Stepping into AR: Exploring Optimal Positioning for Monocular Head-Worn Displays for Reading on the Go

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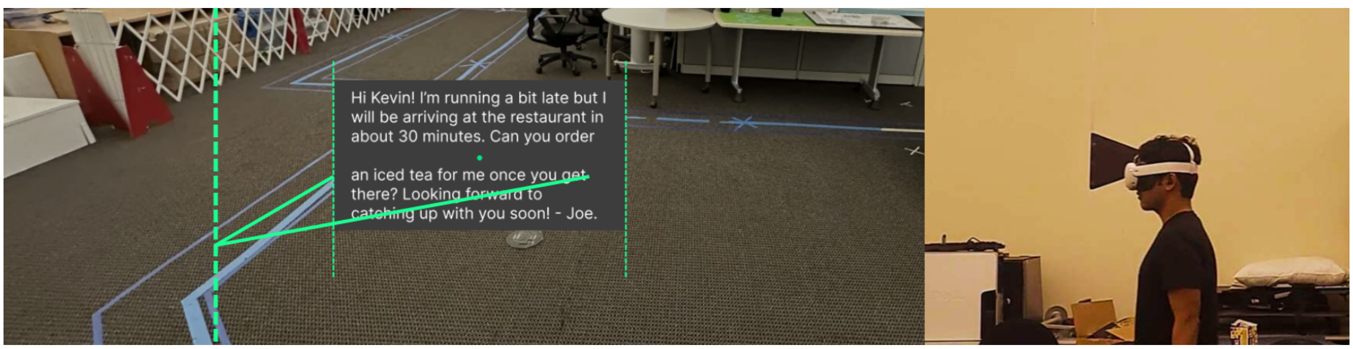

Figure 1: Emulation of a text message message in user's field of view offset from center (left) while walking (right)

ABSTRACT

Head-worn displays (HWDs), like the Vuzix Z100 and North's Focals, are designed to be worn all day as smart eyeglasses while performing everyday tasks. These products aim to display information in our field of view (FOV), enabling multitasking during daily activities. We conducted a study using the Quest 3, a high resolution color video pass-through virtual reality (VR) headset, to emulate everyday augmented reality glasses. Users walked on a predefined track while reading a message to explore the optimal display positioning for HWDs while walking. The use of HWDs was found to decrease walking speed, with display positions closer to the nose (between -24° and 0°) yielding better performance. Our results and observations indicate that closer-to-nose positioning reduces cognitive load and excessive head or eye movements, enhancing overall dual task performance.

CCS CONCEPTS

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

KEYWORDS

Head-worn Display, Glasses, Augmented Reality, Human Factors of Wearables

ACM Reference Format:
Priyanka Mosur, Ethan Kimmel, Parth Arora, Rajandeep Singh, Atharva Rajesh Madiwale, Jenna Kang, and Thad Starner. 2018. Stepping into AR: Exploring Optimal Positioning for Monocular Head-Worn Displays for Reading on the Go. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation emai (Conference acronym 'XX)*. ACM, New York, NY, USA, 7 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

In recent years, head-worn displays (HWDs) with augmented reality (AR) have gained more popularity within the technological

Conference acronym 'XX, June 03–05, 2018, Woodstock, NY

ACM ISBN 978-1-4503-XXXX-X/18/06
https://doi.org/XXXXXXX.XXXXXXX

market [19]. HWDs are wearable virtual displays integrated into eyeglasses or head mounts intended to present data within the user's visual field [19]. Presented through monocular or binocular vision, HWDs can display diverse information, ranging from video footage to text notifications [3, 20]. Some examples include the Magic Leap and the Hololens [22]. With the increase in consumption of HWDs, this growth initiates the exploration of the use of HWDs while performing daily routine activities [1].

Everyday use of HWDs requires that the optimal position of the virtual display be located in an area of the visual field which maintains situational awareness, or the ability to understand and adapt to a changing environment [27]. In this context, when performing activities in an urban environment, such as driving or walking, the placement of the virtual display should not interfere with the activity while also conveying the desired information [16, 20, 28]. Over the years, numerous studies have been conducted to determine the optimal positioning of information for the visual displays; from these studies, it is generally recommended that routine information be displayed away from the Primary Point of Gaze (PPOG) [30, 31]. Although these studies differ in the placement of the location of the display, these studies generally emphasize the importance of placing information away from the PPOG to increase situational awareness and decrease cognitive load [7, 10, 19].

