rash, Colin E. Reese, Editors, Proceedings of SPIE Vol. 5079 (2003)

Figure 1: ARC display with HMPD

In the ARC display, the optics of the HMPD project a left and right image into the augmented VE using a 50/50 beam splitter to reflect light off the retroreflective material. Because the retroreflective material reflects the light in the opposite direction of its incidence, stereo images are returned to the eyes of the user. The limit in user visual acuity, specifically resolution acuity, is imposed by the limited resolution of the microdisplay. One method of overcoming the limitations of the microdisplay is to augment the properties of the retroreflective material (e.g., increase brightness).

Currently, there are two types of retroreflective material used in the ARC display, Scotchlite™ 3M Fabric Silver (Beaded) and Scotchlite™ 3M Film Silver (Cubed). The material for the Scotchlite™ 3M Film Silver (Cubed) should reflect more light, enhancing the apparent brightness of the projected image. This quality should increase the light entering the user's eye, thus improve resolution visual acuity. A computerized version of the Landolt C visual acuity test was used to assess whether the added brightness of the Scotchlite™ 3M Film Silver (Cubed) actually improved resolution acuity of the user in the ARC setup.

1.2 Visual acuity

Table 1 shows the 5 main types of visual acuity; each denoted by different tasks. VA is typically defined as the ability to discriminate objects spaced very close together. It is represented by a ratio of the spatial pattern size in minutes of arc compared to the distance of the observer's eye. Most people are familiar with the Snellen eye chart, which measures recognition acuity. Based on the Snellen chart, the standard definition of normal visual acuity (e.g., 20/20) is the spatial pattern size seen by the observer versus an ideal observer (i.e. 1 arc minute). Comparing resolution VA within and outside the ARC setup would provide a gauge of how resolution acuity changes from a real world setting to a VE.

Detection	Detect target in visual field
Vernier or localizing	Identify displacement two lines in space
Resolution	Perceive the separation of two distinct elements in space (Landolt C)
Recognition	Name targets in space (Snellen)
Dynamic	Locate moving targets in space

Table 1: Visual acuity types

1.2.1 Landolt C visual acuity test

The Landolt C visual acuity test is standard for measuring resolution acuity (National Academy of Sciences, 1980)[1]. The Landolt C is constructed on a 5 x 5 grid with the gap the width of 1 grid unit (See figure 2). The gap is presented in one of four positions: right, down, left, and up. From a visual perspective there are two drawbacks in using the Landolt C: 1) uncorrected astigmatisms may make some orientations of the gap easier to see, and 2) guessing may show biased performance at low acuities, usually toward the right (Rabbett, 1998, p. 32)[6]. Others have found a "gap-down" effect, where correct responses were lowest for downward facing gaps (Schauf & Stern, 2001)[7]. To control for these potential confounds, all participants were tested for resolution acuity using corrective lenses, if needed. As well, the participants were not constrained by time in responding. Although guessing still occurred, there was no added pressure to perform under a time limit. The more challenging problems were translating the printed version of the test into a software application.

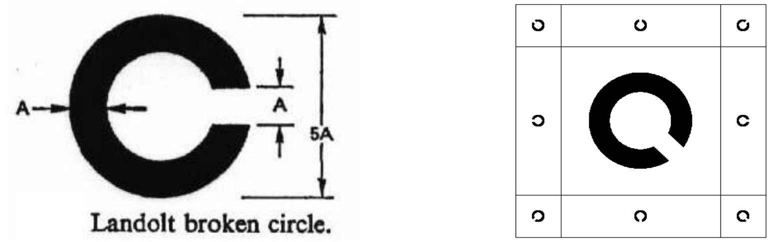

Figure 2: Standard Landolt C visual acuity test

One main issue in converting the Landolt C test into a software application was accounting for anti aliasing effects. Typical stimuli for the Landolt C test, pictured on the right of figure 2, are circular C's. Rendering a circular C requires the use of anti-aliasing techniques to remove the "stair-stepping" effect found in low bandwidth displays. Figure 3 shows typical Landolt C stimuli with aliasing and anti aliasing effects present when rendering the curvature of the C.

