Positioning Glass: Investigating Display Positions of Monocular Optical See-Through Head-Mounted Display

Soon Hau Chua[1], Simon T. Perrault[1,2], Denys J.C. Matthies[1,3], Shengdong Zhao[1]
[1]NUS-HCI Lab, National University of Singapore, Singapore
[2]Yale-NUS College, Singapore
[3]Fraunhofer IGD Rostock, Germany
chuasoonhau@u.nus.edu, simon.perrault@yale-nus.edu.sg, denys.matthies@igd-r.fraunhofer.de,
zhaosd@comp.nus.edu.sg

ABSTRACT

The physical position of the display on a monocular OST-HMD in relative to our eye is an important factor of the performance and usability in dual-task scenarios. We investigated 9 different display positions in a modern dual-task scenario with 27 participants. The experiment-involved participants responding to 3 different types of notifications displayed on the HMD while performing a visually intensive primary task. We found that although the notifications at the middle and bottom center positions were noticed quicker, the top and the peripheral positions were more comfortable, unobtrusive, and preferred. In particular, middle-right strikes the best balance between performance and usability in the dual-task scenario we studied. Our findings and discussions demonstrated the need for further work and a more rigorous investigation in dual-task scenarios with characteristics dissimilar to ours.

AUTHOR KEYWORDS

Monocular Optical See-through Head-Mounted Display, Design Guidelines, User Interface, Display Position.

ACM Classification Keywords

H.5.2 [Information interfaces and presentation (e.g., HCI)]: User Interfaces-Input devices, strategies, Interaction styles.

INTRODUCTION

Monocular optical see-through head-mounted displays (OST-HMD) comprise of a see-through display positioned in front of one eye. One example in the market recently is the Google Glass. Also known as peripheral HMD [11], they are particularly useful in providing additional information secondary to the primary task at hand. In mobile scenarios, it is critical that the information on the HMD is easily noticeable without causing too much distraction to the users. Such noticeability-distraction trade-

off is an important issue in notification system design [12], and display position relative to the user's eye is an important human factor since different display positions necessitate different eye movements that are controlled and influenced by different eye motor and human habits (Figure 1) [2].

Figure 1. We investigated nine display positions on a monocular OST-HMD. The red rectangle on the diagrams located at the top left corner of each image indicates the display position from users' point of view.

In this paper, we study how different display positions of a monocular OST-HMD affect the performance (*noticeability*) and usability (*distraction*, *comfort*) of the primary and secondary task in a dual-task scenario. While previous studies used object tracking as the primary task [9], we used simulated driving as 1) it has similar characteristics to a decent number of mobile use-cases, 2) it can be conducted in a laboratory controlled setting, 3) it uses the same processing structures (visual attention) as a dual-task paradigm with high attention load, making it an often-used primary task in HCI research [15]. Based on our knowledge, our study is the first to investigate this problem in the modern setting. However, our results should not be interpreted as indications of how the display positions would affect driving performance or safety in real life. Our experiment with 27 participants quantified the performance differences between 9 different display positions and showed that milliseconds differences could be crucial for high vigilance tasks. At the same time, usability and task characteristics can influence users' overall preferences. We

discussed this trade-off through the lenses of our qualitative findings and suggested that the middle-right position strikes the best balance for use-cases with characteristics similar to simulated driving. As the trade-offs for different dual-task scenarios are different yet important, we suggested future work to study scenarios with different task characteristics.

RELATED WORK

While there are more research on monocular OST-HMD recently due to the popularity of Google Glass (e.g., on Parkinson [13], colorblind [19], learning and disabilities [1,4,6,10,18]), few studied the effect of display positions on the performance and usability in dual-task scenario. One such research studied the effect of display position on an object tracking primary task while tracking a horizontally moving object within two vertical lines on a miniature cathode ray tube (CRT) display [9]. They found that tracking performances on both primary and secondary tasks decrease as the CRT's azimuth (horizontal) and elevation (vertical) angle increases, and looking upward is slower than downward. This is contrary to the default display position of Google Glass (Figure 2a), and it raises the question of whether it is optimal for processing secondary info while engaging in a primary task.
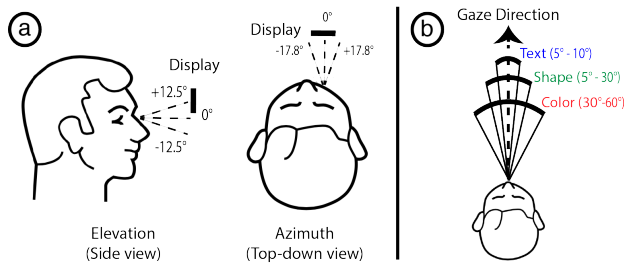

Figure 2. (a) Illustration of the three elevation and azimuth angles on one eye. (b) Perceivable visual angles for color, shapes, and text (data derived from [8]).

