NotiBike: Assessing Target Selection Techniques for Cyclist Notifications in Augmented Reality

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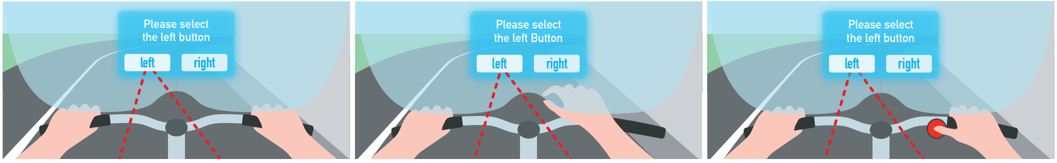

Fig. 1. We present a study evaluating three different notification selection techniques in augmented reality. We compare the selection efficiency, task load, and subjective perception of selections in Augmented Reality using **(Left)** gaze-based *Dwell Time*, **(Middle)** *Gestures*, and **(Right)** *MAGIC Pointing*.

Cyclists' attention is often compromised when interacting with notifications in traffic, hence increasing the likelihood of road accidents. To address this issue, we evaluate three notification interaction modalities and investigate their impact on the interaction performance while cycling: gaze-based *Dwell Time*, *Gestures*, and *Manual And Gaze Input Cascaded* (MAGIC) *Pointing*. In a user study (N=18), participants confirmed notifications in Augmented Reality (AR) using the three interaction modalities in a simulated biking scenario. We assessed the efficiency regarding reaction times, error rates, and perceived task load. Our results show significantly faster response times for *MAGIC Pointing* compared to *Dwell Time* and Gestures, while *Dwell Time* led to a significantly lower error rate compared to *Gestures*. Participants favored the *MAGIC Pointing* approach, supporting cyclists in AR selection tasks. Our research sets the boundaries for more comfortable and easier interaction with notifications and discusses implications for target selections in AR while cycling.

197

CCS Concepts: • **Human-centered computing** → *Empirical studies in HCI*; *Empirical studies in interaction design*; *Interaction techniques*.

Additional Key Words and Phrases: Cycling, Augmented Reality, Notifications, Selection

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1 INTRODUCTION

Today, a large number of road accidents are related to distractions caused by simultaneously using external devices, such as smartphones, while cycling on the road [29]. Distractions through touch input by looking at the smartphone [13, 14] represent a large proportion of cycling accidents [66]. Especially notifications tempt to draw cyclists' attention [22], incentivizing them to interact immediately and making the interaction process a major side activity [51]. The stop-to-interact paradigm may increase the safety and interaction efficiency but is scarcely practiced by cyclists resulting in detrimental on-the-go interaction losing track of the road traffic [15, 52, 67]. current interaction devices are either handheld devices occupying one hand of the cyclist, effectively reducing the cycling performance [65], or compromise the road traffic attention through touch interaction when the device is mounted on the handlebar [13, 14]. A higher risk of accidents is the result, where cyclists are at a higher risk of injuring themselves than others compared to other road users, including car drivers and pedestrians. Although similar issues with external device screens and handheld interaction are present in driving contexts [10, 24], cycling involves motoric coordination while keeping the balance, hence putting them at a high risk of accidents and injuries during on-the-go interaction [65].

To overcome the distractions mentioned above by looking at the device screen or during handheld interaction, past research investigated how on-the-go interaction can be designed safely using Augmented Reality (AR) [6, 7], where information are displayed for cyclists [23, 76]. An advantage of AR is to view virtual content using see-through glasses, where the field of view can still be maintained on the road traffic while viewing content. Here, AR has been researched as a supportive asset for cyclists to safely display information, such as traffic-related routing data or weather information [23, 61, 76]. However, although displaying passive information in AR has benefits for cyclists that actively improve the cycling experience [61], direct AR interaction still lacks intuitiveness. Current solutions rely on either voice commands, which can be acoustically incomprehensible due to environmental noise, interaction with externally mounted displays that draw attention from road traffic [24], or tedious freehand gestures requiring cyclists to temporarily let go of the handlebar [9, 12, 49]. While AR glasses can passively display information to support cyclists while keeping their attention on the road [61], we state that explicit AR *interaction* still lacks sophistication and intuitiveness for cyclists.

Eye gaze tracking, a functionality that has become more commonly integrated into HMDs [34], has been presented as an alternative for AR interaction. Gaze-based interaction requires only eye movements, not compromising a cyclist's safety through physical hand movements. Interacting with gaze has received immense attention for hands-free selections of virtual elements [19, 34]. Dwell time; a typical selection modality is an interaction technique triggering elements after users gaze at them for a specific time; it emerged as a popular selection technique due to its simple interaction principle and resulting low error rates [1, 21]. However, dwell time interaction is affected by the Midas Touch problem [4], where users accidentally select elements by unconsciously looking at them. Manual and Gaze Input Cascaded (MAGIC) pointing was introduced to tackle this issue. MAGIC Pointing is a selection principle that avoids unintended gaze selections by requiring the user to press an additional physical confirmation button [83]. However, previous research did not investigate eye gaze-based interaction in AR for cyclists, hence lacking empirical evidence on how efficient these techniques are in cycling as an attention-demanding activity.

This paper compares three gaze-based selection techniques for cyclists using AR in selection efficiency, task load, and perceived usability. Informed by related work, we adapt the three selection modalities *Dwell Time* (i.e., selections using gaze only), *Gestures* (i.e., selections using gaze and gestures), and *MAGIC Pointing* (i.e., selections using gaze and confirmation with a physical button press) to confirm notifications while users cycle on a bike simulator (see Figure 1). Our results show that *MAGIC Pointing* enables users to perform faster target selections compared to *Dwell Time* and *Gestures*. In contrast, *Dwell Time* achieved a significantly lower error rate compared to *Gestures*. Our results show that *MAGIC Pointing* provides two key advantages when selecting targets in AR while cycling: (1) it removes the need for arm movements affected by shakes that may lead to lower selection accuracies (i.e., compared to *Gestures*), and (2) does not severely compromise the cyclists' road traffic attention by needing to focus on targets compared to *Dwell Time*.

CONTRIBUTION STATEMENT

The main contribution of this paper is the comparison of three different interaction techniques to select targets in AR while cycling actively. In contrast to previous work, we investigate how direct AR interaction can be designed for cyclists while keeping their attention on road traffic. In a user study (N=18), we compare the three different interaction techniques *Dwell Time*, *Gestures*, and *MAGIC Pointing* in a cycling simulation regarding target selection efficiency and usability.

2 RELATED WORK

Designing safe interaction techniques for cyclists' is a challenging task. First, we describe past research concerned with designing, evaluating, and exploring AR selection techniques. Then, we focus on the general development of AR interaction techniques for road users. Finally, we summarize the results and elaborate on the implications of interaction techniques for the study.