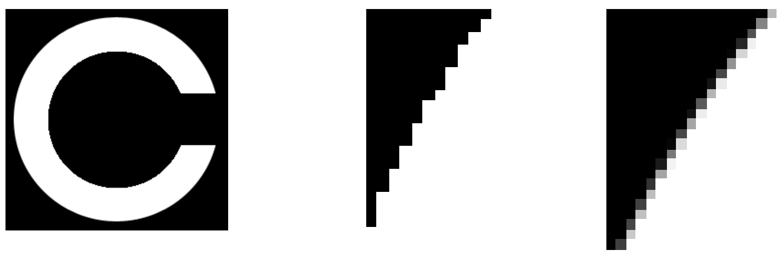

Figure 3: Aliasing and anti-aliasing effects

To remove these effects, a square C was created that retained the 5:1 ration between C size and gap size. To further reduce aliasing and anti-aliasing effects the VA test was changed from an 8 AFC (See figure 2) to a 4 AFC. Figure 4 shows the view of the square Landolt C test from the left and right eyes within the HMPD.

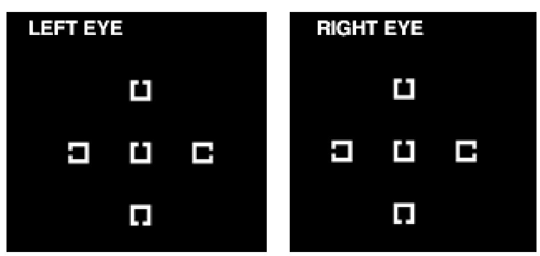

Figure 4: Square Landolt C visual acuity test

1.2.2 Visual acuity and lighting

As pictured in figure 1, the ARC display is a circular structure with retroreflective panels covering the interior. The panels are 0.91 meters wide and 3 meters high. The ceiling and entrance of the ARC is covered with a heavy black cloth to block extraneous light from entering the VE. When interior light levels are increased, the image is eventually lost. Consequently, the ideal environment for viewing images is under low levels of illumination. Studies have shown that decreasing light illumination levels decreases reaction time and accuracy on different visual performance tasks (Murdoch, 1985)[8]. Performance decrements may be attributed to a decrease in luminance, or light emitted from an object (Boyce, 1981)[9]. We used three levels of light to further explore the differences in the retroreflectance of the material. Because of limitations of the ARC display, only mesopic and scotopic light ranges were used. These light levels roughly correspond to illuminance IES Lighting Handbook (1987)[10] for lighting spaces for optimal user performance.

Performance on Tasks of high contrast or large size	200 to 500 Lux (18.58 to 46.45 footcandle)
Working spaces where occasional work is performed	100 to 200 Lux (9.29 to 18.58 footcandle)
Simple orientation for short temporary visits	50 to 100 Lux (4.64 to 9.29 footcandle)

Table 2 : Illuminance categories and values (IES Lighting Ready Reference, 1989, p. 87)

1.3 Probit analysis

Sensory threshold is typically calculated to determine human sensitivity to a stimulus. The threshold value is treated as a statistical measure (Bi & Ennis, 1998).[11] Although there are other methods, the indirect parametric approach of Probit analysis is typically used to determine thresholds of visual acuity (Finney, 1980; National Academy of Sciences, 1980; Pinkus & Task, 1998)[1,2,3]. In Probit analysis the percent correct responses are corrected for chance responding, then they are converted to z-scores or normal equivalent deviates (NED). The NED values are used as the dependent variable in a linear regression with gap size (visual acuity) as the independent variable (e.g., $NED = b_0 + b_1 * VA$). Curve fitting is accomplished using a graphical method (plot probit values against the stimulus intensity and read where P = 0.5) or the exact method (use an unbiased estimator in an iterative procedure). Finney (1980) suggested using a maximum likelihood estimator with probit analysis. The resulting predicted NED values are converted back into percents and evaluated against the threshold value to determine visual acuity. For a 4 AFC design, the threshold is 62.5%.

2. METHODS

We used a first generation see-through projective head mounted display (HMPD) with a 52 degree FOV. The microdisplays for the HMD were off-the-shelf Liquid Crystal Displays with a VGA resolution of 640x480 (See figure 5). Software ran on a computer system with Linux RedHat 7.2 OS and a dual processor graphics card. The LCD monitor was a Dell 17 inch flat screen. Within the ARC, we replaced two if the, Scotchlite™ 3M Fabric Silver (Beaded) panels with Scotchlite™ 3M Film Silver (Cubed) panels.