In the aviation and maritime navigation sector, researchers found that while placing displays at the PPOG can provide quick access to critical flight and maritime information, it also increases cognitive load [2, 27, 29, 34]. In particularly high-stress environments, it is essential that pilots and maritime navigators can process the required information simultaneously. Therefore, the studies concluded that by offsetting the display location slightly from the PPOG, there is less cognitive load on the navigators and will improve overall task performance [2, 27, 29]. With regards to more common routine activities, like walking or driving, similar trends appear. In the automotive sector, studies by Fukano et al. [11] and Watanabe et al. [35] show that information, such as speedometer readings and navigation prompts, should be conveyed to the user where the display is positioned away from the PPOG. Placing the data directly in the line of sight of the user can distract drivers from the road, leading to a concern for safety [5, 16, 18, 23, 24]. As driving requires frequent changes in focus and attention as well, users benefit from having critical information slightly offset [6]. In another study where users were required to read and understand directions while walking around a track with obstacles, users were unable to properly avoid the obstacles, signifying the lack of situational awareness present [10, 20, 28]. All these studies emphasize the importance of the placement of the display for overall safety, and they involve a careful balance where essential data is readily available but with a slight offset from the PPOG in an effort to increase situational awareness and decrease cognitive load during everyday activities [27].

Studies on personal HWDs have also explored the optimal display positions for active displays. Katsuyama et al. [17] and Haynes [14] have shown that while it is essential to keep critical information within easy view, slightly offsetting the display from the PPOG can improve comfort and reduce strain. Similarly, during order picking, workers need to constantly shift their attention between the display and physical items, and an offset display helps in seamlessly integrating this multitasking without causing excessive strain [19, 22, 37]. These findings are particularly important for devices that are used for extended periods, where ergonomic considerations become critical for user comfort. In another study by Haynes and Starner [15, 21], they studied the comfort levels of reading captions for Deaf and Hard-of-Hearing (DHH) users when the active display is positioned at various horizontal offsets from the PPOG. Their findings indicated that displays with a horizontal field of view of 9.2° centered at 0°, 10°, and 20° from the PPOG were comfortable for users [15]. This configuration allows users to read captions without significant head or eye movement, enhancing the overall usability of the device.

In summary, the optimal positioning of see-through displays ultimately affects the safety and comfort of HWDs on the user in everyday routine activities. It can generally be seen that information should be included at a slight offset from the PPOG, which increases situational awareness so users can obtain the information without losing focus from an excess cognitive load. Additionally, keeping the information at a slight offset will improve comfort by minimizing excess strain and excess unnecessary movement in order to understand the visual display. In the study presented here, inspired by Haynes and Starner [15] and Kim et al. [20], we aim to employ a similar methodology to test the optimal display location for receiving information on an HWD while completing an essential everyday task of walking; unlike previous studies, our main focus is to identify whether dual task completion of routine activities causes a notable difference from previous findings for the optimal display location.

2 METHODOLOGY

To determine the optimal display location for receiving information on an HWD while walking, we designed a study where participants walked on a narrow defined track wearing a head worn display while reading text messages [32, 33]. We aimed to evaluate how well participants could function while walking and reading text when the display is offset from the PPOG [25, 32, 33]. Based on Song et al. [31] and Haynes and Starner [15], it was suggested to place the simulated optical combiner of the head worn display between -24.6° and +19.6° where 0° is PPOG. A negative degree is indicative of the display towards the nose and a positive degree is indicative of the display towards the ear. Based on Britain et al. [4] and ongoing research currently in preparation, a 15° field-of-view (FOV) is also suggested for the reading task. Hence, to position a display between -24.6° and +19.6°, we tested 12 different display locations spanning from -24.6° to +19.6°. Specifically, we placed a display with a 15° field of view (FOV) at various positions relative to the PPOG. Table 1 displays the specific conditions tested.

The participants were tasked with reading a short paragraph shown at one of these angles while simultaneously walking along a set path at their normal walking cadence. Our main objective was to determine the most optimal display location that least affects user's primary task, in this case walking, while performing the secondary

Condition	Range (°)
1	(-30, -15)
2	(-27, -12)
3	(-24, -9)
4	(-21, -6)
5	(-18, -3)
6	(-15, 0)
7	(-7.5, 7.5)
8	(0, 15)
9	(3, 18)
10	(6, 21)
11	(9, 24)
12	(12, 27)

Table 1: Tested display positions and ranges relative to the PPOG

task of reading on the HWD. Additionally, we also wanted to identify if sudden external stimuli would affect the user's tasks. Based off of previous works and experiences through everyday usage, we aimed to simulate a distracting external stimuli in the form of a headset malfunction, where a white flashing light momentarily replaces the text box [8, 36]. The optimal location would ideally reduce any potential disturbances caused by the blinking light.