2.1 Selections in AR

Recently, tech companies accelerated their development of Head-Mounted Displays (HMDs). Meanwhile, the mass market is hit by the third iteration of available HMDs. While many factors, including the visual and audio quality, field of view, or weight, improve comfort, AR interaction techniques did not undergo any major revisions. Yet, current interaction consists of either controller- or gesture-based selection [84]. More sophisticated interaction methods, such as gaze-based interaction [74] or brain-computer interfaces [68], gain more attention in the HCI community. While commercial AR solutions offer practical solutions, they are still in their development phase. This includes *controllers*, *head gestures*, and *hand gestures*, representing the default choice for interacting with AR.

Regular controllers consist either of a company shipped remote control or the user's smartphone. Here, smartphones benefit from their ubiquitous availability and their ability to provide multidimensional input. Furthermore, smartphones offer natural selection and manipulation of objects through a familiar as well as natural and convenient user experience [36, 57, 85]. Zhu et al. [85] presented design recommendations for the interaction between AR and smartphones. They present *BISHARE*, a demonstrative application enabling interaction in AR using the smartphone as a controller. In this context, Knierim et al. [36] conducted a user study evaluating the interaction efficiency of BISHARE. The authors showed that object manipulations in AR were executed more efficiently using smartphone input than freehand gestures. The authors conclude that using a smartphone controller improves usability and overall input accuracy. However, users still have to move their hands physically, limiting their hands for other interactions [3, 33]. Research concerning the use of pens [77] or wearables [17, 35, 70] exist, but it requires either additional handheld object or modification of the user's clothes.

Recently, AR-based multimodal interaction moved into the focus of HCI research. Billinghurst et al. [7] remarked that multimodal interactions might be the best way of interacting with AR, hence including an additional interaction channel. In this context, Esteves et al. [20] presented SmoothMoves, a system using integrated accelerometers of an HMD to detect selections based on head movements. SmoothMoves outperformed handheld devices both in error rates and task completion times. Besides head movements, eye tracking has received attention as a complementary AR input modality. Van der Meulen et al. [74] presented how eye tracking can be generally included in HMDs, resulting in frameworks advising the integration of eye tracking into HMDs [34]. Finally, some commercially available HMDs, such as the HoloLens 2, natively include eye tracking capabilities for additional interaction purposes. Blattgerste et al. [8] compared the advantages and disadvantages between head gestures and eye gaze in an object selection task. Using eye gaze with a dwell time of 1.3 seconds improves task completion times, task load, and individual participant preference compared to head gestures. However, too short dwell time selections are susceptible to the Midas touch problem [27, 30, 32], leading to unintended selections. The optimal dwell time duration depends on the use case and the context of the user.

Combining gaze interaction with affirmative user actions has been researched as a gaze-based interaction alternative. Zhai et al. [83] propose *Manual and Gaze Input Cascaded (MAGIC) Pointing*, a technique combining the users gaze selection with an affirmative gesture (i.e., a physical button press or a click). In a user study, *MAGIC Pointing* reduced mouse movements and effectively eliminated the Midas touch effect since the user has to confirm their selection. Furthermore, users can decide when to commit their selection, rendering predefined dwell times unnecessary. *MAGIC Pointing* has been used as a selection technique within several research projects. Kunmar et al. [46] presented different keyboard inputs combined with gaze tracking for accurate input. Drewes and Schmidt [18] combined *MAGIC Pointing* with a touch-sensitive mouse to compensate for inaccuracies in gaze movements. Lischke et al. [50] used *MAGIC Pointing* to compare object selections on large displays. *MAGIC Pointing* decreased the task completion and perceived task load significantly compared to selections using a mouse. Finally, Kytö et al. [48] evaluate different pointing selection strategies using eye tracking as well as head movements in AR, including the simultaneous use of eye gaze with clickers, gestures, and head movements. The results show that using eye gaze only for pointing deteriorates the selection accuracy significantly.

2.2 AR Interaction for Cyclists and Road Users

Participating in road traffic is complex, demanding the cyclists' attention and permanent awareness of their surroundings [58]. Furthermore, the simultaneous interaction with devices poses a distraction, leading to an increase in accidents [29, 66]. Past research has extensively studied smartphone use to design interaction paradigms, improving the safety of road users. In a cycling context, Hochleitner et al. [28] compared the feasibility of interacting with a smartphone game using physical buttons on the bicycle's handlebar, the phone's touchscreen, and a wristband that is activated when flipping the wrist. Their results show that interacting with a physical button on the handlebar resulted in less physical workload, less frustration, and improved task completion time compared to the other interaction modalities. Consequently, touchscreen and wristband interaction was rated higher in perceived workload than button-based interaction, especially since the touchscreen requires looking at the phone screen, lowering the overall cycling performance [13]. Also, the wristband interaction needs participants to memorize the gestures. As a consequence, Wozniak et al. [82] compared physical rotation-based and button-based smartphone input on the handlebar of bicycles. Their qualitative inquiry shows a user preference to operate smartphones while biking. In a user study, the participants desired the rotation-based integration of smartphone controls on the handlebar for interaction during cycling. However, previous research found that cyclists were willing to interact with their smartphones and subsequently presented modalities to interact with smartphones while cycling. AR-based HMD interaction for cyclists has been scarcely researched. The following section summarizes research investigating the impact of AR interaction on cyclists' attention and driving performance.

Various researchers studied the impact of AR on the user's attention. For example, Syiem et al. [72] investigated the effect of AR on attention tunneling, a state where users are highly focused on the virtual content rather than their physical surroundings [79, 80]. The authors conduct two studies in which they find that the mere presence of virtual content does not cause an attentional tunneling effect distracting the user from their physical environment. However, an attentional tunneling effect emerges if users are confronted with an additional task within the virtual content. For example, virtual content might not redirect their attention from their driving task for road users. Instead, the task or interaction with the virtual content might turn their attention from the actual driving task. This conforms with the findings of Wang et al. [78], who found a positive correlation between increased cognitive workload and inattentional blindness in a simulated scenario. Operating a smartphone, either through one-handed interaction or by mounting it on the handlebar, requires touch input compromising the road traffic attention of cyclists [13, 15]. In a series of studies, de Waard et al. [13–15] found that active touch interaction with smartphones reduces the number of head movements, reduced speed, reduced peripheral vision performance, higher cognitive workload ratings, and reduced road traffic attention.