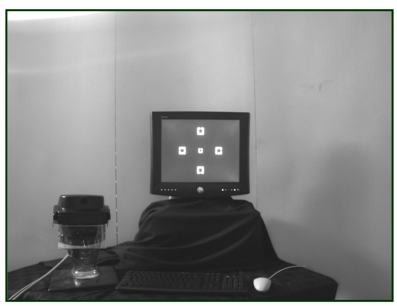

Figure 5: Computer setup and HMPD

2.1 Participants

Twelve participants (11 men and 1 woman, mean age = 28years) performed the Landolt C Visual Acuity test under 3 different light levels (High, Medium, and Low) on both the computer and in augmented reality (e.g., using the HMPD). Half the participants viewed the cubed material while performing the Landolt C visual acuity test in the HMPD, while the other six participants viewed the beaded material. Each participant was either corrected for or had 20/20 vision. Glasses or contacts were worn during each part of the experiment.

2.2 Landolt C Computer versus Augmented Reality Version

Six different gap sizes representing the different levels of visual acuity in minutes of arc were presented. The stimuli were the same in each condition; however, the visual angle corresponding to each size (arc minutes) of the Landolt C changed from the computer to the augmented reality condition. Table 3 below presents the change in visual angle for each environment. To accommodate for these differences, the participants we seated 1.85 meters from the LCD monitor in the computer version and were 2 meters from the retroreflective material in the augmented reality condition.

Computer (Arc Minute)	Snellen Conversion (Ft and Meters)	Augmented Reality (Arc Minute)	Snellen Conversion (Ft And Meters)
1	20/20 or 4/4	4.1	20/82 or 4/16.4
2	20/40 or 4/8	8.2	20/164 or 4/32.8
3	20/60 or 4/12	12.4	20/248 or 4/65.6
4	20/80 or 4/16	16.5	20/330 or 4/66
5	20/100 or 4/20	20.6	20/412 or 4/82.4
6	20/120 or 4/24	24.7	20/494 or 4/98.8

Table 3: Visual acuity conversion values

2.3 Lighting setup

Although other light configurations can be used (e.g., light reflected off the ceiling), we chose to suspend the light from the ceiling of the ARC to better control the effects of glare and extraneous light that may bounce off the floor onto the retroreflective material. Three 13 Watt 4-pin PI fluorescent lamps (780 lumens, Warm 2700K) were mounted on a 51.5 cm by 59.5 cm gator board. The board was attached to the ceiling in the center of the ARC (See figure 6). A diffuser of sheer black material and length .72 meters was attached to the board. The lighting levels were set using a Minolta T-10 illuminance meter. Illumination ranged from High (225 -209 Lux), Medium (140 to 132 Lux), and Low (61 to 53 Lux) to give an average 80 Lux difference between each light level.

Figure 6: Lighting and setup

2.4 Experimental Design

Participants were randomly placed in a retroreflective material condition (beaded or cubed). The three light levels were changed for each participant according to a partially counterbalanced design determined prior to the experiment. Within each test block, each Landolt C gap size was presented in random order. As well, there were five random presentations of each direction (up, down, left, and right) per level of visual acuity. Test blocks were run first with the computer version of the Landolt C test, and then within the HMPD. Participants completed one test block per condition for a total of six tests. There were a total of 720 responses per participant. Once the responses were converted to percent correct and, then converted to NED values, a Probit analysis using light level, visual acuity, and gap direction as independent variables was completed.

2.5 Procedure

The initial lighting level was set for each participant prior to their entering the ARC. Participants were first seated 1.85 meters from the computer monitor. The interpupillary distance (IPD) of each subject was measured using a pupillometer. This value was entered into the Landolt C test to set the correct position for the left and right eye display of the stimuli on the LCD monitor. The IPD on the HMPD was also adjusted to center the optics and the image on the eyes of the observer in the augmented reality condition. This initial setup allowed the participant to visually adapt to the lighting conditions within the ARC prior to the start of the experiment. Once correctly positioned and the IPD entered, the participants were given a keyboard, and instructed to use the arrow keys to indicate the direction of the gap in the Landolt C stimuli.

Each time the participant key pressed a response, a beep would precede the appearance of the next stimuli. The test stimuli would remain on the screen until the participant indicated a response. There was no time limit in responding.

The participant continued to respond until the program indicated that the test was complete. The software program recorded each response in a tab delimited file format that was exported to MS Excel. A combined data file was created for each subject across each lighting and viewing (computer or HMPD) condition.

Once the subject had completed the computer version of the VA test, they were asked to stand on a mark 2 meters from the retroreflective material. The HMPD was adjusted for IPD and head size (See figure 6). Once the VA test was completed within the HMPD, the subject was asked to sit again while the experimenter changed the light level. The procedure was repeated until data was collected for all three light levels.

