Going Blank Comfortably: Positioning Monocular Head-Worn Displays When They are Inactive

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ABSTRACT

Head-worn displays like Tooz and North's Focals are designed to be worn all day as smart eyeglasses. When the display is not lit (often to save battery life), the optical combiners may remain visible to the user as an out-of-focus seam or discoloration in the lens. We emulate seven shapes and positions of optical combiners which 30 participants rank for comfort. Based on these results, we run a second user study with 12 participants comparing the comfort of a combiner with various offset distances from the user's primary position of gaze (PPOG) towards the nose. Results suggest that a combiner's nearest edge should be more than 15° from the PPOG.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**; *User studies*; *Mixed / augmented reality*.

KEYWORDS

Head-worn Display; Glasses; Human Factors of Wearables

ACM Reference Format:
Yukun Song, Parth Arora, Rajandeep Singh, Srikanth T. Varadharajan, Malcolm Haynes, and Thad Starner. 2023. Going Blank Comfortably: Positioning Monocular Head-Worn Displays When They are Inactive. In *Proceedings of the 2023 International Symposium on Wearable Computers (ISWC '23), October 08–12, 2023, Cancun, Quintana Roo, Mexico.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3594738.3611375

1 INTRODUCTION

Head-worn displays (HWDs) have become more mainstream and accessible to the consumer market over the past decade. Some augmented reality headsets strive for a large field of view (FOV) centered at the user's PPOG. These devices are often intended for tasks where the user is only wearing the headset when the display is on. However, smart eyeglasses like Google Glass and North's Focals are more intended for episodic uses such as reading short texts and other micro-interactions [1, 33, 34], and the display is most often off. Determining where the HWD's virtual image should appear in the user's visual field is one of the most important design decisions for an HWD manufacturer, and for smartglasses, that decision should consider the user experience both when the display is on and off.

Extensive research compares different placements of automotive head-up displays (HUDs), concluding that the image should be presented away from the PPOG [5, 14, 19, 25, 27, 36]. Research in aviation has also focused on studying how the positioning of the HUD affects a pilot's performance [13, 35, 37]. Foyle et al. [13] showed that placing displays in PPOG can lead to cognitive capture, which Dowell et al. showed can be avoided by offsetting the display [11]. In general, the literature suggests ordinary telemetry and notifications should be displayed away from PPOG while targeting information should be aligned with the target.

Studies on personal HWDs have analyzed the optimal placement of HWD tasks when the display is on [17, 20, 30, 38, 41]. Chua et al. [7] and Lin et al. [23] found that displays placed in the primary position of gaze (PPOG) are obtrusive to participants when they are performing tasks such as driving or order picking, respectively. For seated reading tasks, Haynes and Starner concluded that displays centered at 0°, 10°, and 20° from the participant's PPOG (towards the ear) are significantly more comfortable than those at 30° [18].

Past studies mostly ignore the potential comfort issues of inactive displays. Even in its inactive state, the visible differences between the plain eyeglasses and the combiner optics that create the virtual image of the HWD may annoy the user. For example, while the image quality of the Epson Moverio series of HWDs can be superb, looking through the optics when the display is off results in prominent grey rectangles in front of both eyes.

The design of combiners in HWDs can heavily influence the visual artifacts a user may observe. Rash states that the combiner's luminous and spectral characteristics heavily influence its transmittance [29]. Kress and Shin state that conventional combiners often need to be thicker in order to achieve a good eyebox [21].

