Understanding the Impact of HMD Notification on User Attention in Outdoor Cycling

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Abstract

Cycling has gained popularity due to a growing interest in healthy and sustainable lifestyles. Simultaneously, Augmented Reality (AR), especially through Head-Mounted Displays (HMD) that present information within the user's field of view, offers an opportunity to assist cyclists without diverting their attention to external devices, such as smartphones. However, providing HMD notifications has inherent challenges, notably in managing attentional demands. Yet, no research to date has investigated the attention cost of HMD notifications in a cycling context. This doctoral research aims to explore the impact of HMD notifications on user attention and cycling experience, particularly in the context of outdoor cycling. This research is expected to offer design insights and strategies for HMD notifications, guiding future researchers and practitioners in integrating AR technology into the cycling experience, and can be extended to other on-the-go activities.

CCS Concepts

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

Keywords

Cycling experience, cyclingHCI, HMD notification, attentional tunneling

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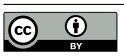
1 Introduction

Access to timely notifications nowadays has become pervasive, and people often seek them while engaged in everyday tasks. This demand is particularly evident in outdoor, mobile contexts, for instance, when users rely on notifications while navigating. Such scenarios have driven growing interest in Augmented Reality (AR) [1], especially through Head-Mounted Display (HMD), as it allows digital information to be overlaid onto the physical environment to support real-time interaction.



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This growing interest is also reflected in cycling, contributing to a noticeable increase in Human-Computer Interaction (HCI), referred to as *CyclingHCI* [21]. For example, AR HMD has shown its potential to provide real-time notifications to assist cyclists for decision-making at intersections [23]. It was also used to provide safety warnings such as potentially opening vehicle doors [31] and approaching vehicles [12]. As a proactive delivery of information, HMD notifications appear to be valuable for cyclists, supporting them while on the go.

However, displaying HMD notifications has inherent challenges, notably in managing attentional demands [14, 28]. Upon receiving a notification, a user's attention typically shifts, diverting them from ongoing tasks [7, 19, 27]. Besides, an attentional tunneling effect is likely to occur when using AR devices, that is, the phenomenon of over-focusing on a single information source at the expense of others [34]. For instance, a user may overlook their physical surroundings if they focus largely on AR contents [25, 30]. Research in dual-task paradigms further highlights these concerns, demonstrating that receiving notifications during immersive interactions disrupts attention allocation [7, 18].

While early works have explored notification display strategies [3, 6, 18], existing studies remain fragmented, as designing AR for on-the-go is still at an early stage [29]. Given that AR HMDs as well as smart glasses are becoming increasingly widespread and commercialized for on-the-go use, it is crucial to investigate how notification should be delivered to avoid distraction and maintain user safety. Here, I use the term *on-the-go* to describe scenarios that involve body-powered locomotion activities [20], including walking, running, cycling, and riding e-scooters or e-bikes, but excludes driving a car and localized movement such as dancing or court-based sports. Accordingly, this PhD project aims to examine how HMD notifications affect user attention during outdoor cycling, with findings intended to inform research on other on-the-go activities.

2 Key Related Work

2.1 HMD-based CyclingHCI Systems

The growing adoption of HMDs is expected to become as integral to daily life as smartphones [15]. One of the key advantages of HMDs is the ability to present additional content directly in the user's field of view, reducing the need to shift attention to external devices like smartphones [16]. This advantage is particularly valuable for cyclists, as it enables the delivery of critical information such as hazard alerts [22, 31] without requiring them to look away from the road. Von Sawitzky et al. [32] presented three HMD concepts to improve cyclists' road safety: displaying warning notifications

at upcoming junctions, enabling cyclists to see through walls, and visualizing cues for road crossing. Matviienko et al. [23] 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 [31], and to provide safety warnings [12, 22].

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 [23, 24]. In addition, Huckauf et al. [13] found that switching attention between AR content and the surrounding imposed an additional 10% attentional load under laboratory conditions, and hypothesized that this cost would be substantially higher in real-world outdoor settings. However, no work to date yet has explored the use of HMD on user attention in cycling contexts. I therefore argue there is a need for research conducted in outdoors and explore how these systems could be safe and effective in terms of feasibility.

2.2 Attention Management in AR

User attention involves the allocation of limited cognitive processing resources [5, 33], and also describes how users distribute their focus [2, 11]. In AR, virtual and physical objects coexist, and AR overlays may increase visual occlusion if they are poorly designed. In response, Bell et al. introduced view management [3], a structured approach that manipulates visual properties (e.g., position, size) to keep virtual elements visible while maintaining users' awareness of their surroundings. Chua et al. [4] categorized HMD placements into nine zones and analyzed how different placements influence noticeability. Their findings suggested that middle-right, top-center, and top-right are optimal for multitasking scenarios where primary tasks require central vision. Fukushima et al. [6] compared different anchoring mode while walking. Results show that a world-locked system, that renders content as if it were a fixed physical object in the real world, improves reading speed and reduces mental workload; whereas a head-locked system, that fixes the content in the user's field of view and follows head movement, leads to unnatural gait.