Consequently, previous research investigated how AR can augment and facilitate interaction for cyclists while maintaining their road traffic attention. For example, Matviienko et al. [53] investigated visual child cyclist augmentation strategies to reduce the risk of traffic accidents. In a user study comparing visual, auditory, and vibrotactile indicators, the authors find that visual indicators require more reaction time than auditory or vibrotactile cues. However, using all three notification modalities simultaneously led to slower reaction times in dangerous situations, such as stopping the bicycle immediately. In this context, both head-up displays and multimodal user interfaces showing passive safety information were helpful to support cyclists in terms of navigation [55], warning signals [56], additional assistance in traffic [54], and increase awareness for maneuver indications for self-driving bicycles [59]. Further augmentation strategies were presented by Sawitzky et al. [76], who investigated different augmentation concepts. For example, AR allows cyclists to see through walls, display warning signals, or visualize safe crossing cues. Besides using visual indicators to augment cyclists, past research investigated vibrotactile feedback as an alternative interaction modality [45]. However, adding additional cues into a cycling scenario can increase the degree of distractions. Finally, Matviienko et al. showed how in-situ information about approaching cars in AR increases the environmental road traffic awareness of cyclists to improve their street crossing safety [61]. The presented research shows that passively displaying information in AR can increase the safety of cyclists. However, direct interaction with AR remains a gap.

Past research looked into the practical implications of using AR in general traffic. Kun et al. [47] investigated the driver performance while performing video calls through an HMD during a simulated drive. The authors compare speech-only conversations with video calls while measuring the participants' gaze. They find that driver attention is not significantly influenced when performing video calls compared to speech-only calls. However, the authors observe that drivers are not directing their gaze on the road when looking at their interlocutor. Consequently, previous work suggested gaze for hands-free interaction without distracting the visual attention significantly [2]. In this context, *Dwell Time* has been researched as an interaction modality for road users. Riegler et al. [69] compare different gaze-based interaction modalities, including *Dwell Time* with two different feedback types, showing that *Dwell Time* is a viable alternative for AR interaction. Consequently, we include *Dwell Time* as an AR interaction modality for cyclists in our study.

Finally, Chatterjee et al. [11] present how AR can be used to simulate road traffic situations, helping researchers to understand better the utility and impact of their prototypes on the driver's attention. They simulate a biking scenario in their study while capturing electroencephalography and eye-tracking data to predict upcoming cyclists' attention changes. Future applications can use this approach to measure the cyclist's attention and provide suitable interventions.

2.3 Summary and Research Questions

Previous research has informed us about two aspects: (1) Current selection techniques in AR and (2) and increased use of AR to improve the cycling experience and safety. Here, previous research showed that AR for cyclists is increasing the safety of vulnerable users [53], while new concepts were investigated to improve the cycling experience [45, 76]. However, the interaction with AR in a cycling environment was not explored yet. Although past research showed that controls on the handlebar to interact were preferred by users [28, 82], they are limited to smartphone use only. Looking at different interaction modalities in augmented reality, we learned that gesture-based selection, the current standard for AR interaction, is outperformed by using physical remote controls [36, 85]. Furthermore, we hypothesize that AR interaction improves usability and efficiency compared to using secondary displays or smartphones by keeping the cyclist's attention on the road traffic. Previous work showed that secondary display interaction is distracting, which can compromise the cyclist's road traffic focus [13–15, 24]. At the same time, AR has recently been established as passive visualization to enhance the safety of cyclists [61]. However, explicit AR interaction modalities for cyclists remain a research gap.

Finally, selections with gaze tracking in AR is a viable alternative [8], but are currently affected by critical limitations (e.g., the Midas touch effect [32]). Therefore, researchers proposed *MAGIC Pointing* as an alternative [48, 50] in the context of large displays and interaction in AR to circumvent this challenge. Finally, researchers are investigating the impact of AR use on attention while driving. Here, we find that AR is redirecting the user's attention [72] when being under a high workload and requiring interaction [78]. We state the following research question concerning the interaction efficiency and usability for AR interaction while cycling:

RQ: How do different AR notification selection techniques influence cyclists' interaction performance, task load, and perceived usability?

3 METHODOLOGY

This section explains the study design, tasks, and apparatus of the conducted study. We investigate the three hypotheses informed by related work:

H1: *MAGIC Pointing* requires the lowest task completion time from cyclists compared to *Dwell Time* or *Gestures* during target selection.
H2: *MAGIC Pointing* elicits the fewest errors from cyclists compared to *Dwell Time* or *Gestures* during target selection.
H3: *MAGIC Pointing* leads to the lowest perceived task load for cyclists compared to *Dwell Time* or *Gestures* during target selection.

3.1 Task

The participants were cycling in front of a video wall displaying a virtual bike tour while wearing a HoloLens 2 in a within-subject study design. Here, notifications were displayed on the HoloLens 2 at semi-randomized times, but at least at some time within 20 seconds. Each notification contained a text and two buttons (“Left”, “Right”), indicating which button to press. First, participants had to identify the correct button by reading the text explicitly stating which button (i.e., “Left” or “Right”) the user must select. Then, they were instructed to interact with the correct button, as indicated in the notification’s text, as fast as possible while continuously cycling. Finally, the participants were asked to observe their environment, similarly to if they would cycle in the real world, to ensure that the AR interaction remains a secondary task.

3.2 Independent Variable: Selection Modality

We interchanged the confirmation modality for committing notifications as a single independent variable. Informed by related work [16, 82], we adapted the three target selection modalities *Dwell Time*, *Gestures*, and *MAGIC Pointing* for cycling. Here, previous research suggested that interaction designs that maintain the focus on the road traffic can increase the interaction efficiency for cyclists [24, 61]. We refrained from using selection modalities requiring cyclists to look away from the road traffic (e.g., external displays or smartphones) [13–15], hence compromising the cyclists’ road traffic attention. Thus, we focus on AR selection modalities maintaining the cyclist’s vision of the road traffic during the interaction. Participants were asked to conduct target selections using the following selection modalities:

3.2.1 Dwell Time. Participants conducted a selection by gazing at the corresponding button for 1.8 seconds. We have selected this adapted dwell time to avoid unnecessary long input times impacting the participant’s cycling performance and too short input times that will result in unintended selections based on previous work [31, 73]. Short *Dwell Times* were often used in experimental lab settings [73], where longer *Dwell Times* were successfully evaluated in practical settings [8]. After initial user tests to determine a feasible *Dwell Time*, we have adapted a *Dwell Time* of 1.8 seconds for our task. We use the integrated eye tracker to obtain eye gaze tracking with the HoloLens 2. In the context of cycling, we have designed and included this selection modality as a hands-free interaction technique that does not require the cyclist to lift their arms from the handlebar while cycling.

3.2.2 Gestures. We use the built-in HoloLens 2 gestures as selection modality. First, participants use their eye gaze to select a button. Then, they confirm the selection using a hand pinch gesture. The hand pinch gesture is executed by pressing the thumb and index finger together. We use the HoloLens 2 hand tracking to detect pinch gestures. We consider gestures a baseline in our study since they are a standardized HoloLens 2 interaction technique. We have included this selection modality as an alternative to *Dwell Time*, where the target selection can be conducted without depending on aa dwell time. In the context of cycling, we anticipate circumventing the Midas touch problem [27] while allowing the user to execute their interaction at opportune moments during the cycling scenario. However, in contrast to *Dwell Time*, *Gestures* requires the user to lift one hand from the handlebar. Including the *Gestures* selection modality enables us to study the impact on the usability of one-handed cycling for target selections.

