Designing Augmented Reality for Cyclists: How Text-Based Notification Placements Influence Attentional Tunneling and Cycling Experience

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Fig. 1. **Left:** An illustration of the notification placements. Top (elevation +10°), Right (azimuth +10°), and Bottom (elevation −10°). The placement is fixed at an optical distance of $2m$ from the user. **Right:** Participant's view of the bottom notification. Here, the bottom notification is displayed with higher brightness, while the top and right notifications are dimmer to indicate their relative placement.

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Cycling has gained popularity due to growing interest in healthy and sustainable lifestyles. Simultaneously, Augmented Reality (AR) Head-Mounted Displays (HMDs) can assist cyclists by presenting notifications within their field of view without diverting their attention to external devices. While previous studies have investigated these advantages, safety concerns have primarily limited them to lab settings, creating a notable gap in understanding their real-world feasibility. We conducted a user study with 20 participants on a shared-use outdoor path and explored the impact of text-based HMD notification placement (top, right, bottom), on attentional tunneling and cyclists' experiences. Our results suggested that while the bottom placement received higher scores for perceived safety and noticeability, HMD notifications induced attentional tunneling, regardless of placement. We discuss our findings and present design insights for future HMD systems aimed at enhancing cyclists' safety and experience.

CCS Concepts: • **Human-centered computing** → *Usability testing*; **Mixed / augmented reality**; *User studies.*

Additional Key Words and Phrases: Cycling experience, cyclingHCI, HMD notification, attentional tunneling

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1 Introduction

Cycling, a popular activity promoting a healthy and sustainable lifestyle, has led to a notable increase in Human-Computer Interaction (HCI) research, referred to as *CyclingHCI* [38]. With advancements in wearable and lightweight technologies, Augmented Reality (AR) Head-Mounted Displays (HMDs), such as smart glasses capable of overlaying digital content onto the physical environment, have become increasingly accessible. Reports forecast the AR glasses market to reach USD 87.2 billion by 2033 [1]. This trend also drives growing research interest in how AR HMDs can support cyclists [20, 30, 41]. For example, HMDs have been used to provide cyclists with visual notifications, such as warnings of traffic at intersections [40, 41], potential hazards [57], and heart-rate data [61]. As a proactive delivery of information, HMD notifications appear to be valuable for cyclists, supporting them while on the move.

However, displaying notifications through HMDs has inherent challenges, notably in managing attentional demands [9, 25, 50]. Prior work indicated that notifications are inherently considered interruptions [42, 49], which increase cognitive workload and raise the likelihood of accidents [19, 56]. Furthermore, Wickens introduced the *attentional tunneling effect* [60], which describes the phenomenon of over-focusing on a single information source at the expense of others. For example, attentional tunneling may occur when users focus largely on AR devices and overlook their physical surroundings [55]. According to later research, such an effect is especially concerning in dynamic environments, which can result in critical delays in reaction times and compromised situational awareness [29, 48].

Recognising these risks, prior work emphasised the need for well-designed HMD notification strategies [52]. One key consideration is notification placement [22, 28, 51], as it determines where the content is rendered and directly affects user's attention shift. For example, researchers investigated how notification placement influences dual-task situations [10, 22, 49], social interaction [50], and walking performance [28, 31, 32]. However, no work has yet explored notification placement specifically for cycling. Compared to sitting and walking, cycling is a higher-paced activity that requires greater physical effort and sustained attention. As a result, providing HMD notifications

[1]https://www.futuremarketinsights.com/reports/augmented-reality-glasses-market

for cycling becomes even more complex, as the interference with the environment increases the potential for distractions and safety risks.

Prior work [40, 57, 61] in CyclingHCI, mainly driven by the novelty of applying HMD to cycling, tended placed notifications at the centre of the user's field of view; this placement, however, is least optimal as it obstructs real-world surroundings and hinders clear visibility [8, 31]. Furthermore, most studies were conducted in controlled lab environments, raising concerns about real-world feasibility, as lab environments often fail to replicate key aspects of cycling, such as balance, movement coordination, and managing effort and exertion [38, 46]. We therefore note a lack of exploration on where to place HMD notifications for cyclists in outdoor settings.

This work investigates the impact of HMD notification, especially its placement, for outdoor cycling. Considering both ethical and practical aspects, we adopted text-based notifications on a shared-use path. This setting provides a conservative yet realistic context, which captures cyclist's real-world demands while enabling ethical and controlled outdoor testing without motor traffic. We specifically focused on text-based notifications given prior HMD-based cycling studies have primarily adopted this modality [30, 40, 57]. Building on Lee et al.'s walking study [31, 32] that identified three key placements as representative of prior research, we narrowed our design space to focus on these placements: top, right, and bottom. We conducted a user study with 20 participants and evaluated cycling experiences such as perceived safety and distraction, as well as attentional measures such as attentional tunneling. Our results show that the bottom placement was the most preferred, with significantly higher scores for perceived safety and noticeability. However, our results also reveal that presenting HMD notifications evokes attentional tunneling, regardless of placement.

Our work moves AR for cycling one step closer to real-world deployments by starting from a baseline: text-based HMD notifications delivered on a shared-use path. With this study design, our work contributes a reusable study protocol which may help researchers and practitioners further exploring safe and effective HMD applications that can be further adapted to other road scenarios and notification modalities (e.g., icon-based notifications). Moreover, the insights gained in our work are also beneficial for researchers who work on augmenting other high-paced, dual-task activities that can utilise HMDs, such as running, skiing, and e-biking. In summary, our work makes the following contributions:

(1) **Study protocol:** We detail a reusable protocol for evaluating HMD notification placements in outdoor cycling and adopted text-based notifications on a shared-use path as a conservative starting point. We also discuss how this study protocol that can be extended to other scenarios and notification types.
(2) **Empirical assessment of HMD notification placements:** We provide empirical findings on how different text-based HMD notification placements affect cycling experience and attentional tunneling in this context, evaluating the feasibility of HMD in outdoor cycling.
(3) **Design insights for HMD integration:** We discuss strategies for effectively integrating HMD notifications into cycling contexts, aiming to enhance the cycling experience.

2 Related Work

In this section, we first review prior work on CyclingHCI systems. We then introduce attentional tunneling and its operationalisation, followed by discussing previous work on view management and notification placement strategies.

2.1 CyclingHCI Systems

Various technologies have been developed to support cyclists, including augmented helmets with ambient light [36, 37], vibration feedback on handlebars [39], and projected interfaces [11, 12]. Augmented helmets convey navigation cues through ambient lighting [36] and aim to enhance cyclists' situational awareness [53]; Vibration feedback was integrated into the handlebar to support navigation [37, 39]. However, prior research also identified that ambient light cues can be easily overlooked [37], and vibration signals often have low perceptibility [39]. In contrast, HMDs offer distinct advantages by displaying information directly in the cyclist's field of view, thereby enhancing intuitiveness [39, 41].