2.1 Display Location

Each individual's eye gaze is unique due to their interpupillary distance (IPD) [9]. Therefore, it was necessary to calibrate the positioning of the text box at each of the 12 positions. This calibration was achieved by using a poster with several vertical lines indicating the degree of horizontal gaze separation between angles as shown in Figure 2. Users stood at a distance of 1.5 meters from the poster. A vertical line was placed in the center of the user's field of view in the HWD. To calibrate the display location, users had to ensure that they align the virtual center line with the 0° line on the poster. Additionally, they had to ensure that the edges of the text box were at -7.5° and 7.5° to confirm the 15° FOV. We adjusted the size of text box and lateral offset remotely based on their feedback by asking them to ensure the left or right edge aligns with the desired line on the poster. To test the actual condition, the text box was offset left or right based on the required condition being tested. To randomize the order of the positions for the 12 participants, we used a 12 by 12 Latin square [12].

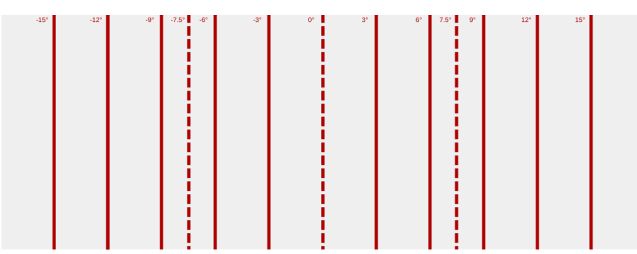

Figure 2: Calibration poster for different lateral positions

2.2 HWD Setup

To emulate this experience, we needed a see-through headset with a high FOV. We conducted pilots with the Hololens 2 and the Magic Leap 1 with limited cases and noticed significant chromatic aberration while users walked on the track, making the text unreadable. Therefore, we decided to choose the latest pass through headsets with a higher FOV for this task. Among the two primary color pass-through headsets on the market, the Meta Quest 3 and the Apple Vision Pro, we chose the Meta Quest 3 due to its reduced weight, which helped to minimize fatigue during the walking task. The display on the HWD comprised of an image with a simulated text box message and a purple virtual center line behind the text used for calibration purposes (Figure 3). To simulate a monocular display, the app was set to a multi-view rendering mode, and the HWD was set to its own layer only visible on the right eye. In this case, the left eye displayed the pass through, while the right eye displayed a heads up display imposed over the pass through. We built a pairing app to remotely control the content, scaling, and lateral positioning of the text box. Additionally, the remote app was able to trigger the white flashing light, signifying a headset malfunction.

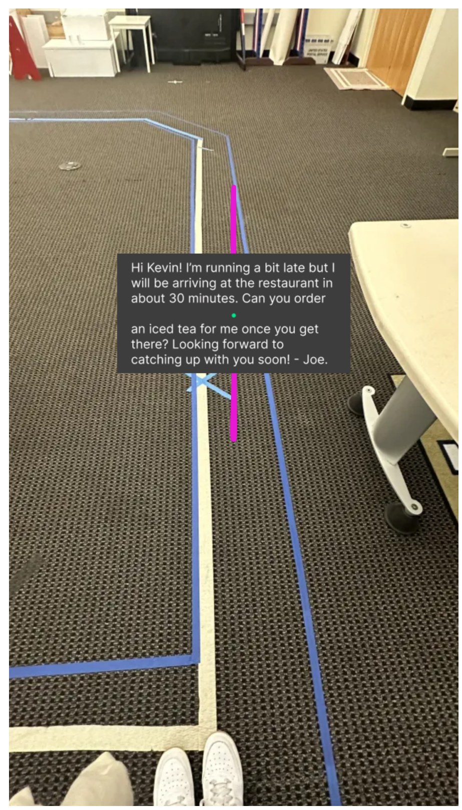

Figure 3: UI of HWD used for experiment

2.3 Walking Task Environment

During the experiment, participants were instructed to walk along a path outlined in tape, identical to the pattern depicted in Figure

4. This path was defined by two parallel lines of blue tape, which served as boundaries which participants were expected to stay inside of while walking with the HWD. Plastic pennant flags were suspended from the ceiling at regular intervals over the path to emphasize the importance of staying within the path. 12 white pieces of tape were placed on the track to create six subsections along the path, each two meters in length, which assisted with timing and triggering the simulated malfunction. One of the subsections of the actual track is shown in Figure 5.