While their findings were useful, their present-day applicability is limited (the study was done in year 1989) as their experiment setup did not reflect the characteristics of most modern mobile use-cases. Moreover, the study did not investigate usability aspects of the display positions extensively. A few more recent studies have looked into display-related issues of OST-HMD, but none of them were studying the positions of the display in relative to our eye with different types of visual stimuli [7,14]. Therefore, we believed a renew study is necessary and timely. In this paper, we conducted a user study with three major adjustments: (1) we replaced CRT with a monocular OST-HMD (2) we chose simulated driving and reacting to mobile notifications as the primary and secondary tasks as both tasks are more modern and reflective of mobile use-cases; (3) we studied azimuth angles in both directions (left and right) from the center while previous study only investigated azimuth to the right.

EXPERIMENTAL DESIGN

Participants

Twenty-seven participants (11 females) aged 20-27 (M=23.4) were recruited from host institution. All participants had at least one year of driving experience and normal or corrected to normal eyesight. Sixteen of them were right-eye dominant (Miles Test), and none had used monocular OST-HMD before the study.

Apparatus and Software

We used Google Glass (Explorer Edition 2.0) as the monocular OST-HMD since it is one of the few with a monocular form factor in the market. The experiment software was developed in Java with the Glass SDK to present stimuli and collect data. For the simulated driving primary task, we used a customized version of OpenDS, a reliable and easy to use open source driving simulator used by a number of HCI researchers [4]. Both the experiment software and driving simulator were run on a Windows-based PC (Intel Core i7 3.4GHz) with a 23-inch LCD monitor that provides ~62° horizontal viewing angle from 50cm away. A Thrustmaster Ferrari GT Experience Racing Wheel was used to operate the driving simulator (Figure 3).

Figure 3. Physical setup – the participant's eye is fixed 50 cm away from the screen, providing a ~62° horizontal viewing angle. Driving simulator is controlled with a racing wheel.

Display Positions and Calibrations

We investigated 3 elevation (+12.5°, 0°, -12.5°) and 3 azimuth angles (-17.28°, 0°, +17.28°) to generate 9 display positions (see Figure 1 and 2a). The display was placed in front of the right eye. The maximum elevation (~12.5°) were chosen based on Google Glass's default angle of elevation above a user's straightforward line-of-sight, whereas the azimuth (~17.28°) were chosen based on the maximum outward angle that the display hinge can afford. The angles we studied are similar to previous work [9]. The upward and downward elevation and leftward and rightward azimuths were kept identical to ensure that the velocity and angular distance for each vertical and horizontal saccades were roughly the same [2].

The depth of view between the primary and secondary display was also kept consistent in the experiment. The monitor presenting the primary task was positioned 50cm away from the users to achieve a depth of view of 1/0.5m =

Display Positions	Reaction Time (s)				Comfort Score (1: not comfortable at all, 7: very comfortable)	Preference Score (1: not preferred at all, 7: most preferred)
	Color	App	Text	Overall		
Bottom Left	1.14	1.46	2.06	1.54	3.44*	3.26‡,†
Middle Left	1.13	1.51	1.89	1.51	4.19	4.00
Top Left	1.15	1.49	2.29*	1.64*	3.67‡	3.48*
Bottom Center	1.14	1.35	1.76	1.41	4.19	4.30
Middle Center	1.12	1.21*‡	1.63*	1.32*‡,†	4.63	4.37
Top Center	1.11	1.58‡	2.00	1.56‡	4.70	4.67‡
Bottom Right	1.16	1.61	1.90	1.55	4.19	4.07
Middle Right	1.06	1.49	2.02	1.52	5.07*‡	5.00*,†
Top Right	1.13	1.64*	1.90	1.55†	4.67	4.44

Table 1. Results for reaction time (s) and mean score for comfort and preference in 7-pt Likert Scale. * ‡ † represent significant post-hoc tests (*p* < .05).