Von Sawitzky et al. [59] presented three HMD concepts to improve cyclists' road safety: displaying warning signals at upcoming junctions, enabling cyclists to see through walls, and visualising cues for road crossing. Matviienko et al. [41] took a step further in assessing these concepts by designing two HMD notifications: one highlights occluded cars through an X-ray vision, and the other illustrates the remaining safe crossing time at intersections. Their results showed that with the support of HMD notifications, cyclists made faster road-crossing decisions. Similarly, HMD has been employed to alert cyclists to hazards such as potential opening vehicle doors [57], and to provide safety warnings [40].

While these studies have advanced HMD-based cyclingHCI systems, their focus has mainly been on evaluating novel concepts, with most studies conducted in controlled lab settings. This raises concerns about real-world feasibility, as lab environments often fail to replicate key aspects of cycling [41, 46]. Currently, limited CyclingHCI research is conducted outside the lab. Von Sawitzky et al. [58] used a fully controlled test track to investigate cyclists' experiences with and without HMD hazard notifications. However, their focus was on evaluating the validity of HMD simulations without introducing the potential for real danger, which is what we are adding. Zhao et al. [61] conducted outdoor experiments showing that HMD enhances access to information like heart-rate data while preserving hazard awareness. However, their study did not assess how HMD notification influence cyclist's attention. Therefore, there is a need for research conducted in outdoors to explore how these systems could be effective in terms of feasibility.

2.2 Attentional Tunneling

Despite the potential benefits of HMDs, concerns have been raised about attentional issues that could have profound implications for user safety [13, 60]. One related phenomenon is the *attentional tunneling effect*, which Wickens et al. [60] defined as: "the allocation of attention to a particular channel of information, diagnostic hypothesis or task goal, for a duration that is longer than optimal, given the expected cost of neglecting events on other channels, failing to consider other hypotheses, or failing to perform other tasks".

Prior work demonstrated that attentional tunneling leads users to overlook unexpected events and significantly delays their reaction times to events occurring in different channels [15, 29]. Technologies such as Head-Up Display (HUD) [13, 16, 60] and AR systems [48, 55] are found to particularly influence attentional tunneling. Fadden et al. observed a significant delay in pilots' reaction times to unexpected traffic events using HUD, attributing the delay to attentional tunneling [15]. Similarly, Fischer et al. [16] found that pilots using a HUD had significantly slower reaction times to unexpected obstacles compared to a conventional instrument. However, Syiem et al. [55] argued that previous work on attentional tunneling often confounds the presence of virtual content with the additional tasks associated with it. To address this, they conducted a lab study and found that the presence of virtual content does not induce attentional tunneling, but introducing additional tasks associated with the content does. Parmar et al. [48] adopted a similar experimental setup to investigate the role of user mobility (sitting and walking) by measuring reaction times to external audio stimuli. Their finding showed that walking significantly amplified this effect. This suggests that activities involving greater physical demands, such as cycling, could potentially exacerbate attentional tunneling. However, no study to date has examined how the use of AR information affects cyclists' attention. Therefore, our study seeks to address this gap by exploring how HMD notifications may influence attentional tunneling in cycling. As reaction time is commonly used as an operational measure of attentional tunneling [15, 29, 48], we followed Parmar et al. [48]'s approach and operationalised attentional tunneling by measuring reaction times to audio stimuli.

2.3 Notification Placement

Notifications are designed to support user access to additional information from secondary sources to current activities [43]. HMD notifications reduces the need to visually scan or repeatedly check an external device such as smartphones [23, 24, 49]. However, presenting notifications via an HMD has inherent challenges.

In AR, virtual and physical objects coexist, yet physical objects cannot be controlled, and the augmentable portion of the FoV is often limited [2]. In response, Bell et al. introduced *view management* [2], a structured approach to keep virtual elements visible and prevent occlusions. According to the view management theory, placement plays a critical role, as it defines how visual elements are arranged within the view to maintain clarity. Similarly, Mccrickard et al. [43] identified focus location as a key factor influencing the attention costs of notifications. These theoretical foundations highlight the interplay between visual arrangement and attention costs, emphasising the need for well-designed placement strategies.

Prior work has investigated HMD content placement strategies. Chua et al.[10] categorised HMD placements into nine zones and analysed how different placements influence the noticeability and perception. Their findings suggested that middle-right, top-centre, and top-right are optimal for multitasking scenarios where primary tasks require central vision. Imamov et al. [22] tested 18 placements varying in horizontal angle, vertical angle, and distance. They found that content placed at or below eye level facilitated faster task completion. Rzayev et al. investigated how text placement affects reading while walking and sitting [51]. Their results showed that the bottom-centre placement enhanced reading comprehension while walking. More recently, Lee et al. [31] identified three placements based on previous studies and explored how HMD notifications influence user experience while walking. Their results demonstrated that notifications placed at the bottom (similar to the bottom-centre placement in Rzayev et al.'s case [51]) improved noticeability and comprehension. Similarly, another study [7] highlighted the bottom-centre placement as the most effective while walking in the wild, balancing safety and content focus.

While these studies offer valuable insights, their applicability to cycling remains limited as they predominantly address walking or sitting activities. Cycling presents unique challenges due to higher speeds, greater physical exertion, and the need to maintain focus on the road, making it a more demanding context. Delivering notifications through HMDs in this context is particularly complex, as environmental interference increases the risk of distractions and safety concerns. Hence, there is still a need to understand strategies designed specifically for cycling.

3 Method

Our work focuses on the effects of HMD notification placements on attentional tunneling and the outdoor cycling experience. To explore this, we built on Lee et al.'s work [31, 32] and focused on three placements: top, right, and bottom. Consistent with their choice, we excluded the left-side placement, as Imamov et al. [22] reported that placing content on the left side was equivalent to the right side. This section provides a detailed overview of the notification design, outdoor study settings, experimental design, and procedures. The university's human ethics committee approved our study.

3.1 Apparatus

The Unity game engine (version 2022.3.20f1) was used for implementation, and a Microsoft HoloLens 2 [2] was used to display notifications. All participants used the same entry-level mountain bike (shown in Figure 1) to ensure consistency. The bike featured a 15-inch frame, 26-inch tires, with an adjustable seat height. An Arduino button was mounted on the handlebar to measure reaction times, adjustable for left- or right-handed use. The button was connected to the same network as the HoloLens and used Open Sound Control [3] via a UDP network to transmit press events. Figure 3d illustrates the reaction button setup.