3.2.3 MAGIC Pointing. MAGIC Pointing combines gaze with a physical button press to confirm a selection. Again, participants were asked to gaze at the selection. However, instead of confirming their choice with *Dwell Time*, participants confirmed their selection immediately by pressing a physical button mounted on the handlebar. This approach is inspired by previous work that used *MAGIC Pointing* for gaze-based interaction with large displays [18, 50, 71, 75]. Similar to the *Dwell Time* condition, gaze tracking is realized using the integrated HoloLens 2 eye tracker. In the context of cycling, *MAGIC Pointing* allows target selections while keeping both hands of the user on the handlebar using the user’s gaze, representing a combination of *Dwell Time* (i.e., for the initial selection) and *Gestures* (i.e., confirming the selection). We designed *MAGIC Pointing* to include additional cycling control by leaving both hands on the handlebar during target selections.

We chose a within-subject design and balanced Latin square to counterbalance the conditions. Participants were cycling for approximately six minutes during each condition, where 18 notifications were displayed (i.e., three per minute). Each participant was confronted with 54 notifications throughout the experiment, conducting 54 target selections (i.e., 18 per condition). We measure the Task Completion Time (TCT) to confirm each notification, the number of errors, and the perceived task load. Participants filled in NASA-TLX questionnaires and were invited to provide verbal feedback about the selection modality. Finally, we conducted semi-structured interviews at the end of each experiment to obtain qualitative feedback from the participants.

3.3 Dependent Variables

We operationalize the following measures for the study.

Task Completion Time. We measure the time between the appearance of the notification and the successful selection of the notification. The task completion time is calculated for each notification.

Error Rate. We measured the number of errors to calculate the error rate per condition. An error is counted when a participant selects the wrong confirmation in a notification. Correct and incorrect selections are measured for each notification. Notifications that timed out after ten seconds were counted as errors and were not considered for the analysis of the task completion time.

Task Load. We measure the task load using the NASA-TLX questionnaire [25, 26]. Each participant answered the NASA-TLX questionnaire after every condition.

User Experience. We assess the subjectively perceived user experience using five five-point Likert questions[1]. Participants were filling in the Likert questions after every condition. An overview of the questions is depicted in Table 1.

Table 1. Questions participants were asked after each condition.

Question ID	Question
Q1	I enjoyed to use the notification selection modality in the AR environment.
Q2	I can imagine to use the notification selection modality while biking.
Q3	I can imagine to use the notification selection modality in daily life.
Q4	The selection modality appears innovative to me.
Q5	Overall, I enjoyed using the notification selection modality.

Interviews. We conducted semi-structured interviews to obtain qualitative feedback at the end of the experiment. We began by inquiring the participants about their general feedback and preferences regarding the selection modalities. We then continued to ask about the potential preferred notification placement and the desire to view notifications during cycling. Afterward, we discussed how the selections can be improved and what alternative use cases for interactions while cycling could look like.

[1] 1: Strongly disagree; 5: Strongly agree.

(a) (b)

Fig. 2. Used setup for the study. **(a):** We used a bike simulator to imitate a realistic cycling scenario. The scenario itself is visualized on a video wall consisting of six screens. **(b):** A participant is interacting with gestures while using the bike simulator.

3.4 Study Setup and Apparatus

The system consists of an indoor bicycle in a controlled lab environment and a video wall consisting of six displays showing an ordinary inner-city street environment in front of the user, aiming to simulate the normal day-to-day use. We decided against using a regular bicycle on real roads to improve the experiment's internal validity while preventing dangerous situations for our participants. We did not consider a simulator in virtual reality for safety reasons since participants might have difficulties managing their balance or might have an increased susceptibility to motion sickness [62, 63, 81]. In contrast to studies in the automotive sector, where virtual reality simulations are common, biking involves active motoric movements while holding the balance. Unexpected situations in virtual environments (e.g., toddlers running before the bike) combined with no awareness of the real-world (e.g., balance and steering limitations) can lead to dangerous situations for the cyclist. Hence, we used a bike simulator to simulate a realistic biking situation using a prerecorded video displayed on a video wall. The bicycle itself had a 28-inch wheel, placed on a fixed platform with lateral suspension (Kinetic Rock and Roll[2]) (see Figure 2a). The setup allows cyclists to turn the handlebar of the bicycle to the left and right. This ensures a realistic cycling scenario when using the bicycle simulator. Participants had to cycle on the indoor bike within a virtual bike tour[3]. The bike tour was presented to the participant using a video wall consisting of six 4K monitors (i.e., a 2×3 arrangement) (see Figure 2b). The cycling route consisted of a straight road with slight curves, comparable to a real-world cycling scenario. We instructed the participants to follow the flow of the simulation and cycle according to the velocity and turn the handlebar to the direction of the simulation when cycling a curve. To reflect a realistic cycling scenario, we have selected a part of the video where the scene was busy, including intersections, other cyclists, pedestrians, and approaching cars. Throughout the simulation, we showed no special occasions, such as accidents or abrupt events.

[2]www.kurtkinetic.com/trainers-products/rock-and-roll-smart-2 - last access 2022-08-01
[3]The tour was an excerpt of a biking tour through Amsterdam: www.youtube.com/watch?v=PcKXjFCC2f0 - last access 2022-08-01

(a) (b)

Fig. 3. Video wall simulating a cycling scenario while participants were receiving AR notifications using a HoloLens 2. All notifications contained a text, advising participants which button to press. **(a):** Participants were inquired to select the left button. **(b):** Participants were asked to press the right button.

We use a HoloLens 2[4] to display the notifications during all conditions. The user's eye gaze and gestures are detected by the HoloLens 2 through its two infrared light eye-facing and four visible light front cameras. We decided to use the HoloLens 2 and its mobile gesture detection because it has been successfully used in studies considering cycling and road contexts [60, 61]. We established a Bluetooth connection between an ESP32 microcontroller with a single button and the HoloLens to provide the *MAGIC Pointing* functionality. Participants were invited to mount the button in a preferred position on the bike's handlebar. We use Unity[5] for the implementation and visualization of the notifications.