2 dioptries (DPT), while the Google Glass has a depth of view of $1/2.4m = 0.416$ DPT [20]. In our setup, the depth of views between the primary and secondary display exceeds the limit of human eye's depth of view (approximately ± 0.3 DPT). Therefore, a switch of focus is required when subjects shift their attention from the primary to the secondary task, mimicking most real world scenarios where two stimuli of interest are not in focus at the same time [3].To ensure HMD's display positions were consistent across participants, we performed a calibration procedure with the participants before they started each block. First, we positioned the participants 50cm away from the monitor and affixed their eye-level to the center of the monitor by adjusting their chair height. A red dot was drawn at the monitor's center as the reference point. Then, 9 red dots were shown on the monitor. Each dot represents the center of the HMD's display at the 9 positions we studied, and they were pre-drawn to the correct elevation and azimuth angles 50cm away from the monitor. Participants were then told to adjust the display position by aligning the respective red dot to the center of their HMD's display while looking straight. The adjustments were achieved by tilting Google Glass's display hinge horizontally (for azimuth angles) and its frame vertically (for elevation angles). After ensuring the red dot was aligned and the four edges of HMD's display were visible and not clipped, we stabilized and affixed the frame adjustments with an elastic headband to finalize the calibration.

Tasks and Stimuli

Since monocular OST-HMDs are used in mobile scenarios, we designed a lab-based dual-task experiment that mimics such scenarios, with simulated driving as the primary task and notification responding as the secondary task. We chose simulated driving as the primary task as it demands high visual and attention resources, according to previous work [17]. However, we do not claim that our findings can be applied directly to or reflective of real life driving. In the driving task, participants drove on a three-lane road consisting of straight paths and curve turns, and they were instructed to keep their car in the center lane as much as possible. At the same time, they were told to pay attention to incoming notifications on the HMD and to respond as fast as possible. To response, participants were told to

memorize the information and then pressed the gear shoulder button behind the steering wheel. This paused the simulator and removed the notifications from the HMD, and a post-trial multiple-choice test was given to ask participants to indicate the information they saw (Figure 4).

The type of multiple-choice questions was different based on the notification types. For color notifications, participants were asked to identify the color they saw from a set of 6 colors. For applications, participants responded by selecting the icon that appeared from a set of 6 and identifying the number (randomly assigned between 1 and 12) that was displayed in the upper right hand corner of the icon. For text, participants were asked to indicate either the information or number they saw. The texts were generated from 6 stubs, each with 6 substrings and a number between 1 and 12. The simulator resumed after recording the response and a minimum of 10 seconds was given to the participants to correct their steering to a normal driving state before the next trial began. To balance the difficulty of the primary and secondary task, the notifications were designed to appear just before their car reach the curvy turns. The appearance is randomized so the participants did not know on which turns the notification would appear.

Figure 4. Three types of notifications evaluated: (i) color (ii) application icon with a number and (iii) text.

We designed three types of notifications: color, application, and text (Figure 4), and each represents visual elements with different perceivable visual angles (Figure 2b) and information complexity [8]. We measured the lateral deviation from the lane center to determine how the display positions affected the primary task. For the secondary task, we measured their reaction time and error rate in responding to the notifications correctly.

The experiment was a 9×3 within-subject design with two independent variables: display positions (9 positions) and notification types (color, app, text). Sequence of the

	App Reaction Time (s)			Text Reaction Time (s)			Comfort (1-7 ratings)			Preference (1-7 ratings)		
	Left	*Center*	*Right*	*Left*	*Center*	*Right*	*Left*	*Center*	*Right*	*Left*	*Center*	*Right*
Top	1.49	1.58	1.64	2.29	2	1.9	3.67	4.7	4.67	3.48	4.67	4.44
Middle	1.51	1.21	1.49	1.89	1.63	2.02	4.19	4.63	5.07	4	4.37	5
Bottom	1.46	1.35	1.61	2.06	1.76	1.9	3.44	4.19	4.19	3.26	4.3	4.07

Table 2. Summary of quantitative and qualitative results in the study. Columns are coded using green, yellow, and red color scheme to indicate their ranking from best to worst for each metrics.

position was counter-balanced using Latin Square while the appearance sequences of the notifications were randomized within each block. A short practice was given before the actual study. The actual study consisted of 9 blocks (9 positions), and each block consisted of 9 trials with 3 repetitions for each of the 3 notification types. Display position calibration was conducted before each block. After each block, participants evaluated the comfort level and preference of the position on a 7-point Likert scale. After the study, we conducted interviews to get their overall evaluation. In total, there were: 27 participants × 9 display positions × 3 notification types × 3 repetitions = 2187 trials.

RESULTS
For reaction time, error rate, and lane deviation, we ran two-way repeated measures ANOVAs on both factors for general statistical test and pairwise t-tests with Bonferroni correction for post-hoc analysis. For comfort level and preference, we ran Friedman tests and pairwise Wilcoxon signed-rank tests with Bonferroni correction for post-hoc analysis. Detailed data from our study is shown in Table 1. As there is a lack of evidences on eye dominance leading to better visual acuity [16], we did not compare the results of participants with different dominant eye in our study.