2 DISPLAY DESIGN STUDY

We define glass-display difference (GDD) as the difference in perception of the region of the smartglasses that is normal optics versus

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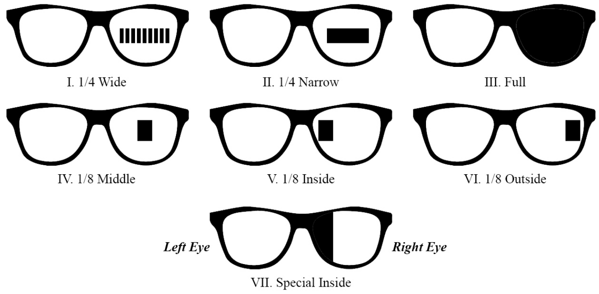
ISWC '23, October 08–12, 2023, Cancun, Quintana Roo, Mexico

ACM ISBN 979-8-4007-0199-3/23/10.
https://doi.org/10.1145/3594738.3611375



	I	II	III	IV	V	VI	VII
I	0	-0.67	-1.50	-1.00	-2.37	-3.03	-2.87
II	0.67	0	-0.83	-0.33	-1.70	-2.37	-2.20
III	1.50	0.83	0	0.50	-0.87	-1.53	-1.37
IV	1.00	0.33	-0.50	0	-1.37	-2.03	-1.87
V	2.37	1.70	0.87	1.37	0	-0.67	-0.50
VI	3.03	2.37	1.53	2.03	0.67	0	0.17
VII	2.87	2.20	1.37	1.87	0.50	-0.17	0

Cell_Value = $\underset{p \in \text{participant}}{AVERAGE}\left(\underset{p}{RANK}(Model_{col\_id}) - \underset{p}{RANK}(Model_{row\_id}) \right)$

Figure 1: Seven models used in the display design study (top) along with average difference in rank given by participants (bottom). Black parts in the models are covered by semi-transparent films. 1/4 and 1/8 indicate the approximate portion of the area covered on one lens.

the perception of the optical area of the smartglasses that includes the combiner for creating the virtual image. The GDD is affected by several important features of the optical combiner and display: (1) position, (2) area, (3) shape/number of borders, (4) the opacity of the plain glass, (5) the delta opacity between the display and the plain glass, and (6) the binocularity of the HWD.

The virtual image position, area, and shape are typically determined early in the design of an HWD. We focus on these parameters and control the other factors to create seven prototypes for participants to judge for preference (see Figure 1). To control factor (6), we decided to make all models right-eyed and monocular, which is also the choice made by commercial industrial products like Google Glass, Tooz, North's Focals, and Vuzix Blade. Presumably, these commercial devices made this choice because the majority of the population is right-eye dominant. Each model is inspired by optical combiner design choices made by commercially available HWDs, industry prototypes, or specialty eyewear: I (Tooz, OptInvent ORA-1, Lumus), II (Sony Smart Eyeglasses, movie theater captioning glasses), III (Magic Leap 1, Nreal Light), IV (Epson Moverio), V (Engo), VI (LaForge Shiva), VII (Engo, low-vision "bifocals"). To emulate the optical combiner, semi-transparent films were fixed to off-the-shelf plano eyeglasses using transparent tape. The change in opacity between the plain glass and the glass plus "combiner" was over 40%. We recruited 30 participants (16 identifying as male and 14 as female; 12 wearing eyeglasses) who tried the seven models. The participants then ranked the models based on their preferences. We chose to use rankings instead of ratings for comparing the models, which have been used in related studies comparing HWD conditions [23, 24] and are preferred for avoiding non-differentiating responses [22]. Average ranks were I (5.63), II (4.97), III (4.13), IV (4.63), V (3.27), VI (2.60), and VII (2.77). Following procedures for comparing multiple ranked conditions in standard statistical packages [3, 10, 39] and similar experiments in the literature [17], we utilized the Friedman test [28] and tested for differences among participants' preferences on the seven models ($p \ll 0.0001$). We then followed the test by the Conover-Iman method [9] adjusted by the Benjamini-Hochberg procedure [2] to discover which specific pairs of conditions are different. This procedure of statistical tests analyzes the variance among different samples from the same participant group and limits type I errors [6].