The whole AR interface consists of notifications only. No other visual elements were displayed. The notifications were designed as simple rectangular text boxes with two buttons on the bottom, which the participants must select. We kept the overall number of occurrences (i.e., 18 notifications per condition) and the size of the notifications static. However, we semi-randomized the popup positions within the field of view to prevent participants from memorizing and adapting to the time intervals or positions. The notifications show short messages consisting of two sentences, where one sentence contains a task-unrelated message and the second sentence describing which button to press using one of the three input modalities described before. We equally randomized the order of the sentence describing which button to press (i.e., the first or second sentence) to avoid learning effects through memorizing which parts of the text are relevant for the task. If a participant does not select the correct button within 10 seconds, the current selection is logged as a timeout error. Figure 3 shows the video wall and how users were inquired to press the correct button for a notification.

3.5 Procedure

We adhered to our universities health department guidelines for user studies during the COVID-19 pandemic. All testing equipment was disinfected, and the experiment hall was aired out for a minimum of one hour between the participants. Every experiment was done with one participant at a time. The participant was greeted and introduced to the research objectives. We then collected demographic data, possible former experience with head-mounted displays, and the overall bicycle

[4] www.microsoft.com/en-us/hololens - last access 2022-08-01
[5] www.unity.com - last access 2022-08-01

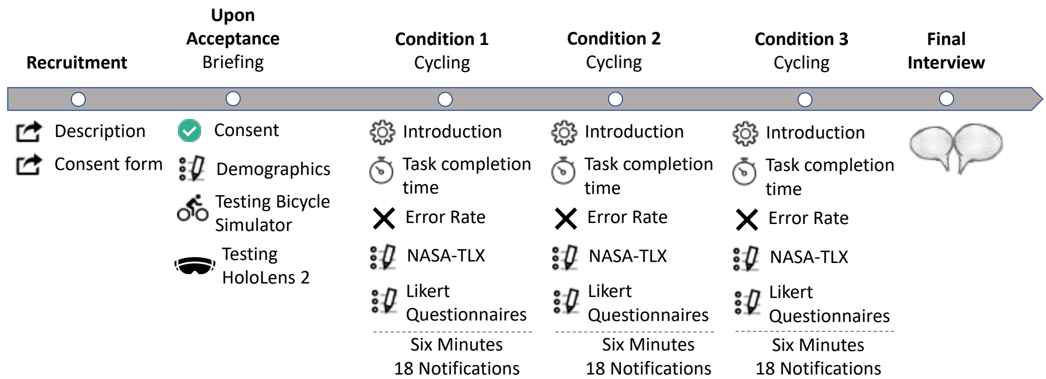

Fig. 4. Illustrated study procedure. After briefing the participants and obtaining signed consent, participants started to confirm notifications using the described selection modalities while we collected data for later analysis. We conducted semi-structured interviews at the end of the experiment.

experience. Participants were familiarized with the system using the bicycle simulator and interacting with the HoloLens 2 independently for five minutes each. This was done to reduce learning effects by knowing the particular components without influencing the task afterward.

We then assigned the selection modality according to the balanced Latin square. The participants tested the respective selection modality before every condition while sitting on the bicycle. The participants then started with the assigned selection modality. They were cycling for six minutes per condition while wearing the HoloLens 2. 18 notifications were displayed during each condition. Next, participants answered a NASA-TLX questionnaire on the perceived task load and five five-point questions after each condition (see Table 1). The same procedure was repeated for the remaining two selection modalities. Finally, the participants conducted a semi-structured interview after accomplishing all conditions. The whole study procedure took one hour in total. Figure 4 depicts the study procedure.

4 RESULTS

This section presents the analysis of the collected data. The data were tested for compliance regarding normality using Shapiro-Wilk tests before applying statistical testing. Mauchly's test was used to ensure sphericity for all measures. We applied Bonferroni corrections to all post hoc tests (i.e., a Bonferroni corrected alpha value of .05 divided by the number of comparisons). Figure 5 shows the mean values of the measures.

4.1 Participants

We recruited a total of 18 participants (12 male, 6 female) with an age ranging from 22 to 61 ($\bar{x}$ = 31.39, s = 13.52). All except one participant reported that they are interested in new technologies and generally like to update on emerging innovations. Ten participants reported that they cycle at least once a month. Eight participants reported that they cycle at least once a week. We then explained the purpose of the study to the participants and informed them they could cancel the study at any point without affecting their compensation.

4.2 Task Completion Time

A Shapiro-Wilk test did not reveal a deviation from normality, $p > .05$. A repeated measures ANOVA revealed a significant main effect on the task completion time between the notification

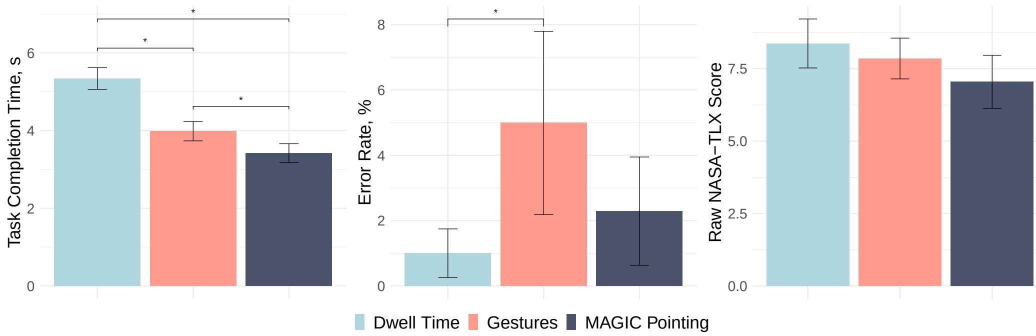

Fig. 5. Averaged results of our measures. **Left:** *MAGIC Pointing* results in the lowest task completion time. **Middle:** *Dwell Time* results in the lowest error rate. **Right:** *MAGIC Pointing* elicits the lowest task load. The error bars depict the standard error. The brackets indicate significance.

selection modalities, $F_{2,34} = 42.90$, $p < .001$. Bonferroni-corrected pairwise post-hoc tests showed a significant effect between *Dwell Time* and *Gestures*, $p < .001$, *Dwell Time* and *MAGIC Pointing*, $p < .001$, and *MAGIC Pointing* and *Gestures*, $p < .036$. *MAGIC Pointing* was the fastest selection modality ($\bar{x} = 3.42s$, $s = 1.02s$) followed by *Gestures* ($\bar{x} = 3.98s$, $s = 1.06s$) and *Dwell Time* ($\bar{x} = 5.34s$, $s = 1.19s$).

4.3 Error Rate

We fitted a generalized linear mixed model (GLMM) with the selection success as a binominal (logit) outcome variable and the commit modality as a fixed effect. Further, we added the participant as a random effect. The analysis of deviance tables using Type-III Wald χ^2 tests indicated a significant effect of the commit modality, $\chi^2(2) = 8.45$, $p = .015$. Bonferroni-corrected pairwise post-hoc tests confirmed a significantly higher error rate between *Dwell Time* to *Gestures*, $p = .002$. However, no other significant effects were found. *Dwell Time* resulted in the lowest error rate ($\bar{x} = 0.01s$, $s = 0.03$) followed by *MAGIC Pointing* ($\bar{x} = 0.02$, $s = 0.07$) and *Gestures* ($\bar{x} = 0.05$, $s = 0.03$).