Reaction Time (RT)
Display position has a significant main effect on RT ($F_{8,208}$=2.42, $p<.05$). While the average RT in responding to notifications was quick (<2.5s), some positions were faster than others (Table 1). Post-hoc analysis revealed that middle center (M=1.32s) was significantly faster than top center (M=1.56s, $p<.05$) and top left (M=1.64s, $p<.05$).

Notification type has a significant main effect on RT ($F_{2,52}$=79.8, $p<.001$) as well. Post-hoc analysis revealed significant differences between all 3 types (all $p<.001$), with color (M=1.12s) being faster than app (M=1.48s) and text (M=1.94s) (Table 1). This is consistent with prior findings on the perceivable angle of different visual stimuli [8].

We also found a significant interaction between display position and notification type ($F_{16,416}$=2.41, $p<.05$). While display position did not have an effect on color, it was significant for app ($F_{8,208}$=2.76, $p<.05$) and text ($F_{8,208}$=3.09, $p<.05$). Post-hoc analysis revealed significant differences (all $p<.05$) between middle center (M=1.62s) and top left (M=2.29s) for text; and between middle center (1.21s) and both top center (M=1.58s) and top right (M=1.63s) for app.

Error Rate (ER) and Lane Deviation (LD)
Overall, participants were able to perceive notifications accurately (M=97%). ANOVA revealed a strong main effect of notification type on ER ($F_{2,52}$=10.97, $p<.001$). Post-hoc analysis suggested that color notifications (M=99.5%) have a significantly lower ER than app (M=95.5%, $p<.01$) and text (M=96.2%, $p<.01$). Meanwhile, LD was affected only by notification type ($F_{2,52}$=11.27, $p<.001$). Post-hoc analysis revealed significant differences between each notification type (all $p<.05$), with a lower LD on color (M=2.4 meters) than on app (M=2.6m) and text (M=3m). We did not find significant effect of display positions on ER and LD.

Comfort Level, Preference, and Ranking
While noticeability of the display positions was revealed mostly in the quantitative data (RT), the qualitative results elucidated the distraction and comfort level as well as how participants weighted this trade-off with noticeability. We found a significant difference in subjective comfort level depending on display positions ($χ^2(8)$=25.96, p=.001). Post-hoc analysis revealed that middle right was deemed more comfortable than both bottom left and top left (all $p<.05$, Table 1). Subjective preference scores were also affected by the display position ($χ^2(8)$=29.08, $p<.001$). Post-hoc analysis indicated that middle right was significantly preferred over bottom left ($p<.01$) and top left ($p<.05$), while top-center was preferred over bottom left ($p<.05$).
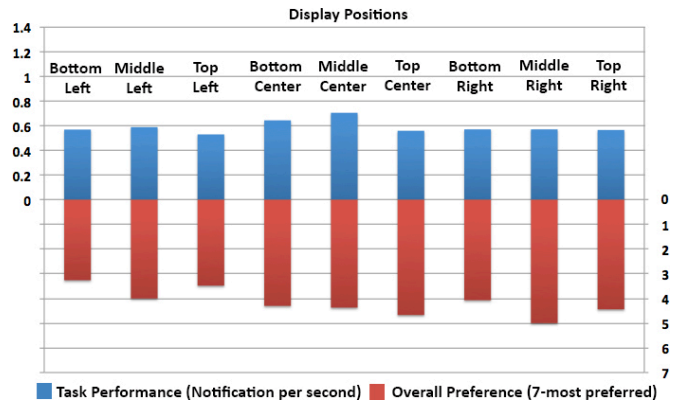