Via pair comparisons using the Conover-Iman method, we discover that models VI and VII were significantly more preferred than models I, II, III, and IV ($p < 0.005$ for all comparisons), and model V was significantly more preferred than models I, II, and IV ($p < 0.005$ for all comparisons). This result suggests that having the optical combiner in the user's line of sight may not be desirable, which is supported by other trends in the literature [17]. Of the models not in line-of-sight, participants commented that model VII might be preferred as it "contains fewer edges." This preference is supported in practice by examining the lenses made for the low-vision community, which tend to have one hard edge, if any. Even commonplace old-fashioned bifocal and trifocal lenses tend to avoid extraneous edges. In addition, creating an optical combiner with one edge is less difficult from an optics manufacturing viewpoint. Thus, we decide to continue our investigations using an optical combiner of the style of model VII.

3 DETERMINING COMFORTABLE POSITIONS

We construct eight new model glasses using the same base frame and plano lenses (see Figure 2). To control factor (4) opacity, we use the same off-the-shelf lenses for each model. To control for (5) the delta opacity between the display and the plain glass, we emulate the Vuzix Blade monocular head-worn display, which has a delta opacity of 14.20%, by laminating five layers of semi-transparent films to non-prescription glasses (see Figure 2). The resulting delta opacity was 13.38%.

Figure 2: Model glasses. Labels are model numbers with ideal perceived location of display combiner edge. We use negative values to indicate offsets from PPOG towards the nose.

3.1 Participants and Task

We recruit 12 participants to try our simulated smartglasses while attending a controlled art exhibition provided by us. We then collect preferences and feedback from the participants on those models. This task mimics the usage of HWD in an application often studied in the literature [8]. Also, since the art exhibition task is sedentary and requires low attention and physical effort, the results should establish a most permissive bound for GDD in such AR optics. Specifically, we investigated the largest area that can be covered by a display starting from the nasal position, with respect to participants' comfort. More active use cases, such as guided repair [38], collaboration with remote experts [40], or order picking [16], may be more restrictive in the user's needs.

Our 12 participants (1) did not wear glasses (including any kind of contact lenses and orthokeratology lenses) and (2) had Snellen visual acuity of 20/40 or better on both eyes. Among all the participants, eight identified as males and four as females. 11 out of 12 participants identified as Asian, and 11 out of 12 participants were aged 21-25. In addition, seven reported never using sunglasses, and the majority (9 out of 12) had extensive computer usage (ranging from 6 to 12 hours per day). In addition to demographic information, we also collected the interpupillary distance (IPD) for each participant for calibration purposes.

3.2 Calibration Process

Due to individual variations in how people wear glasses, each participant may perceive the border between the area covered by the film and the plain glass at a different position with each pair of glasses. To determine the specific angle covered for each user, we positioned a visual display terminal (VDT) 80 cm in front of the center of the participant's right eye, as only the right eye can see the border on the glass. Using a mouse, we asked the participants to move a cursor to indicate the boundary between the covered and uncovered layers within their field of view. By doing so, we were able to calculate the visual angle using trigonometry. To ensure optimal focus on the screen, we adjusted the background to a bright white color and instructed participants to concentrate solely on the screen. In cases where participants were unable to identify a distinct boundary (since the boundary is so close to the eye such that focusing is impossible) and instead observed a broad transition in opacity in the form of a strip, we instructed them to mark the leftmost section of that transition strip (in other words, where the visual field becomes consistently darker). Note that with this procedure the simulated optical combiner starts affecting the user's visual field slightly to the right of the angle reported (i.e., if the boundary is reported at -15 degrees, the user probably starts noticing the change at -13 degrees). We then repeat this calibration process and note the angles perceived by each participant for each of the models we created. From the seven models we created, we pick the six models which have a perceived scope of angles more aligned to the range 0° to -30° (either model 1 - 6 with corresponding modeled angle from 0° to -25° or model 2 - 7 with corresponding modeled angle from -5° to -30°). We then give the six models to the participants following a sequence assigned by a balanced 6x6 Latin Square [15], which offsets the carryover order effects.

One unexpected thing from the participants was that the majority of them found it difficult to see the border between the area covered by the laminated film and the area of plain glasses. 7 out of 12 participants commented on the border between the areas with "hard to see," "extremely blurry," and "moves as I try to figure out its position." In response to this issue, we analyzed the results with both the perceived angles (the angles that participants reported during the calibration process) and the calculated angles (the angles that participants should perceive given their IPDs and an assumed average vertex distance of 13mm [4, 31]).