4.4 Task Load

We used the raw NASA-TLX to measure the subjectively perceived task load [25]. After each condition, participants filled out a NASA-TLX questionnaire to investigate if the modalities induced different task loads.

A Shapiro-Wilk test did not indicate a deviation from normality, $p > .05$. The analysis of the raw NASA-TLX values yielded no significant differences ($F_{2,34} = 1.59$, $p > 0.05$) between all three modalities. *MAGIC Pointing* elicited the lowest task load ($\bar{x} = 7.05$, $s = 3.98$) followed by *Gestures* ($\bar{x} = 7.85$, $s = 2.99$) and *Dwell Time* ($\bar{x} = 8.37$, $s = 3.59$).

4.5 Five-Point Likert Questionnaires

We statistically analyze the five-point scales for statistical significance[6]. A repeated measures Friedman test found a significant main effect for the selection modalities in Q1, $\chi^2(2) = 6.62$, $p = .04$, and Q2, $\chi^2(2) = 14.77$. Bonferroni-corrected post-hoc tests revealed a significant difference between *Dwell Time* and *Gestures*, *Dwell Time* and *MAGIC Pointing*, and *Gestures* and *MAGIC Pointing* for both questions (all $p < .05$). No significant main effect was found for the other

[6] 1: Strongly disagree; 5: Strongly agree.

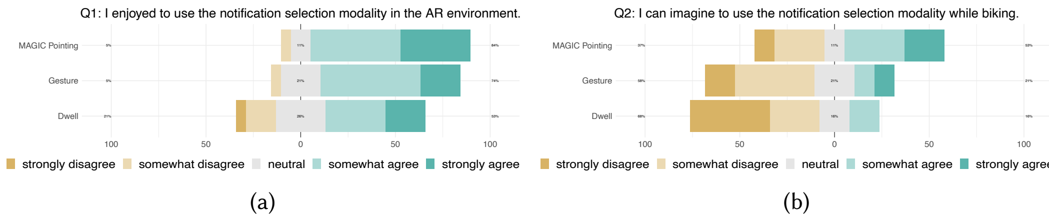

Fig. 6. Distribution of ratings for Q1 and Q2. All pairwise comparisons showed significant differences. *MAGIC Pointing* was favored in both inquiries.

questions. Figure 6 shows the distribution of ratings for the questions with significant differences (i.e., Q1 and Q2).

4.6 Qualitative Feedback

After each experiment, we conducted semi-structured interviews, inquiring participants about their subjectively perceived usability and experience. The participant statements were noted down by the experimenter during the interview.

We asked the participants about their perceived mental and physical demands when answering notifications during their rides. We then continued to ask about their perceived usability, personal preferences of their commit times using *Dwell Time*, how distracting notifications were while maintaining attention on the biking task. Finally, we asked participants about general feedback regarding the notification selection modalities, preferred notification placements, and future use cases.

4.6.1 Mental Demand. The participants were asked about how distracting the system is perceived. Fourteen participants indicated that the interaction with the notifications was distracting. However, the notification confirmation modalities elicited varying levels of mental demand. *Dwell Time* was subjectively ranked as most distracting by 14 participants. Four participants found *Gestures* distracting, while no one felt distracted by *MAGIC Pointing*. The participants felt that employing many different and novel aspects, such as AR popups of notifications, control of the cursor via gazing, or using a haptic single-use button, seemed "intuitive" and did not actively distract after a couple of minutes of using it.

The different tasks of focusing on the traffic, cycling, reading notifications, committing their choice in combination were reported as mentally exhausting. In addition, many participants mentioned the trouble of changing their visual focus while trying to select the button via *Dwell Time*[7]:

> *"I have nausea from jumping back and forth between the layers of perception."* (P8)

Here, participants reported that interacting with *Dwell Time* while cycling limited the visual focus. One participant reported difficulties noting the notification, selecting a button, and simultaneously paying attention to the road. Overall, *Dwell Time* was tampering with the participant's visual attention:

> *"Simultaneously searching for information and interacting both with the eyes was conflicting. The gaze is led astray as soon as one sees something from the corner of one's eye.*

[7]Quotes presented in this paper have been transcribed from their original native language into English.

This is unpleasant if one already knows what to do and still needs the eyes to commit it." (P1)

4.6.2 Physical Demand. We asked participants about their perceived physical demand. Participants reported having difficulties in maintaining their balance on the bicycle when using *Dwell Time* or *Gestures*. At the same time, unoccupied hands were generally perceived as necessary to hold the handlebar or to use the break. However, one participant can imagine using *Dwell Time* interaction in another context:

> *"I would rather use it at home or in any other static context where my hands are busy, for example, when cooking or repairing."* (P18)

It is not required to let go of the handlebar with *MAGIC Pointing* or *Dwell Time*. Nevertheless, *MAGIC Pointing* does confine the full unoccupied use of one hand. Participants positively remarked that it would be an easy solution to attach the hardware button to the handlebar of their bike. While most participants mentioned skepticism with interacting on a device while biking, *MAGIC Pointing* was the most preferred interaction device. In the case of day-to-day usage, the preferred modality changes from *MAGIC Pointing* to *Dwell Time* and *Gestures* due to the hindrance of an always occupied hand and additional hardware.

4.6.3 System Feedback. All users endorsed some feedback for their selection and committed to increasing their trust in the reliability of the modalities. The subjectively perceived reaction time also played a role, where *Dwell Time* was perceived as sluggish, inefficient, and unclear regarding a successful commit. This is most likely due to the required dwell time itself. Different results can be expected when setting the *Dwell Time* itself lower. Hence, *Gestures* and *MAGIC Pointing* were preferred considering their precise ways of selecting notifications:

> *"Gesture control, in general, has been an established option since the first use of smartphones. Therefore, this kind of submission is already known. However, in 3D space, it is very prone to wrong interpretation. Often it either fires much too fast or not at all, even after several attempts."* (P10)

One participant highlighted the relevance of haptic feedback when selecting a button. *MAGIC Pointing* was preferred due to the button integration and direct way of confirming the feedback:

> *"I knew that if I clicked the physical button, the virtual one would be clicked as well."* (P18)

However, participants reported that both *Dwell Time* and *Gestures* invoked the fear of wrongful or missing commits for some users. This is also echoed by the higher error rate when using *Gestures*. Twelve participants saw the aspect of a realistic physical input directly related to the interaction as helpful. One user noted that any kind of feedback would be sufficient for them.