While these studies offer valuable insights on HMD design, their applicability to cycling remains limited, as they predominantly address sitting or walking activities. Cycling, on the other hand, is a higher-paced activity that requires balance and movement coordination, while simultaneously placing stronger constraints on attentional resources [20]. Consequently, designing HMD notifications for cyclists becomes even more complex, as the interference with the environment increases the potential for distractions and safety risks.

3 Research Objectives and Approach

This PhD project seeks to understand the impact of HMD notifications on user attention in outdoor cycling by addressing the following research questions:

- RQ 1: What are the key design factors for AR HMD notifications in on-the-go contexts?
- RQ 2: How do existing HMD notification designs influence user attention in outdoor cycling?
  - RQ 2.1: How do AR notification placements influence cyclist's attention and experiences?
  - RQ 2.2: How do world-locked AR notifications influence cyclist's attention and experiences?

To address RQ1, I conducted a literature review and extended it to include on-the-go contexts, given the limited prior work focused specifically on cycling. Based on this review, I designed and developed a set of prototype systems on the Microsoft HoloLens 2 that present AR notifications with different designs. To address RQ2, I design user studies to examine how these designs affect user attention and cycling experience. User attention was assessed using quantitative measures such as reaction time [25] and eye tracking, while experience was captured through self-reported workload (NASA-TLX [8]), custom questionnaires, and interviews.

4 Results and Contributions

4.1 Literature Review of On-the-Go AR Design Factors [Completed]

I conducted a comprehensive review of literature in on-the-go AR, aiming to understand the existing AR HMD design factors that influence user attention. This synthesis has allowed me to identify key design factors. One of the primary design factors is notification placement, as it determines where content is rendered and directly affects users' attentional shifts. Another key factor is the frame of reference, including head-locked and world-locked systems. These identified design factors motivated my subsequent user studies.

4.2 Effect of HMD Notification Placement [Completed]

Drawing on the results of the review, user study 1 [9] aims to explore the effect of HMD notification placement in a cycling context. I built on the methods from Lee et al.'s study [17, 18] and chose three different placements: top, right, and bottom, as shown in Figure 1. The notification content was designed by drawing on results from semi-structured interviews with eight cyclists regarding their preferences, such as weather forecasts, safety alerts, and points-of-interest [10]. Participants were required to view the notifications and then completed post-study questionnaires to evaluate their comprehension of the notifications and their subjective experience. They were also asked to respond to randomly presented external auditory stimuli, and their reaction times were recorded as a measure of attentional tunneling. The results showed that although reaction times did not differ significantly across the three placements, the bottom placement was the most preferred, receiving significantly higher ratings for perceived safety, noticeability, and understandability. This study contributes a reusable protocol and empirical findings for evaluating HMD notification placements during cycling on a shared-use outdoor path.

Figure 1: The experimental setup of user study 1 [9]. 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.

4.3 Effects of World-Locked Notifications [Ongoing]

Previous work has shown that a user's attentional process and response time may vary across different frame of reference [26]. However, to date, no research has explored how a world-locked system may influence cycling experiences. Therefore, user study 2 aims to address this gap.

User Study 2 also employs HMD notifications; however, the notifications are rendered in a world-locked system, meaning that they are anchored in the physical environment like traffic signs rather than following the user's movement. In addition, the notification content is limited to safety warnings and points of interest, as these two were identified as most relevant to the shared-use outdoor path in user study 1. The measures for this study also includes participants' perceived safety, notification readability and understandability. Eye-tracking data will be included to provide an objective, physiological perspective on attentional processes.

4.4 A Framework of HMD Notification Design and User Attention [Planned]

Based on the findings from the user studies, I plan to propose a framework that articulates how different design factors influence user attention. The framework aims to provide a more theory-driven explanation of these effects and, in turn, to inform corresponding design strategies. Although grounded in the context of AR-assisted cycling, the framework may also offer insights applicable to the design of other on-the-go activities.

5 Expected Contributions and Long-Term Goals

This PhD research aims to make the following contributions:

(1) **Assessment of HMD notifications in real-world contexts.** The user studies aim to provide empirical findings on how different HMD notification designs influence cycling experience and user attention. As the user studies target an outdoor, real-world cycling context, this work advances cyclingHCI research toward greater ecological validity.

(2) **Understanding user attention in AR cycling.** Through the proposed framework, this research aims to contribute to a foundational understanding of user attention and design factors in AR cycling.

(3) **Design recommendations for HMD integration.** Drawing on these insights, this research will propose design recommendations for effectively integrating HMD notifications into cycling contexts. These guidelines may potentially benefit other on-the-go activities.

Looking ahead, the ultimate goal of this research is to serve as an early exploration of AR HMD use in outdoor activities. This work aims to support both researchers and practitioners in designing better HMDs and smart glasses. As these devices are likely to become increasingly prevalent, understanding how such systems can be used safely and effectively in on-the-go contexts is critical. This project contributes to that understanding and informs the design of interactive AR systems for real-world settings.

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