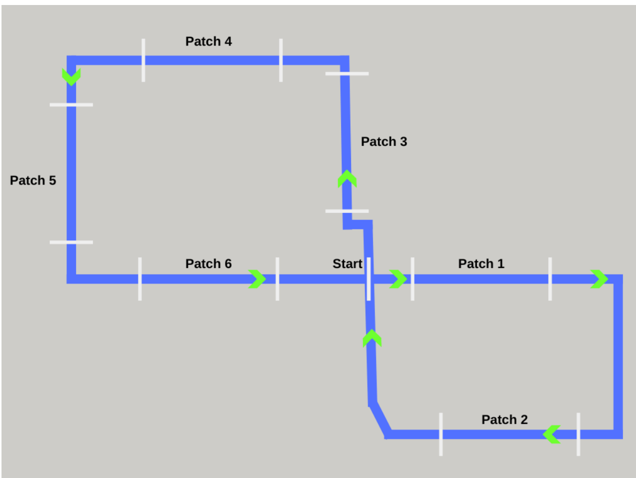

Figure 4: Track path used for study

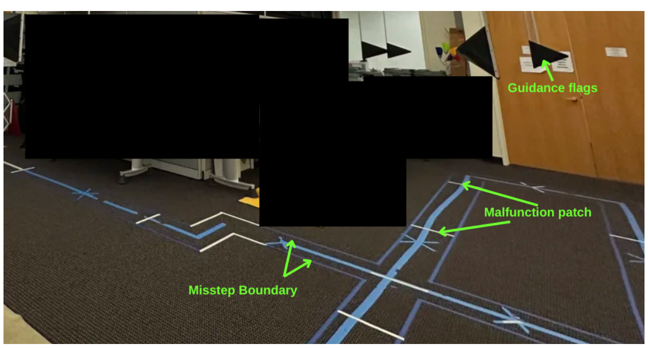

Figure 5: Section of actual walking track used for study

2.4 Procedure

The study required two researchers to be present during each trial. One instructed the participants, timed their walking speed, and assisted with calibration. The other controlled the headset during walking and calibration, as well as counted missteps for each trial. Our participants consisted of 12 Georgia Institute of Technology students aged 18-25 years old. Eight of the participants identified as male and four identified as female.

The participant was instructed to walk around the track for 1 lap without a HWD to get used to the path. We recorded the time taken to walk this lap. Next, we instructed the participants to wear the headset, walk around the track, and continually repeat the paragraph out loud until they were finished. The participant was also misled to believe that the white flashing would occur due to hardware troubles. During this preliminary trial, they were told to walk at a comfortable pace for 30 seconds, and the number of steps taken during this time was recorded. This number was used to calculate the beats per minute (BPM) of their walking pace.

For the 12 cases, participants were instructed to repeat the task but walk for 3 laps at the speed of a metronome set based on the participant's walking pace in BPM. Before each case, participants would be led to calibrate the display. The participant was reminded about staying on the path and it was specified that they were able to look down at the track, if needed. After this, the metronome was activated and a countdown from three indicated when the participant should start walking to complete the given tasks.

As mentioned before, there were six two-meter subsections scattered along the path. Out of the six subsections, two were picked randomly for each case and for each chosen subsection, one out of three laps was chosen randomly. When the participant crossed either of the two chosen patches in the specific randomly chosen lap, we triggered the flashing malfunction while they crossed the patch. The time they took to cross the patch while experiencing the malfunction was then compared to the time taken without the malfunction. For example, if the malfunction was triggered at the second patch in the third lap for a given case, the time taken for the participant to cross the second patch during the third lap would be compared to the average time taken without the external stimuli in the first and second lap for that same case.

Throughout the study, for each case, one researcher recorded the time taken per patch using a custom stopwatch for efficiency and accuracy, while the other counted missteps (defined specifically as any part of the foot exiting the outer edge of the tape) and triggered two flash events according to the Latin square. The participant was then stopped after the third lap, and the results were recorded.

The content of the text box was altered, and the participant was asked to state who the text was from, who it was addressing, and what it was about to reinforce that they should read the text with full attention. The image was then moved to the second case according to the Latin square.

This process was repeated for the rest of the 12 display locations, with a short break after the sixth trial. The participant was asked to fill out a NASA TLX after the sixth trial and after the final case. [13].