3.2 Notification Design

3.2.1 Notification Placement. Like Lee et al.'s study [31, 32], we set an offset of 10° from the centre of vision for the three notification placements to keep them within the optimal field of view for human vision. More specifically, the top placement was displayed 10° above the centre at an elevation of +10°; the bottom placement was displayed 10° below the centre at an elevation of −10°, and the right placement was displayed at an azimuth angle of +10° from the centre, as shown in Figure 1. The offset angles of the placements were determined based on the headset's wearing position. Eye calibration was performed for each participant to ensure the offset angles across the three placements were as consistent as possible.

Billboard-style notifications with white text on a blue background in Arial typeface, sized at 30 pt, were displayed at a virtual distance of 2 metres from the user, following previous studies [28, 31, 32]. The notification window size had a fixed width of $440mm$, with a variable height of either $290.64mm$ or $363.66mm$, depending on the length of the notification content (see 3.2.2). Correspondingly, the notification had an angular size of 12.55° in width and either 8.31° or 10.39° in height, occupying approximately 29% of the horizontal FoV and either 28.65% or 35.83% of the vertical FoV relative to a HoloLens 2.

Additionally, same as Lee et al.'s work [31, 32], we used a *body-locked* coordinate system, based on the recommendation for user comfort [28]. In a body-locked system, information is presented at a fixed distance relative to the user's body, independent of head movement. Notification placement remains horizontally fixed unless the participant exceeds a head rotation threshold of 10°, while vertically, the content is fixed relative to the user's head, ensuring that looking up or down does not cause the content to move. The implementation used the Radial View script from the MixedRealityToolkit, as shown in Figure 2.

3.2.2 Notification Content. As previous research commonly adopted text-based HMD notifications for cycling [30, 40, 57], our study specially focuses on text-based notification.

The notifications were pre-designed by the first author, guided by He et al.'s [20] findings on cyclists' preferences for content, such as weather forecasts, safety alerts, and context-related information. Notifications were then reviewed and refined through collaborative discussions among all co-authors, who are experts in cognition, data visualisation, interaction design, and AR/VR. Notably, all authors are active cyclists, bringing professional and practical perspectives to the process. Through these discussions, content that might raise participants' concerns was revised. For instance, initial notifications included safety tips like *"Tire pressure check"*, but it was noted that such messages could prompt participants to stop and inspect their bikes, potentially disrupting

[2] https://www.microsoft.com/en-au/hololens/hardware#document-experiences

[3] https://assetstore.unity.com/packages/tools/input-management/extosc-open-sound-control-72005

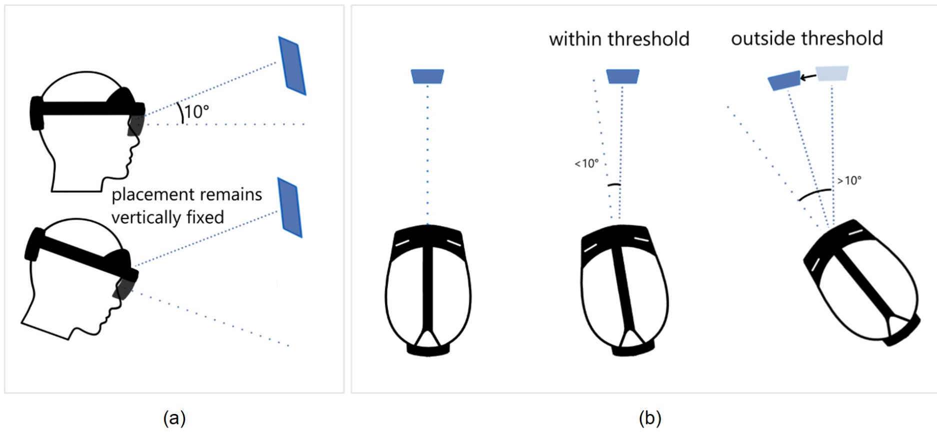

Fig. 2. Illustration of the body-locked system: (a) vertically fixed content unaffected by head tilt; (b) notifications remain horizontally fixed unless head rotation exceeds a 10° threshold

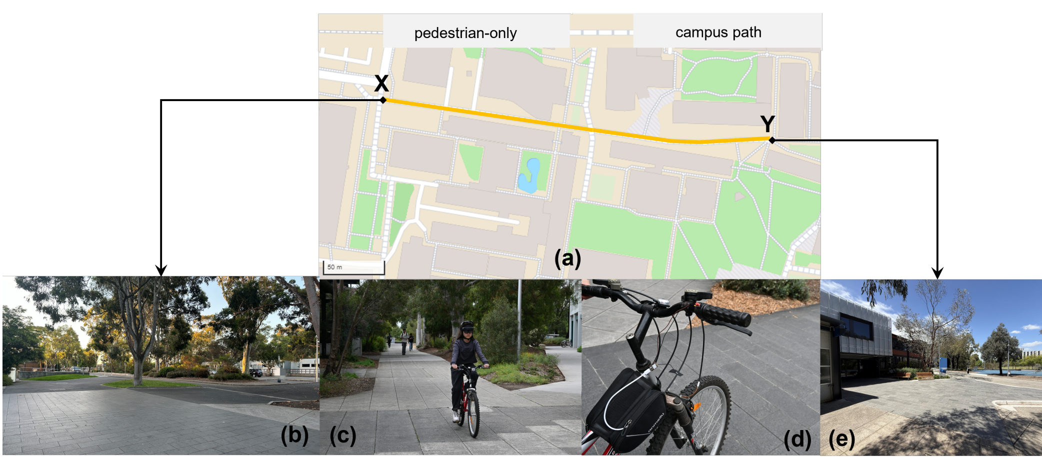

Fig. 3. Outdoor setting: (a) Schematic of the path (yellow line) with endpoints X and Y; (b) and (e) views of one endpoint; (c) participant during pilot test; (d) reaction button on handlebar.

their cycling task. Such notifications were therefore removed, and the final content emphasised relevant yet non-disruptive messages, such as *"Speed limit 20 km/h"*, *"Watch out for pedestrians"*, and *"McDonald's 300 meters ahead"* (there is a McDonald's shop near the path). These notifications simulated common information needs during cycling, such as safety warnings or point-of-interest updates. The length of notifications was also carefully considered to ensure safety. According to prior work [4], the average reading speed of a human is 238 words per minute, approximately four words per second. Meanwhile, Klauer et al. [27] reported that car drivers looking away from the road for more than 2 seconds double their risk of accidents due to distraction; that is, a notification containing more than eight words could cause this level of distraction. Therefore, we limited our notifications to 4-6 words. Also, to ensure participants receive different notifications for each placement, we designed three sets, each corresponding to a different placement. The notification length was kept as consistent as possible to avoid influencing the results.