Figure 5. The tradeoffs between task performance (in notifications per second, blue bars) and overall preferences (in 7-point Likert scale, red bars) for each display position. When considering both time efficiency and user preferences, middle center and middle right positions have the best-combined scores, as shown by the longer bars.
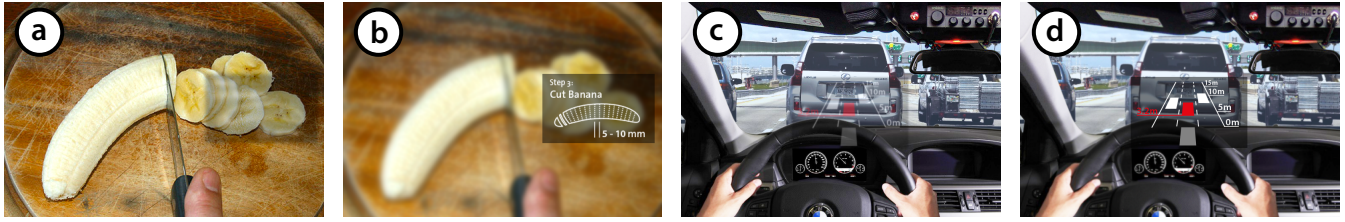
Figure 6. Illustrations of the cooking scenario (a and b) and the traffic police pursue scenario (c and d) from the first person point of view. (a,b) In the cooking scenario, putting the display in the middle-right allows the user to see the knife clearly while receiving cooking instructions on the HMD. (c,d) In the traffic police pursue scenario, putting the display in the middle-center allows the police to track the position of the pursuit vehicle on the HMD without turning the gaze away from the road. The scenarios demonstrate that task requirement is an important factor of the ideal display positions for a specific task.

DISCUSSION AND SUGGESTIONS FOR FUTURE WORK

Our findings have highlighted important differences between different display positions in a dual-task scenario from the performance and usability perspective. A summary of our results and the overall ranking of the display positions are shown in Table 2 and Figure 5.

RT wise, it was not surprising that middle-center position is the fastest in overall, and its difference with the slowest (top-left) position is 320 milliseconds (24.2%) in our study. This gap was higher for more demanding tasks such as reading text-based notifications (660ms, 40.5% difference with top-left, see Table 2). While this difference may seem small, it is significant in the context of tasks that require frequent or rapid eye movement, such as police pursue (see Figure 6c and 6d for details). Therefore, our study has showcased the need to investigate this further in other scenarios in a more rigorous manner in the future.

We also found that the average RT for bottom positions were slightly faster, but not significantly, than the top for app and text, which is consistent with previous finding [9] and research in upward and downward saccadic velocity [2]. This slight difference can possibly be explained by the fact that most people are more accustomed to looking straight/down than looking up for most of the time [5], as most tasks in daily life, such as walking on the street, involve looking downwards or straight ahead, whereas tasks that involve looking upwards is usually less frequent, such as looking at the clock.

On the other hand, our study has also uncovered the need to balance performances with usability measures. In terms of perceived comfort and overall preferences, our data showed that middle-right position is the best, followed by top-center and top-right (Table 2). Middle-center, while being the fastest, is not the most comfortable and preferred, as some participants found middle center and all the bottom positions to be too distracting to the primary task. According to post-study interviews, this distraction is caused by the overlays of the HMD's images onto the road ahead. The middle-right and the top positions did not have this problem. Participants also commented that their preferences could be different in other scenarios such as reading, where lower region of their vision is not occupied and not as pivotal as driving. Hence, while our study has

revealed users' preferences in dual-task scenarios with task characteristics similar to simulated driving (such as walking, cycling, etc.), more future work is needed in other dual-task scenarios with different task characteristics.

LIMITATIONS

There are several limitations in the scope of our study. First, our results and recommendations could be different in dual-task scenarios where the primary and secondary stimuli are within the focal distance, in which a switch in focus is not necessary to transition between the stimuli. This should be studied in future work. Second, apart from not overgeneralizing our findings to dual-task scenarios with different task characteristics, we also advised against overgeneralizing our findings to other classes of OST-HMD, such as binocular OST-HMD like Optivent ORA or Epson Moverio, since the underlying mechanism and form factor are different.

CONCLUSION AND DESIGN RECOMMENDATIONS

We investigated 9 displays positions of a monocular OST-HMD and how they affect the performance and usability in a modern dual-task scenario. We supported our investigation with quantitative and qualitative data in a well-controlled laboratory study. We found that even though the middle-center position was the most noticeable, participants most preferred middle-right as it does not occlude and distract the primary task in our experiment. As the characteristics of the primary and secondary task can influence the ideal positions, we suggest future work to investigate this problem in other dual-task scenarios. We plan to carry out some of these studies as future work.

Based on our findings, we made the following recommendations on the display positions of monocular OST-HMD. Middle-right, top-center, and top-right are suitable for dual-task scenarios 1) where the HMD has to be used for an extended period of time, 2) when the center of vision is important for the primary task, and 3) while the secondary stimuli is less urgent and important, such as the cooking scenario shown in Figure 6a and 6b. On the other hand, middle-center and bottom-center positions are suitable for dual task scenarios that require high noticeability on the secondary stimuli, such as the police pursue scenario illustrated in Figure 6c and 6d.

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