3 RESULTS

For each participant, we measured the time they took to complete the tasks without a HWD and the time they took for each of the 12 cases with an HWD, as shown in Figure 6. We normalized the time for each participant using min-max normalization [26]. For the conditions, we created a bar chart comparing the normalized mean time taken for each case and a whisker plot comparing the median time taken for each case to understand the variance across participants. Figure 7 depicts the bar chart and Figure 8 depicts the whisker plot. We also calculated the mean time taken for each participant across cases and subtracted the time it took for them without a headset. On average, it took participants 26.67 seconds extra or 18.15% more time to perform the task with the headset.

Participant ID	1	2	3	4	5	6	7	8	9	10	11	12
Without HWD	102	78	84	72	87	64	56	67	64	69	66	93
(-30,-15)	158	185	88	98	100	103	83	110	93	74	90	108
(-27,-12)	147	176	92	99	90	96	63	88	92	73	90	110
(-24,-9)	148	178	90	99	88	95	62	86	91	74	89	103
(-21,-6)	133	195	97	93	93	101	62	89	95	75	90	102
(-18,-3)	144	168	85	103	89	91	63	92	90	74	90	106
(-15,0)	156	173	87	96	90	92	64	90	95	74	87	107
(-7.5, 7.5)	146	191	88	93	90	94	61	88	94	78	92	105
(0, 15)	157	170	88	97	99	92	64	90	88	76	89	109
(3, 18)	117	192	90	96	91	92	63	92	101	78	93	100
(6, 21)	150	175	90	99	88	94	62	87	97	73	91	112
(9, 24)	163	180	87	97	95	90	64	92	103	82	90	104
(12, 27)	150	195	93	93	88	89	61	91	97	74	91	104

Figure 6: Time taken by each participant (in seconds) for each case

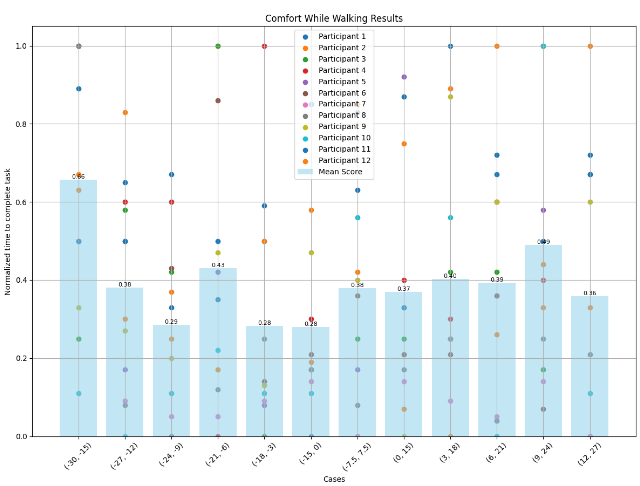

Figure 7: Comparison of mean time taken by participants across 12 cases

In addition, as described in the methodology, we measured the extra time it took for each of the participants during the simulated external stimuli. Throughout the three laps for each case, we marked the two out of six unique spots where a malfunction was triggered. We then took the average time it took participants to cross those two spots in the two laps they did not experience a flashing light (4 cases) and the average of the two times they crossed the patch when they did experience the flashing light (2 cases). We then subtracted the average time to cross without the stimuli from the time with the stimuli to observe the extra time it took the participant to cross the subsection for that particular case. Unfortunately, this data did

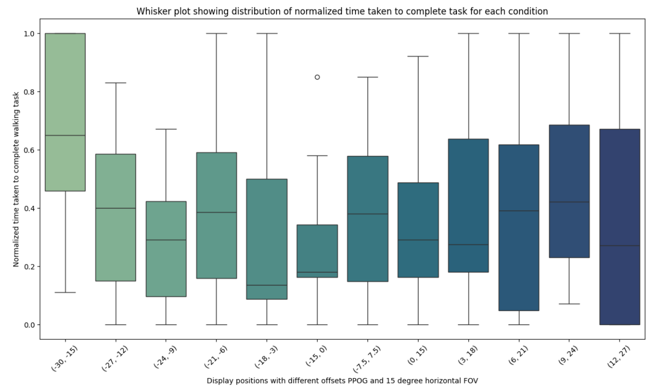

Figure 8: Whisker plot of time taken by participants across 12 cases

not show any trend, and it was also observed during the study that the pace of participants did not change at all when the malfunction occurred in any condition. All the extra time differences were less than 1 second, and for 65.27% of cases, no or negative extra time was observed.