3.3 Controlling Head Movement

To let the participants maintain a perpendicular head position relative to the VDT during the calibration process, we implemented a technique inspired by Haynes and Starner [17, 18]. As shown in Figure 3, the participant placed their head on a chin rest and wore a headband equipped with a laser pointer that was directed toward a 1-inch circle positioned approximately 0.75 meters away, which allows up to ±0.42° of head rotation. By utilizing a microcontroller and a photoresistor, we were able to deactivate the cursor when the laser pointer was not aligned with the circle. The chin rest is positioned with an offset of 31.5mm from the center according to the 63mm averaged adult IPD [12], which makes the participant's center of right eye facing the center of the VDT. Additionally, we had calibrated the laser using a Microsoft XBox's "Kinect for Windows v2" to initially verify that the participant's head is perfectly straight, with no tilt (0° roll) or rotation (0° yaw).

Figure 3: Calibration (left) and experimental condition (right)

3.4 Experiment

After the calibration process, participants take off all the equipment used in the calibration process, and the VDT starts to present interactive art exhibits sourced from the National Gallery of Art [26]. Participants were able to zoom and navigate the exhibits to explore them in great detail, accompanied by a background narration (Figure 3). We prepared a list of 11 artworks with narration recordings, each of which lasted between 1 and 3 minutes. Upon completion of each artwork's exhibition, participants would exit the current exhibition page, and researchers would proceed with the next exhibition page for them, along with its corresponding narration.

Participants begin viewing the exhibition wearing the first pair of glasses given to them. Every 2.5 minutes from the beginning of the exhibition, the researchers prompt them to rate their comfort level on a rotatory selector which corresponds to a Likert scale ranging from 1 to 7, with 7 indicating the highest level of comfort, 1 indicating the lowest, and 4 representing a neutral state. They were asked the question "How comfortable do you feel while wearing this pair of glasses in the art exhibition we provide?" Subsequently, participants were provided with a new pair of glasses, and this process was repeated for all eight pairs of glasses, regardless of the time spent on individual art exhibitions. Each timer of 2.5 minutes

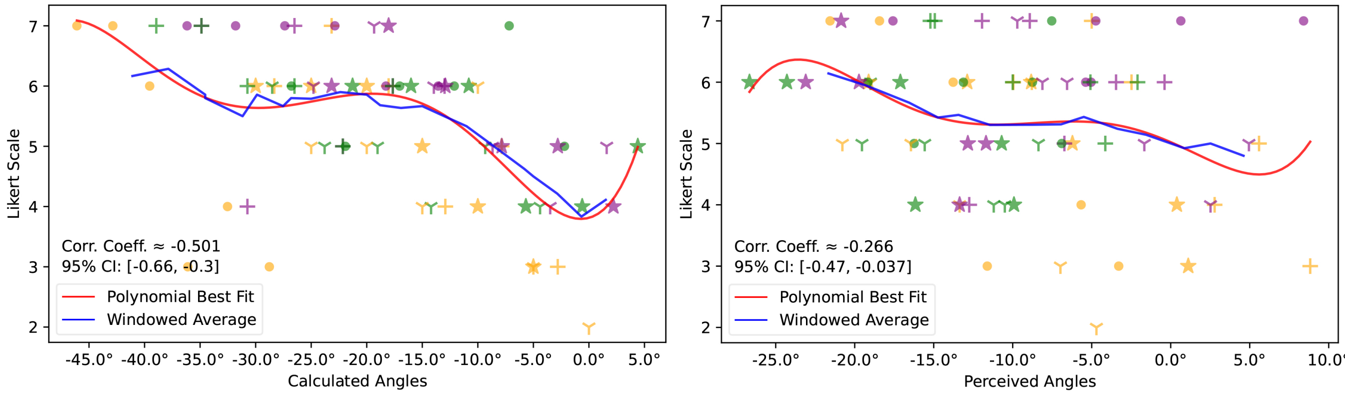


Figure 4: Calculated (left) and perceived (right) angles of the simulated display optics border vs. Likert ratings (12 participants x 6 ratings). Participants are differentiated by combinations of marker color and style.