3.3 Experiment Design

Our study had three notification placements, we also included a control condition with no HMD notification. Therefore, we had in total four conditions: *Top*, *Right*, *Bottom*, and *None*. To reduce discomfort from prolonged HoloLens use, we designed each condition to last approximately 5 minutes, with the total cycling and HoloLens-wearing time around 20 minutes.

3.3.1 Path Selection. Due to ethical restrictions, we selected an outdoor campus path instead of a busy main road, ensuring a realistic setting while prioritising participant safety. In the city [4] where the study was conducted, there are over 1900km of shared cyclist/pedestrian paths without vehicle traffic, making the selected path representative of such settings. The selected path is 500 meters long, free from major traffic, and limited to golf cart-sized vehicles, pedestrians, cyclists, and scooter riders. Participants cycled back and forth along the path, typically covers approx. 1.5km for each condition. Both ends of the path have irregular shapes, each measuring approximately 10 metres across at its widest point, with an area of 100 square meters. This space was sufficient to facilitate smooth U-turns without disrupting the ride. Figure 3 illustrates the schematic map of the path, along with views of both ends.

3.3.2 Pilot Testing. We conducted a pilot testing with four participants (two male and two female; mean age = 23.5, SD = 3.0) to refine our study design, including the frequency and duration of notifications per condition. In the testing, participants experienced a total of five, seven, and ten notifications within 5-minute time frame. Seven notifications per condition was identified as the optimal balance: higher frequencies felt overwhelming, while lower frequencies lacked engagement. Participants also preferred a 10-second display duration, finding 5 seconds too rushed and 15 seconds less effective. Therefore, in the formal user study, participants received seven notifications per condition, with each notification displayed for 10 seconds. Notifications intervals were set between 20-30 seconds.

3.3.3 Study Design. In each condition, participants were asked to wear the HoloLens and cycle along the path. In the *Top*, *Right*, and *Bottom* conditions, participants received HMD notifications. To simulate the road distraction, we adopted a similar approach to previous work [37, 48] by using an audio stimulus (a "ding" sound) as an unanticipated interruption and measuring participants' reaction times. Participants were instructed to press a button upon hearing the audio stimuli. To avoid learning effects, audio stimuli appeared randomly, either alongside the notifications or separately, with approximately 10 occurrences per condition. In the *None* condition, participants wore the HoloLens but only received audio stimuli. At the end of each condition, participants were required to complete questionnaires related to the notifications and their experiences.

3.4 Measurements

Based on prior work [30–32], we assessed subjective **user experience** by using seven-point Likert scales, covering *perceived safety*, *distraction*, *noticeability*, *understandability*, and *acceptability*. The smallest scale '1' represents the lowest level of impact. For example, for perceived safety, the question was, "How safe do you feel while cycling with this type of notification placement?" On the seven-point scale, '1' represents "not safe at all", and '7' represents "extremely safe". Participants completed the questionnaire at the end of each condition, except for *None*, where no notifications were provided.

In line with prior work [5, 48], we measured **reaction times** to operationalise attentional tunneling. Participants were asked to press the button as quickly as possible upon hearing an audio

[4]Melbourne, Australia. https://justapedia.org/wiki/Bike_paths_in_Melbourne

stimulus. The reaction times were recorded in milliseconds and logged in an XML file. No data was logged if a participant failed to respond before the next audio stimulus appeared.

We used the NASA-TLX questionnaire [5] to assess **task load**, evaluating six dimensions: mental demand, physical demand, temporal demand, overall performance, effort, and frustration. Following von Sawitzky et al. [58], all scales were adapted to a seven-point Likert scale to achieve consistency in questionnaire responses, and the Raw TLX approach was adopted to calculate the workload score by averaging the six subscale ratings. Participants were asked to answer the questionnaire at the end of each condition.

Comprehension of the notifications was assessed using multiple-choice questions similarly to those used in prior work [21, 32]. For example, one question was, *"What is the speed limit reminder?"* The options included one correct answer (the shown notification), two incorrect answers, and one *"Not sure"* option. The accuracy rate was calculated based on the number of correct answers. Participants completed the questionnaire at the end of each condition, except for the *None* condition, where no AR notifications were provided.

At the end of each study, participants completed a questionnaire on their **overall experience** (i.e., overall safety, overall acceptability, and comfort while cycling with an HMD) using a 7-point Likert scale. They also ranked their preferences for the three notification placements. Additionally, semi-structured interviews were conducted to gather detailed feedback. The interviews were audio-recorded, transcribed, and coded by the first author. Themes were collaboratively identified with two other authors using an inductive thematic analysis approach [3].

3.5 Participants

Following Lee et al. [32], we expected a medium effect size of .5, which requires a sample size of at least 10 participants given a significance level of .05, a power of .95, and 4 conditions. Additionally, previous research recommends 20 participants for HCI studies for analysing numerical data with about any distribution [14]. We therefore recruited 20 participants in our study. Of these, twelve identified as male, eight as female, and none as non-binary or self-described. The mean age is 26 years ($SD = 3.9$). The mean height is $168.68cm$ ($SD = 7.86$), with a minimum of $156cm$ and a maximum of $181.5cm$. All participants are proficient cyclists, and their purposes for cycling varies, including commuting, recreation, exercise, and competition. All participants have normal or corrected-to-normal vision through glasses or contact lenses. Regarding HMD familiarity, six have experience using the HoloLens, while fourteen have no prior experience. All participants volunteered for this study and were not compensated.

3.6 Procedure

Participants received an explanatory statement before the study began. Upon arrival, they were briefed on the study's objectives and signed a consent form to confirm their participation. They were then introduced to the HoloLens, along with an eye calibration. Afterwards, participants completed a test ride without the HoloLens to familiarise themselves with the bike and path, as well as to adjust the seat height and reaction button placement. After getting comfortable, participants wore the HoloLens and completed a training ride with three identical notifications (*"This is a test info"*) placed centrally to avoid bias. They were instructed to comprehend the notification and respond to the auditory stimulus, with an opportunity to ask questions afterwards.