3. RESULTS

Responses for all participants were combined into a single MS Excel data file and ported into the statistical package STATGRAPHICS plus 5.1. This statistical software provides a Probit analysis across multiple independent variables using a maximum likelihood regression (See figure 7). The results showed that there was no difference between the groups in terms of visual acuity (M_{Cubed} = 98.64, *SD* = 3.22; M_{Beaded} = 99.07, *SD* = 1.96). For visual acuity corresponding to 20/20 vision, the participants in each group performed well above the 62.5% threshold (M_{Cubed} = 93.70, *SD* = 4.82; M_{Beaded} = 97.04, *SD* = 2.89). Although performance was poorer in the HMPD for the smallest visual acuity (4.1 arc minute), the proportion of correct responses was still above the 62.5% threshold (M_{Cubed} = 88.89, *SD* = 11.91; M_{Beaded} = 81.48, *SD* = 14.66).

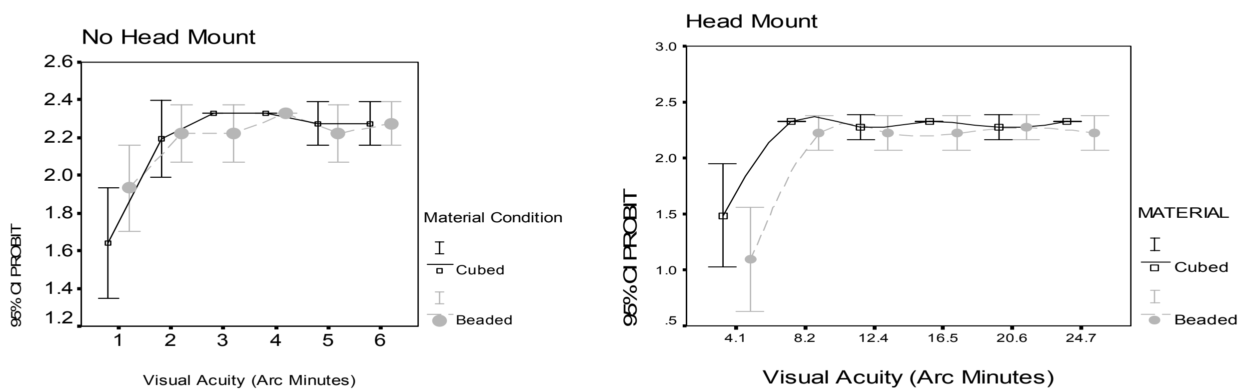

Figure 7: Probit analysis computer versus HMPD

Also apparent from the above analysis is a difference in visual acuity measured between the two materials when the Landolt C test was given in the HMPD. An analysis of percent correct for each direction of the gap showed that the there is a difference in bias responding between the two groups.

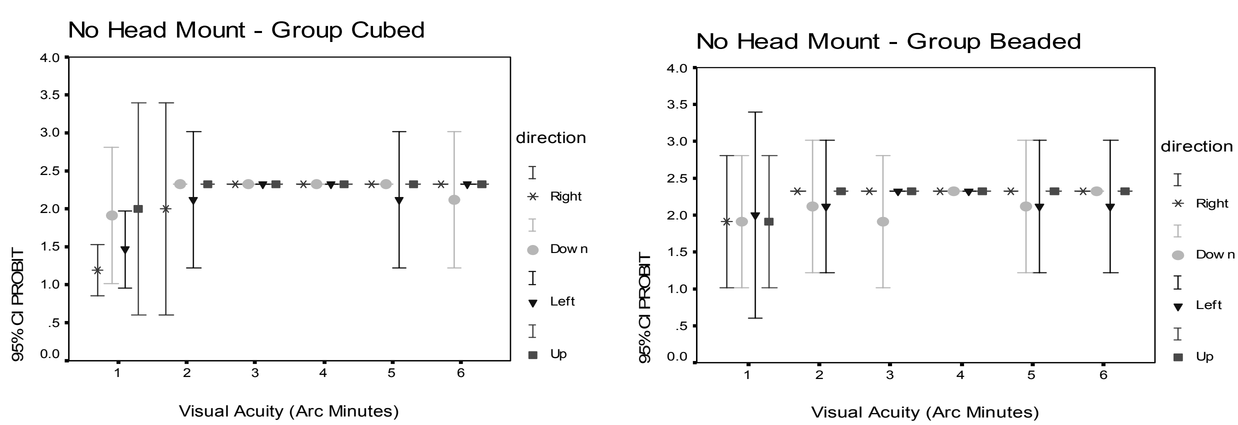

Figure 8: Bias in responding- no HMPD

Figures 8 and 9 show that those participants viewing the cubed material were more likely to guess down, up, or left; however, scored 100% on the right facing gap for the smallest C. Those participants viewing the beaded material showed a right facing bias across all C sizes. They also showed a mixture of down, left, and up errors.