4.6.4 Notification Placement. The participants did not show a clear tendency towards the notification placement. Nine participants favored an always centered notification placement, helping them immediately notice notifications. The other nine participants preferred to see them aside, not to block their view, and, therefore, ignore the message if necessary. For example, one participant proposed that the notifications could even intentionally appear outside of their field of view and only notify them via sound so they could have a look when necessary.

However, most participants found the varying placement confusing and disliked it when notifications appeared entirely outside their current field of view. The discussion around the field of view and popup area was also driven by the semi-transparent design of the notifications (see Figure 3). Most participants favored seeing through the notifications while visually perceiving the environment through the notification itself. For this reason, placement in the middle was a suitable option for the participants.

4.6.5 Time Parameter of Dwell Time. The additional time needed having to keep their gaze still when using *Dwell Time* was described as annoying, tiring, and highly distracting by all users:

> *"Dwell Time requires the least movement, yet it is exhausting over time with needing nearly two seconds without moving the eyes. It is perceived even longer."* (P10)

However, the consideration of a shorter time for committing was also seen as problematic:

> *"Dwell Time would have been better if the time needed were shorter. But then again, one couldn't correct anything and had no time to think about the action."* (P11)

> *"A shorter time would be bad because one would constantly choose things unintentionally."* (P10)

4.6.6 Use Cases. The participants brought up different ideas for possible use cases, including chances for the work environment, museums, or leisure parks. Twelve participants saw some profitable opportunities to use and interact with AR while cycling or driving a car. Nevertheless, half of the participants would prefer to read relatively short texts and perform simple interactions:

> *"I admit that sometimes you need to interact with your bicycle and an app on your smartphone. It is unnecessary to do on the way, but I can imagine using them for short notifications or confirmations. Therefore, it should be short, clear, and not requiring much of my attention, which was the case with the physical button."* (P18)

Another participant favored the micro-interactions when using *MAGIC Pointing*:

> *"It has great potential, for example, when using one's smartphone while cycling: calling, navigation, controlling music. Due to the gazing, it is easy and intuitive to use."* (P9)

One commonly mentioned aspect was the connection between their primary task and the AR application. While one participant explicitly highlighted the possibility of doing different things in parallel, most emphasized that AR should assist them in what they are currently doing, rather than providing additional other functions:

> *"With increasing connectivity, cycling is a chance for a mental break. As such, in my opinion, the interaction with notifications on the bicycle would increase the daily stress level. However, apart from cycling, it is considerable if one often looks at one's phone anyway. Yet, if the matter in focus is apps that help cycling itself (navigation, warnings, etc.), usage in this area is possible."* (P7)

4.6.7 Influences by External Circumstances. Several situational conditions shaped the opinion about using AR and a notification selection modality while cycling. Over 50 comments concerned the factor of time-critical environments and attention in general, which require quick reactions. Here, *Dwell Time* is preferred in non-time-critical use cases:

> *"The requirement of having to look in one particular direction is inappropriate on the road. In production or for non-time-critical activities, however, it would be a comfortable alternative."* (P3)

> *"In everyday life, fast reactions are seldom required and Dwell Time is sufficient."* (P5)

> *"Using this may be possible for activities without a relevant time component. It is inappropriate for everything that needs permanent attention apart from the AR control."* (P13)

The possibility of ignoring popups is important, letting users decide when to deal with them. This goes hand in hand with attention, safety, or being a danger for others, as mentioned by one participant:

> *"Facing challenges of safety, such as on the road, I would use it only if I am convinced by the reliability of the system and given that I do not get distracted too much."* (P17)

Six participants remarked that already being proficient in the primary task is very important. Automatism or even slight insecurities can highly influence how critical the distraction or the additional hand requirement is. This was mentioned especially often regarding *Gestures*.

An aversion to using them in public spaces was mentioned, especially for *Gestures*. Participants feared privacy implications when other people were watching them performing gestures. *Dwell Time* is perceived as the least disruptive and most discreet, followed by *MAGIC Pointing*. In this context, the participants remarked that passively reading notifications without interaction while cycling is entirely sufficient in most cases:

> *"AR is great on the road when only used as a 'passive assistance' element. If one is forced to focus on what is happening on the glasses, one quickly loses attentiveness towards the environment. For example, when controlling navigation, music, calls."* (P3)

Finally, participants mentioned additional use cases outside of cycling scenarios:

> *"Another possible application I can imagine is as a pure information source, for example, like navigation or speed indication."* (P13)

> *"I imagine notifications while cycling as less distracting than interacting with the device."* (P5)

> *"Selecting buttons with the eyes only can be very helpful in many situations, e.g., if one is cooking or has dirty hands, or if one holds an object and cannot lay it down at this moment."* (P14)

5 DISCUSSION

The quantitative and qualitative results of the study reveal the overall feasibility of AR interaction while cycling. Our results show different advantages and disadvantages depending on the cycling context and use case. The opinions towards the three study modalities under test change significantly depending on the use case. The following section interprets our results and contrasts them with the previously stated research questions.

5.1 *MAGIC Pointing* has the Lowest Task Completion Time

The analysis of the TCT reveals a significant difference between the three interaction modalities *MAGIC Pointing*, *Dwell Time*, and *Gestures*. Moreover, a clear distinction can be made between *Dwell Time* compared to the two other modalities, *Gestures* and *MAGIC Pointing*. Both *Gestures* and *MAGIC Pointing* do not require a temporal component compared to *Dwell Time*-based interaction, allowing an instant selection. In contrast, *Dwell Time* requires the participant's focus over some time. Many participants reported *Dwell Time* being highly distracting from the actual biking task since a deliberate effort was needed to interact with the system. Therefore, they perceived it as exhausting and as a source of permanent distraction from the primary task at hand. This significant difference probably also influences the further hypotheses and research questions. The waiting times during the *Dwell Time* selection are, however, an essential parameter of the modality, comparable to other selection modalities needing physical movements (e.g., *Gestures* when raising the hand). However, shorter *Dwell Time* could rectify this at the increased risk for false-positive selections due to the Midas touch effect [32]. Since the duration of *Dwell Time* highly depends on the use case and individual preferences, future research should consider the impact on the cycling performance using adaptive *Dwell Time* strategies [64]. *MAGIC Pointing* showed a significantly shorter TCT compared to *Gestures*. Participants reported that the physical movement and adjustment of the hand while cycling costs time, where *MAGIC Pointing* does not need participants to let go of their hands from the handlebar. Furthermore, hand movements in front of the HMD occluded the field of view and made it difficult for the cyclists to hold their balance. **If short AR interactions are necessary while cycling, designers of mobile interfaces should consider the use of *MAGIC Pointing* to reduce the interaction duration during demanding cycling scenarios.** Finally, we conclude that *MAGIC Pointing* is a viable alternative to *Gestures* when interacting with notifications while biking. **Hence, we confirm H1.**