Once ready, participants were assigned to the four conditions using a balanced Latin square. They cycled back and forth along the outdoor path at a comfortable, self-selected pace. Each condition typically covers approx. 1.5 km at an average speed of 18 km/h. Participants were free to take breaks

[5] https://humansystems.arc.nasa.gov/groups/tlx/

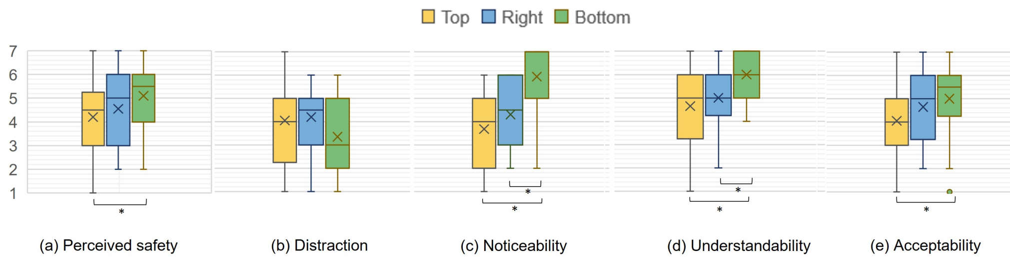

Fig. 4. An overview of the cycling experience for each condition. The symbol * indicates $p < .05$

between rides with no time limit. After each condition, participants completed questionnaires, followed by a brief interview at the end of the study. The entire procedure took about one hour per participant.

No signage was used to indicate that a study was being conducted; participants rode as they normally would, sharing the path with others. To ensure safety, all studies were conducted during off-peak periods, specifically on weekends or during the semester break when foot traffic along the path remained relatively consistent across study sessions. Each condition (a five-minute cycling task) typically involved an average of 22 road users, primarily pedestrians, along with two to three cyclists, skateboarders, or scooter riders dispersed along the route. Pedestrians were generally spread out and rarely moved in groups. (In comparison, during semester peak hours see an average of 70 road users.) Foot traffic data was based on an internal survey provided by our University traffic and transport data specialist.

4 Results

We conducted Shapiro-Wilk tests to assess data normality for the quantitative results. As none of the data were normally distributed, we applied a Friedman test to evaluate differences across conditions, followed by post-hoc pairwise comparisons using a Wilcoxon signed-rank test with Bonferroni correction. Effect sizes, including Kendall's W for Friedman test and r values for Wilcoxon tests, are reported.

4.1 User Experience

4.1.1 Perceived Safety. As shown in Figure 4 (a), *Bottom* received the highest perceived safety score ($Median = 5.5$, $IQR = 1.25$), followed by *Right* ($Median = 5$, $IQR = 3$) and *Top* ($Median = 4.5$, $IQR = 3$). A Friedman test showed a difference between all three conditions ($\chi^2(2) = 20, p = .030, W = .175$). A Wilcoxon-signed rank test with Bonferroni correction revealed a significant difference between *Bottom* and *Top* with a medium effect size ($p = .033$, $r = .476$), but no difference between *Bottom* and *Right* ($p = .061$, $r = .419$) nor *Top* and *Right* ($p = .409$, $r = .185$).

4.1.2 Distraction. As shown in Figure 4 (b), *Bottom* was perceived to be less distracting ($Median = 3$, $IQR = 3$) compared to *Top* ($Median = 4$, $IQR = 2.25$) and *Right* ($Median = 4.5$, $IQR = 2$), though a Friedman test showed no significant differences between the three conditions ($p > .05, W = .090$).

4.1.3 Noticeability. As can be seen in Figure 4 (c), *Bottom* was considered to have the highest noticeability ($Median = 6$, $IQR = 2$) compared to *Top* ($Median = 4$, $IQR = 3$) and *Right* ($Median = 5$, $IQR = 3$). A Friedman test revealed a significant difference among all three conditions with a medium effect size ($\chi^2(2) = 17.099, p < .001, W = .427$). A Wilcoxon signed-rank test with Bonferroni correction proved significant differences with a large effect size between *Bottom* and

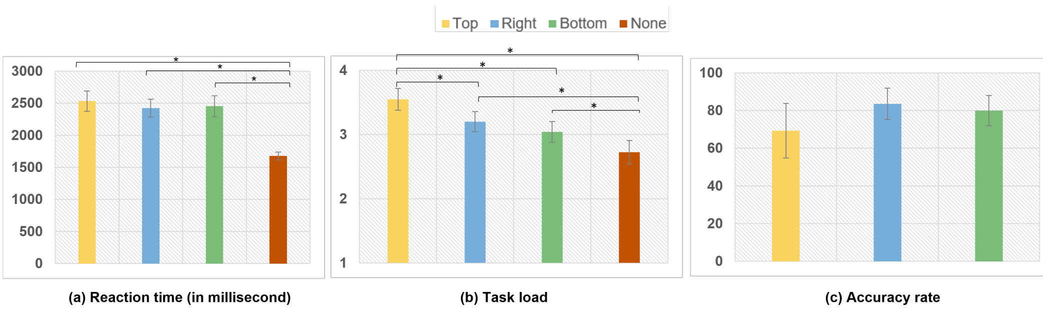

Fig. 5. (a) Average reaction time for each condition (in milliseconds); (b) average task load; (c) accuracy rate for the multiple-choice questions. The error bars depict the standard error, and the symbol * indicates $p < .05$

Top ($p < .001, r = .790$) as well as *Bottom* and *Right* ($p = .005, r = .632$), but not between *Top* and *Right* ($p = .260, r = .252$).

4.1.4 Understandability. As shown in Figure 4 (d), *Bottom* was considered to have the highest understandability ($Median = 6$, $IQR = 2$) compared to *Top* ($Median = 5$, $IQR = 1.5$) and *Right* ($Median = 5$, $IQR = 1.25$). A Friedman test revealed a difference among all three conditions ($\chi^2(2) = 10.969, p = .004, W = .274$). A Wilcoxon signed-rank test with Bonferroni correction suggested a significant difference with a large effect size between *Bottom* and *Top* ($p = .003, r = .658$) as well as *Bottom* and *Right* ($p = .018, r = .528$), but not between *Top* and *Right* ($p = .384, r = .195$).

4.1.5 Acceptability. As shown in Figure 4 (e), *Bottom* had a higher acceptability ($Median = 5.5$, $IQR = 1$), followed by *Right* ($Median = 5$, $IQR = 2.25$) and *Top* ($Median = 4$, $IQR = 2$). A Friedman test showed a difference between all three conditions ($\chi^2(2) = 6.310, p = .043, W = .158$). A Wilcoxon-signed rank test with Bonferroni correction showed a significant difference between *Bottom* and *Top* with a large effect size ($p = .009, r = .586$), but no significant difference between *Bottom* and *Right* ($p = .216, r = .277$) and Top and Right ($p = .092, r = .377$).