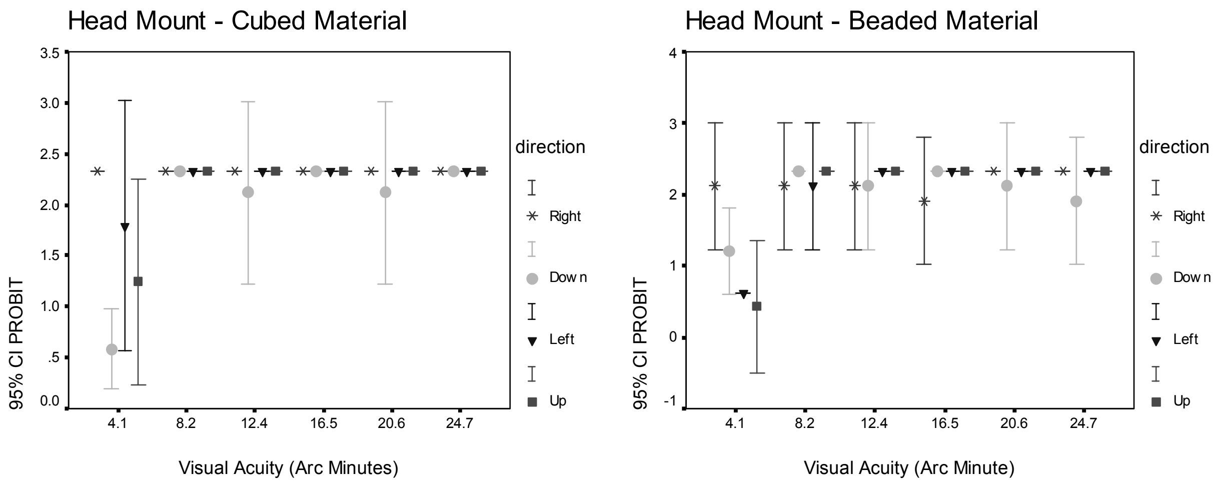

Figure 9: Bias in responding- HMPD

Table 4 displays the mean percent correct across all levels of the independent variables. The table clearly shows that there was no effect of light on correct responding. This result also holds across all levels of visual acuity and gap direction.

Material Type	Computer vs. Augmented	Light Level	Mean	Std. Deviation	N
Beaded	No HMD	High	.99	.098	720
		Medium	.99	.091	720
		Low	.99	.117	720
		Total	.99	.103	2160
	HMD	High	.98	.133	720
		Medium	.99	.117	720
		Low	.99	.117	720
		Total	.98	.123	2160
Fabric	No HMD	High	.99	.074	720
		Medium	.99	.098	720
		Low	.99	.074	720
		Total	.99	.083	2160
	HMD	High	.97	.180	720
		Medium	.98	.152	720
		Low	.97	.156	720
		Total	.97	.163	2160

Table 4: Percent correct across material, viewing, and lighting conditions

4. CONCLUSION

The results of the experiment confirmed that the visual acuity limit using the current see-through HMD system was 4.1 arc minutes. The microdisplay, and not the retroreflective material impose this VA limit. However, as we are able to use higher microdisplay resolutions, the retroreflective material may become the system limiting factor. The experiment also showed that given the constraint in lighting imposed by the HMPD, there is no benefit to visual acuity in changing light levels within a scotopic or mesopic range. Lighting conditions within the ARC may also become less constrained as head mounted displays become less reliant on the contrast created between low levels of illumination and the projected image. Studies on the effects of contrast given the current ARC display are currently being conducted. In addition, biases in responding using the Landolt C should be explored further. There may be a recognition advantage when viewing a right facing C on the Cubed material. The methodology proposed will be used to assess future displays under multiple conditions.

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ACKNOWLEDGEMENTS

This research was supported by the Office of Naval Research Grants N000140210261 and N00014-02-1-0927.