5.2 *Dwell Time* Results in Lower Error Rates While Requiring More Attention and Focus

Dwell Time leads to the lowest error rate. We find a significant difference between *Gestures* and *Dwell Time*, where *Gestures* have the highest error rate compared to *Dwell Time*. One reason is the higher inaccuracy of selecting the correct button when using *Gestures*. Besides lifting one hand from the handlebar, the other movement through cycling made it more difficult for the participants to select the appropriate notification button. *Dwell Time* was not affected by this. The HMD moved with the participants, hence compensating for the bicycle movements. Furthermore, *Dwell Time* provides a more robust selection by requiring participants to look at the correct button for 1.8 seconds which is enough time to make robust selections even when cycling. Previous work confirmed more robust selections when using *Dwell Time* [1]. However, in our qualitative inquiries, one participant echoed that *Dwell Time* was perceived as distracting and tedious. **Although *Dwell Time* reduced the error rate, further research for different dwell times is necessary to investigate how shorter selection times affect the error rate in contrast to usability.**

MAGIC Pointing did not show a significant effect between the other two conditions, with an error rate lying between *Dwell Time* and *Gestures*. **Hence, we cannot confirm H2.** Participants favored keeping both hands on the handlebar while interacting with notifications. At the same time, they also remarked that they have to visually refrain from the street for a shorter time than *Dwell Time*. *MAGIC Pointing* can resemble an alternative to the other modalities by reducing visual distractions through efficient selections.

5.3 *MAGIC Pointing* does not Lower Task Load, but is Subjectively Preferred

The subjective task load did not significantly differ between the three conditions, **thus not confirming H3.** However, the interviews revealed individual preferences and sentiments towards the selection techniques. A majority of participants reported being more confident using the subjectively more accessible modalities *Gestures* and *MAGIC Pointing* compared to *Dwell Time* both mentally and physically. Furthermore, participants preferred the haptic feedback provided by the *MAGIC Pointing* input. While the haptic aspect was essential to some participants, extensive feedback of all kinds might improve confidence, especially when using *Dwell Time*. Hence, confirmation feedback should be included in future selection techniques (e.g., haptic feedback). We attribute the lower need for feedback due to the nature of *MAGIC Pointing* and *Gestures*. Both techniques provide a separate confirmation mechanism, something that lacks for *Dwell Time* selections. A selection can be committed instantly with a tap of the finger or a hardware button. With this integrated feedback, the user does not have to put much effort into recognizing if an input has been detected and can therefore continue with other tasks quickly. *Dwell Time* however, it requires more attention, thus occupying the mind of the user much more. As mentioned before, gesture detection did have some trouble detecting hand pinches, achieving an overall reduced preference. Also, many participants reported issues with keeping their balance while raising the hand from the handlebar, increasing this modality's physical and mental demand. Thus, we identify this as an additional influence on the cognitive load and their choice. **Finally, the participants mentioned keeping the interaction**

at a minimum with all selection modalities, advising to either use *MAGIC Pointing*, which provides cyclists with more control, or use *Dwell Time* with shorter selection times.

5.4 Limitations and Future Work

Our study was affected by several limitations. First of all, participants interact for a fixed amount of time during the *Dwell Time* modality. Past research suggested a fixed amount of time with different ranges [8, 73] while recent research proposed the use of dynamic *Dwell Times* [64]. Short *Dwell Times* were often used in experimental lab settings [73], where longer *Dwell Times* were usual in practical settings [8]. Hence, we have chosen a longer *Dwell Time* since biking is a practical task where false positive selections are more likely to occur. We plan to conduct further research on the dynamic selection of *Dwell Times* based on the cyclists' attention and context. We have conducted a lab study, and the implications of our results in real-world settings can be different. Vibrations or jolts are common while biking in the real world and could have influenced the resulting number of errors. Finally, participants reported the HMD itself as a key limitation. Some participants reported that gesture recognition did not always work as expected and that the narrow field of view of the holograms restricted their immersion. The weight of the HoloLens 2 and its fastening to the head further prohibited some participants from moving their heads freely. Hence, the choice of hardware might lead to different results than reported in this study.

The study focused on reacting to relatively short notifications by interacting with one of two buttons. Future work might continue this field of research by studying the use of AR for a smartphone replacement, interacting not just with notifications but with a complete mobile operating system. Safe long-term usage of such a system might yield fruitful results as the novelty of using AR slowly wears off. Therefore, the preferred modalities will be researched in a long-term study within a day-to-day scenario. Furthermore, we will compare the results of the in-the-wild study with the findings of the present study, assessing the validity of simulated and real-world studies, including their safety aspects and different road busyness levels. The future study will compare the preferred *MAGIC Pointing* and *Dwell Time* selection modality with smartphone interaction in a real-world study regarding efficiency and safety.

Another interesting approach might be to study how the acceptance changes depending on how much the interface and the portrayed information are related to the primary task. Various parameters of the modalities tested herein can also be varied to see how the experiences with the modalities change, such as mapping the interface onto the physical world, the extent of interactions, the length of texts, or the timings of *Dwell Time*. Further factors, including emotion measurements [5, 39, 41], cognitive assessments through gaze [38, 40] and cortical behavior [37, 42, 43] will be investigated for adjusting *Dwell Times* dynamically in real-time. Furthermore, AR and its modalities could be tested for demanding primary tasks. Stationary tasks do not require keeping balance, and more minor or more challenging tasks, in general, might show other users' preferences. In this context, the placement of interaction and information areas is an objective for future research.

Finally, novel study hardware can lead to a biased participant perception regarding the study results, wearing comfort, usability, and gesture recognition quality [44]. Although we have used the HoloLens 2 as a consumer standard, we expect this type of technology to mature in the future, providing a performance close to professional visualization (e.g., improved field of view) and gesture recognition (e.g., tracking quality similar to professional-grade equipment such as OptiTrack). However, we acknowledge the choice of portable hardware as a study limitation.

6 CONCLUSION

In this study, we investigated the performance of three different selection modalities in Augmented Reality (AR) for cyclists. We evaluated the three selection modalities *Dwell Time*, *Gestures*, and

MAGIC Pointing, finding that *MAGIC Pointing* yields the fastest target selection. *Dwell Time* and *Gestures* showed a significant difference in the error rate while *MAGIC Pointing* did not show a significant effect. However, semi-structured interviews revealed a preference for *MAGIC Pointing* when answering notifications in AR. At the same time, *Dwell Time* was distracting and detrimental to the interaction efficiency of the cyclist. Participants reported different factors influencing their preferences, where potential improvements and use cases were stated. We conclude that a multi-modal approach combining gaze-based and immediate physical confirmation is an efficient and accepted type of interaction while biking. Our study sets the boundaries for future AR interaction for cyclists who intend to perform efficient on-the-go interaction while maintaining visual road traffic attention.

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