4.2 Reaction Time

In the interview, three participants (P7, P10, P11) reported mistook the audio stimuli for notification reminders, which might potentially influenced their reaction times. Therefore, to ensure the validity of the reaction time results, the analysis focused on the remaining 17 participants, who explicitly stated that they understood the task. This result is further discussed in 4.5.3 and 5.3.

As shown in Figure 5 (a), participants had the shortest reaction times in the *None* condition ($Mean = 1678.59ms$, $SD = 61.47$), followed by *Right* ($Mean = 2424.85ms$, $SD = 139.10$), *Bottom* ($Mean = 2453.23ms$, $SD = 162.66$), and *Top* ($Mean = 2533.69ms$, $SD = 158.29$). A Friedman test revealed a difference between the four conditions ($\chi^2(3) = 28.745, p < .001, W = .124$). A post-hoc analysis using a Wilcoxon-signed rank test with Bonferroni correction showed significant differences between *None* and all three conditions (all $p < .05, r > .5$), while no significant difference among *Top*, *Bottom*, and *Right*.

4.3 Task Load

As shown in Figure 5 (b), *None* was perceived as the lowest task load, followed by *Bottom*, *Right* and *Top*. A Friedman test suggested a difference between all conditions ($\chi^2(3) = 30.044, p < .001, W = .083$). Posthoc tests with Bonferroni correction revealed a difference between *None* and the three other conditions (all $p < .05$), as well as between *Top* and *Right* ($p = .009, r = .238$), and *Top* and *Bottom* ($p < .001, r = .317$). No significant difference was found between *Bottom* and *Right* ($p = .130, r = .138$).

4.4 Comprehension

Based on the accuracy rate of the multiple-choice questionnaires, no significant difference was found across conditions. However, *Top* showed the lowest accuracy (69%) compared to *Right* (83%) and *Bottom* (80%), as shown in Figure 5 (c).

4.5 Subjective Feedback and Overall Experience

4.5.1 Placement Preference. Figure 6 (a) shows participants' preferences for the three notification placements. 18 out of 20 participants preferred the bottom placement over the top and right, describing the bottom as *"within the natural field of view"*, *"easier to see"*, and *"more comfortable"*. For example, P12 stated: *"I prefer the Bottom because when I'm cycling, my view is usually in the middle or slightly downward, I rarely look up"*. P20 also said: *"It feels very comfortable for me to look at the bottom since it is our natural position"*.

14 out of 20 participants preferred the right over the top. They explained that the right remains within the field of view, while the top *"requires constantly looking up"*, therefore *"requires more effort"* and *"is more risky"*: *"If the message appears at the top, it distracts me more because I need to look at the road and be aware of pedestrians [...] When the message appears on the right, I often want to move it to the centre. However, it's still better than the top because looking up isn't natural for me while cycling."* (P12)

In addition, while the outdoor path had no clear distinction between left and right lanes and participants could cycle on either side, they emphasised considering the side placements as if they were on a regular street with typical traffic patterns: *"I am thinking about whether the notification should be on the left or right, I think you should also consider the traffic rules."* (P10)
"Since we are riding the bicycle on the left lanes, if it appears on the right, there should be a distraction with the incoming vehicles [...] I think put on the left will be better." (P20)

In general, participants preferred the bottom placement, which aligned with their natural view and required less effort to notice. The right placement was relatively favoured over the top, although some participants highlighted potential traffic-related distractions.

4.5.2 Feedback on HMD Notification. Our study focused on evaluating text-based notifications, as previous studies have generally adopted [20, 40, 57]. However, participants' experience with text-based notifications varied. P1 had a positive feedback, saying: *"It [the notifications] feels like there is someone next to me giving reminders, so I don't feel lonely. Especially when there is a building ahead, it lets you know what's coming up, which feels fresh and enjoy[able]."*

However, others found that information sometimes seemed *"out of context"*: *"Some of the notifications don't make sense to me. For example, when I first saw notification about a nearby coffee shop, I feel like 'are you telling me some kind of knowledge or something'. During that time it is completely out of context, I don't know why it shows up, so I have to spend more effort to understand it"* (P10).

P11 had a relatively neutral attitude, explaining that context-related notifications are only helpful if they are relevant to their interests or needs: *"For example, 'McDonald's 300 metres ahead', it is only useful if I'm interested in going there. But if I'm not in the mood for McDonald's and you tell me there's one ahead, then it's just, you know, distracting."*

Most participants agreed that the notifications were *"easy to understand"* and did not consider safety a major concern due to minimal occlusion. However, like three other participants (P13, P17, P18), P14 noted that the space the notifications occupied in the FoV was *"too big"*, saying: *"I don't*

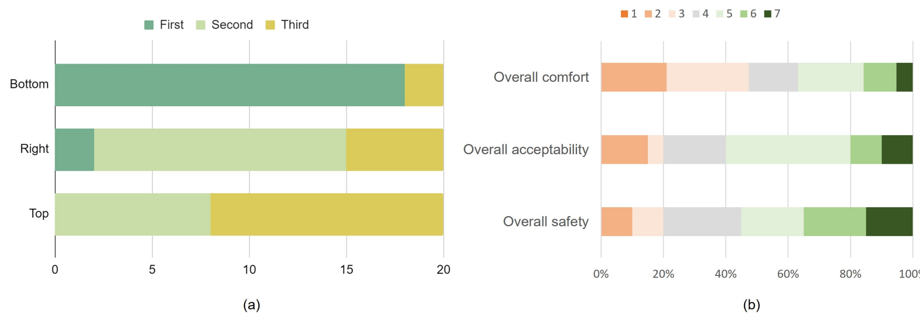

Fig. 6. (a) Participants' rankings of notification placements. (b) Participants' overall experience with wearing an HMD while cycling.

think it was really occluding, but I feel like it was too big". In response, they suggested that the notifications could be smaller or turned into an icon, so that the information can be quickly received at a glance.

4.5.3 Feedback on Simulated Distraction. As we reported in 4.2, three participants (P7, P10, P11) reported occasionally mistaking the audio stimuli for notification reminders: *"At first, especially when the sound and the notification came at the same time, I hesitated and wondering, should I press it? (P7)"* P10 and P11 mentioned the same, saying they initially forgot to press the button, assuming the audio prompted them to check the notification. They realised they needed to press the button only when they heard the audio without any accompanying notification. In reaction, they suggested combining audible cues with notification prompts may be more suitable while cycling outdoors.