We noted the missteps for each participant for each case. We expected significant missteps throughout the study as well, but we noted that most participants were able to walk within the path without having many missteps, with an average number of missteps for 12 participants across 12 cases being only 9.02 in the three-lap course.

Additionally, we measured the workload of participants using NASA TLX [13] to evaluate fatigue after the first 6 cases and then after 12 cases as shown in Figure 9. There was no identifiable effect from the workload on the different conditions.

3.1 Discussion

This study aimed to determine the optimal display location for receiving information on a head-worn display (HWD) while walking. Our primary objective was to evaluate whether reading information from an HWD while walking affects a participant's performance in their primary task, which, in this case, was walking. We also aimed to identify the display position within the visual field that minimally impacts performance based on dual task completion.

As expected, the use of the HWD did affect walking performance, as indicated by a decrease in participants' speed. Regarding the ideal display position, our findings suggest that positions closer to the nose, between -24° and 0°, are associated with higher walking speeds. This trend could be attributed to our eyes' familiarity with convergence. Conversely, at extreme positions beyond -27° and 24°, walking speeds were notably slower. These findings align with those of Song et al. [31], who reported similar results for reading using an HWD in stationary condition. In this case, our findings indicate that the suggested trend for the optimal display location being slightly offset from the PPOG still applies when applied to

Participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Overall
P1	25	30	15	40	50	60	36.67
P2	60	15	10	55	65	20	37.5
P3	65	10	25	65	60	10	39.17
P4	70	55	55	40	45	40	50.83
P5	90	70	65	50	85	75	72.5
P6	90	20	50	85	85	85	69.17
P7	70	35	55	30	65	35	48.33
P8	85	60	50	35	80	65	62.5
P9	80	25	80	25	65	75	58.33
P10	80	40	50	35	70	35	51.67
P11	80	45	75	25	65	65	59.17
P12	95	35	75	80	95	5	64.17
Average	78.64	37.27	53.64	47.73	70.91	46.36	55.76
Standard Dev	11.2	19.15	21.22	21.26	14.11	28.03	11.4

Participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Overall
P1	20	20	20	45	40	45	31.67
P2	55	15	35	45	30	10	31.67
P3	60	10	10	75	30	20	34.17
P4	55	45	45	35	55	45	46.67
P5	65	60	60	65	60	60	61.67
P6	85	20	50	80	95	85	69.17
P7	55	75	60	40	65	70	60.83
P8	80	60	50	45	65	55	59.17
P9	80	65	80	20	85	90	70
P10	75	40	50	35	70	35	50.83
P11	45	35	35	65	55	30	44.17
P12	75	30	75	85	85	15	60.83
Average	66.36	41.36	50	53.64	63.18	46.82	53.56
Standard Dev	13.25	21.69	19.49	21.34	20.89	27.59	13.1

Figure 9: NASA TLX Results after the first 6 cases (top) and then after 12 cases (bottom)

the completion of the dual tasks, namely walking and reading.

It is important to note that our sample size was small, and the whisker plot shows a lot of variance, indicating our results may not appear significant enough to draw strong conclusions. However, a clear trend indicates that closer to the nose is a more optimal position for displaying text on an HWD.

Additionally, we wanted to assess the safety of presenting information on an HWD. Throughout the study, participants managed to focus on both walking and reading simultaneously better than expected, with minimal missteps, even when simulating a malfunction on the HWD. As participants were able to uphold situational awareness during the given tasks that presented a cognitive load, this important observation suggests a need for alternative methods to test the safety of displaying information and performing routine activities on HWDs.

4 CONCLUSION

This study investigated the optimal display position for HWDs while performing everyday tasks, specifically walking and reading. The results show that using HWDs decrease walking speed. Display positions closer to the nose, between -24° and 0°, are associated with better performance, likely due to the ease of visual convergence. In contrast, positions beyond -27° and 24° hinder walking speed significantly, aligning with existing research by Song et al. [31] on reading efficiency with HWDs. Despite a limited sample size, the data suggests that displays positioned near the nose reduce cognitive load and minimize the need for excessive head or eye movements, enhancing task performance and maintaining situational awareness. Participants managed to walk and read simultaneously with minimal missteps, even under simulated challenging conditions like a hardware failure that causes the display to flash. This indicates the potential for HWDs in everyday activities, though further research is necessary to explore more rigorous safety testing methods.

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