only continues when the participants gain cursor control, which is after giving comfort ratings and excludes the time during exhibition switches. In total, the participants try seven pairs of glasses, including the selected six modeled pairs of glasses followed by one control pair. We always let the participants try the control pair last. The 11 exhibitions are guaranteed to last longer than the experiment would actually require.

4 RESULTS

Given that every participant gave the top rating of 7 when given the control pair of glasses, the ratings on the other pairs of glasses can be directly compared. In addition, since the majority of participants (7 out of 12) found it hard to determine the border between the two areas on the glass, we analyze the data using both the perceived angle and the calculated angle, as stated previously.

We plot graphs comparing angle and comfort scores with best-fit polynomial curves and windowed average lines, for both the calculated angles and the perceived angles (Figure 4). Both of the graphs use a polynomial fit of degree 5, where the residual errors start to converge. The windowed average curves are also shown. When we utilized the calculated angles, the data yields a moderate negative correlation ($r \approx -0.501$), where r is the Pearson's correlation coefficient [32], and a 95% confidence interval of $[-0.66, -0.3]$. On the other hand, data with the perceived angles yields a weak negative correlation ($r \approx -0.266$) and a 95% confidence interval of $[-0.47, -0.037]$. Both sets of data yield a negative correlation supported by the confidence intervals, confirming that as the film approaches the PPOG it negatively impacts participants' comfort.

5 DISCUSSION

Both studies suggest that having the optical combiner near the PPOG should be avoided. Looking at the graph with the perceived angles, we see that angles farther than -15° (towards the nose) receive mostly positive scores (4 being neutral). The same can be seen with the calculated angles. Due to physiological factors like pupil size, the edge of the optical combiner may still be perceptible closer to the PPOG, but -15° seems to be a good limit for display manufacturers to avoid encroaching on the PPOG. If one were to make a HWD with a virtual image the size of a standard smartphone (9.2° by 16.3°) [18], the horizontal extent would be to -24.2°. Haynes [18] studied reading on HWDs offset towards the ear and found a region between 5° and 25° where text could be read comfortably. If a similar comfortable region is found for reading toward the nose, it would suggest a good location for HWD optics.

Depending on the graph, the next distinct step in comfort seems to be either -21° or -35° depending on the graph. In either case, the resulting display would extend beyond -30° (towards the nose). While Haynes's reading experiments only examined offsets towards the ear, his results suggest that this amount of offset from PPOG would be unacceptable for many initial users. Similarly, it is unlikely that this amount of offset would be acceptable towards the nose.

6 FUTURE WORK

Our second study has only 12 participants and focuses exclusively on positioning model VII, resulting in a limited testing scope. Increasing the number of participants, the models considered, and the tasks would produce a more holistic view. Of particular interest is exploring placing an optical combiner more towards the ear, which previous work suggests may be well tolerated during use [17]. In addition, as the majority of participants had difficulty identifying the border position between the area covered by the laminated films and the plain glasses, it is preferred for future studies to use darker films to make the difference more evident during calibration and switch back to the more transparent film during the art exhibition. Furthermore, the current study only investigates displays with offsets towards the nose and only for a stationary task without much eye motion. Future work should also investigate offsets towards the ear with more complex, longer, mobile tasks. Increasing the complexity of tasks may also help reveal higher contrast in participants' comfort under different modeled conditions.

7 CONCLUSION

Our first study (and the literature) suggests that user comfort can be improved by avoiding the user's PPOG. Comfort may also be improved by keeping display optics boundaries simple to avoid unnecessary edges. The second study suggests that the nearest optical boundary to the PPOG should be placed with a more than -15° offset from PPOG (towards the nose).

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