4.5.4 Overall Experience. Figure 6 (b) presents participants' ratings of overall perceived safety, acceptability, and comfort while using an HMD for cycling. Participants rated acceptability ($Median$ = 5, IQR = 1) and perceived safety ($Median$ = 5, IQR = 2) positively, like P11 explained: *"I think an AR HMD is really useful, having the information right in front of me, and using it for cycling is definitely something with a lot of potential."*

Most participants indicated that the cycling experience is closely related to road conditions. While cycling on campus is perceived as safe, participants expressed concerns with commuting on main roads: *"I find it acceptable and enjoyable, probably because it's on campus and there aren't many people, but the experience might be different in crowded areas."* (P3)
"if the road is bumpy, you won't want to use an HMD because you need to focus on the road. But if the road is flat, it can be fun, like having an assistant." (P7)

In addition, the HoloLens hardware presents a notable issue, as overall comfort received a moderate rating ($Median$ = 4, IQR = 2). Several participants described it as heavy, with lighting conditions occasionally affected readability.

5 Discussion

Overall, participants preferred notifications at the bottom, with quantitative results supporting higher perceived safety, noticeability, and understandability. However, reaction time results revealed that HMD notifications induced an attentional tunneling effect. Based on these findings, we present the following discussion.

5.1 Bottom Placement Facilitates Perceived Safety

Our results showed that participants perceived the bottom placement as providing the highest sense of safety, with a significant difference compared to the top but not to the right. Participants explained that their attention naturally focused on the centre and lower areas of their field of view, where potential threats are more likely to appear. In contrast, the top region was generally perceived as less critical, making upward glances less frequent. The right placement, while better than the top, was still less favoured than the bottom. This finding aligns with Chang et al. 's study [7] who found the bottom-centre (similar to the bottom placement in our case) to be the most popular, as it effectively balances safety and focus. Similarly, Klauer et al. [27] reported that drivers who look away from the road for more than 2 seconds double their risk of an accident, further supporting the importance of maintaining attention on critical areas, i.e., the bottom and side areas for cyclists.

In terms of occlusion, participants did not identify it as a major concern in our study. They reported that the transparent billboard design did not impede their ability to notice the surroundings. This contradict the results by Klose et al. [28], where they found the bottom placement caused more occlusion than the top in walking tasks. However, unlike their study that required participants to navigate traffic cones as obstacles, our study was conducted on an unobstructed campus path without intentionally placed barriers. As a result, participants only needed to avoid other path users and did not have to navigate specific barriers. However, participants mentioned that uneven or bumpy roads could introduce occlusion problems, indicating that outcomes might vary under different road conditions. This aligns with Chang et al.'s findings [7], highlighting the need to consider diverse road conditions when evaluating feasibility.

These findings suggest that, on shared-use paths, bottom placement of text-based HMD notifications offers higher perceived safety by supporting focus on the road. Nevertheless, the impact of occlusion under more complex road such as cycling on main roads remains unclear. Future studies could explore diverse road conditions and further investigate the relationships between road surface characteristics, perceived safety, occlusion, and placement strategies.

5.2 Bottom Placement Facilitates Noticeability

The bottom placement received significantly higher scores for noticeability than the top and right. This is likely linked to the task load results, where participants reported significantly lower task load with the bottom than the top, though not significant compared to the right. One possible explanation is that looking downward is generally more comfortable than looking upward, and the optimal viewing angle is typically wider below eye level than above [45]. Our results are consistent with prior research that lower placement tends to enhance noticeability. For example, Rzayev et al. reported participant preference and improved comprehension for bottom-center under both walking and seated conditions [51], and Chua et al. found a trend toward shorter response times for bottom relative to top placement [10]. Similarly, recent walking studies [6, 7, 31, 32] also suggested that the bottom placement is the most noticeable.

However, the higher perceived understandability scores for the bottom placement did not translate into improved accuracy in the multiple-choice questions, as no significant differences were observed across placements. This is different with Rzayev et al.'s study [51], which found that text shown in the bottom resulted in the highest comprehension during walking tasks. However, the texts they used were considerably longer, with an average of 551 words, notably different from the brief notifications in our study. We therefore infer that the simplicity and brevity of our notifications likely ensured comprehension, highlighting a distinction from prior studies that used longer texts.

5.3 Designing for Minimal Attention Cost Needs Further Exploration

Our results showed that providing HMD notifications consistently affected participants' reaction times for external auditory stimuli across all placements compared to the *None* condition. The significantly longer reaction times suggest an attentional tunneling effect induced by HMD conditions. Syiem et al. [55] and Parmar et al. [48] found that displaying virtual content in handheld AR systems did not significantly increase reaction times unless the content was directly relevant to the user's task. In contrast, our results indicated that the virtual content (notifications) displayed in an HMD does increase reaction times. This difference might be because of three reasons: First, unlike using spheres as virtual content in their studies [48, 55], our study used text-based notifications, likely requiring more attention even without a specific task. Second, the level of user mobility differed across the studies. Syiem et al.[55] conducted their study in a seated context; Parmar et al. [48] required participants to walk in a fully controlled setting closed to the public. In contrast, our work took place outdoors, where participants had to remain alert to their surroundings. This setting likely affected their ability to process both the notification and audio stimuli. Third, both Syiem et al. [55] and Parmar et al. [48]'s work focused on handheld devices, whereas we used an HMD, resulting in a different FoV. As prior work suggested [1, 47], handheld AR typically confines user attention to the device screen, creating a focused and intentional interaction context. In contrast, HMDs integrate digital content with the broader environment, requiring users to divide their attention between augmented elements and physical surroundings. Hence, we believe that using an HMD changes how information is presented and perceived, potentially affecting user behaviour and cognitive processing. However, our study did not specifically examine the impact of different displays on this phenomenon, we therefore cannot conclude from our findings whether HMDs amplify attentional tunneling.

On the other hand, we observed that the audio stimuli used in our study, while consistent with prior research [37, 48], may not have been entirely suitable in outdoor cycling. Despite having clarified the role of the audio stimuli before the experiment, three participants (P7, P10, P11) reported occasionally mistaking the audio stimuli for notification reminders, potentially affecting their reaction times. This may be because the notifications in the actual study increased task difficulty, compared to the training session where the notifications were generic and identical (i.e., "this is a text info"), which may have led participants miss the audio stimuli. Nevertheless, during the study, the researcher did not observe any notable trajectory deviations or signs of insecurity among participants: all participants successfully avoided other path users and navigated intersections without incidents like collisions or falls, demonstrating their ability to manage physical distractions effectively. These observations suggest that cyclists can manage attention to their surroundings while using an HMD, but also raises concerns regarding the use of audio stimuli as a simulated distraction for investigating attentional tunneling. Since cyclists primarily need to respond to real-world events, relying on reactions to virtual stimuli may not provide an ideal measure of attention, especially in an outdoor context. Therefore, we recommend that future studies investigate attentional tunneling with realistic distractions (e.g., traffic lights, road hazards) and, where feasible, incorporate trajectory analysis to quantify effects on attention and cycling performance.

5.4 Consider Context for Notifications

Our participants highlighted that notifications directly related to their cycling tasks, such as speed limit alerts, were helpful and meaningful. Conversely, notifications related to the contexts, such as informing them that a McDonald's was ahead, were only perceived useful if it was their intended destination. This confirms the importance of considering cycling contexts [20, 38, 57]. For instance, in urban cycling, notifications might focus on safety-related elements such as traffic signals. In rural cycling, they might prioritise navigation or terrain updates. Similarly, commuting cyclists may value notifications about route optimisation or traffic conditions, while sport cyclists may benefit from performance metrics. As our work adopted text-based notifications on a shared-use path as a starting point, we targeted general-use scenarios and thus did not tailor them to specific road contexts or cyclist groups.

In addition, while previous studies [30, 40, 57] mainly adopted text-based HMD notifications to assist cyclists, our results suggested that text-based notifications may not always be ideal for outdoor cycling. Several participants reported that text-based notifications can be distracting, with some recommending smaller pop-ups or using icons. However, Janaka et al. [26] compared text- and icon-based notification in walking studies, where they reported that icons may outperform text-only notifications, but the effectiveness depends on factors like icon familiarity. While our current study examined text-based notifications on a campus shared-use path, future research could build on our study to evaluate how other notification formats, such as icons, audio, or smaller pop-ups influence user attention and feasibility, to identify notification formats that balance attentional demands with clear communication.

Beyond cycling, our study design can be extended to other forms of mobility, such as running, e-scooters, or motorbikes, where users face similar challenges of maintaining balance, situational awareness, and safe interaction with their environment [35]. Taking motorbikes as an example, it introduces additional road complexity due to surrounding traffic compared to cycling on a shared-use path, which may require integrating sensors for road scenario detection alongside notification designs. While our work may not directly transfer to these settings, it provides a baseline protocol and design insights that can inform broader mobility domains and support a more thorough, iterative design process.

5.5 AR HMDs: A Promise, But Not Yet a Solution

Based on the Likert ratings and subjective feedback, participants found using HMDs for outdoor cycling acceptable, with many considering it a promising concept. One notable benefit is the potential to minimise the need for cyclists to shift their attention, such as by placing notifications at the bottom that can be easily noticed. Participants also noted the perceived sense of companionship it provided, which made the cycling experience more engaging. However, they also pointed out that notifications should be context-aware, as an overload of information could compromise safety. Furthermore, the information should align with the cyclist's needs, though achieving effective personalisation remains a challenge [20, 57]. Hardware limitations, such as device weight, battery life, and the impact of lighting and rainy conditions, also pose challenges [38, 41]. Taken together, using AR HMDs for outdoor cycling holds promise, but there is still a long way to go before it achieves mainstream adoption.

6 Limitations and Future Work

While our study offers foundational empirical insights into the use of HMD notifications for outdoor cycling, it presents several limitations that should be acknowledged.

First, our study was conducted on a shared-use campus path with minimal curves, elevation changes, or heavy vehicle traffic. This setting allowed for better experimental control but limited our ability to capture the full range of physical and cognitive demands cyclists face in more complex conditions. While future studies could explore environments like urban roads, the increased variability would pose challenges, requiring more sophisticated study designs that carefully balance the trade-off between internal and ecological validity [54].

Second, our work was also limited to text-based notifications within a body-locked coordinate system. While this was recommended in previous work [30, 32], which we adopted as a starting point for outdoor cycling, we acknowledge that the design process could have been further validated through preliminary user studies or surveys involving UX designers or experienced cyclists, to reduce reliance on the authors' subjective expertise. Future work may also benefit from VR-based simulations to rapidly prototype and evaluate notification designs before conducting outdoor studies. Advances such as point cloud–based processing and compression in VR [44] could support semantic recognition tasks by enabling movement tracking. In addition, feedback from prior investigations suggest that using different types of notifications, such as icons [26], spoken notifications [18], or alternative AR coordinate systems [33, 34], might lead to differences. Future studies could further evaluate how these alternatives influence attention and cycling experiences.

Third, our study targeting a broad audience for general use. Therefore, we used only pre-designed notifications and did not tailor the design to specific specific cyclist groups (e.g., professional or recreational cyclists). This prevented us from including a more diverse range of cyclists and hindered the exploration of their specific needs. Using the same bike for all participants may have also introduced variability due to height differences, especially when compared to other bike types, e.g, road bikes. We acknowledge these limitations and recommend that future research target more specific contexts; compare different types of cyclists (e.g., professional vs. recreational), bikes (e.g., road vs. mountain), and notification modalities; and adopt Wizard-of-Oz or GPS-based notification systems to better reflect real-world usage.

Another limitation is the exclusion of the left-side notification placement from our design, which restricts our ability to explore the impact of side placements on the cycling experience. Although previous work [22] found no difference between left and right placement, our participants noted a potential difference, despite the on-campus path allows cycling on either side without lane distinctions. Participants reported that while the right placement did not pose a notable risk, it might obscure oncoming road users on busier roads. Given that our study involved a higher-paced activity requiring more physical effort and attention, these factors could amplify the differences between side placements. Therefore, we recommend designing notification placements aligned with traffic rules and exploring the impact of side placements in future studies.

Finally, participants identified the HoloLens as a major limitation, particularly for long-term use, and under challenging conditions such as rain, nighttime, or varying lighting. The limited display brightness also reduced notification visibility in very sunny conditions, prompting us to conduct most of our studies on cloudy days. However, these environmental factors play a critical role in outdoor usability [17, 41]. We recommend that future work prioritise hardware innovations to develop HMD specifically designed for these scenarios.

7 Conclusion

This study investigated the effect of text-based notification placements on the cycling experience. We compared the top, right, and bottom placements and their impact on attentional tunneling, perceived safety, distraction, noticeability, understandability, comprehension, and task load. We found that the bottom placement facilitated perceived safety and noticeability. The study also revealed that HMD notifications consistently affected participants' reaction times across all placements, suggesting an attentional tunneling effect. However, we propose that incorporating alternative types of simulated distractions, such as traffic lights or road hazards, could offer additional insights into attentional tunneling in outdoor scenarios. Our work provides empirical findings on how HMD notification placements influence attentional tunneling and the overall cycling experience, moving AR for cycling one step closer to ecological validity.

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