

Facing Danger Head-On: Eye Tracking-Supported Visualizations for Cyclists to Improve Traffic Awareness at Intersections

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(a) Bicycle simulator setup. Cycling speed was tracked with a Tacx Neo 2, steering via an Elite Sterzo Smart, and visuals with a Varjo Aero VR headset.



(b) The Bicycle Warning System (BWS) prototype: Vehicles highlighted with color-coded overlays (yellow = attention, red = critical), independent of gaze direction.

(c) The Bicycle Warning System with Eye Tracking (BWS-ET) prototype: Overlays dynamically adapt to gaze: opacity decreases when looking directly at a vehicle, while peripheral glows fade to confirm awareness.

Fig. 1. In this paper we present concepts for supporting cyclists' traffic awareness at intersections (b) by highlighting upcoming vehicles and (c) adapt them based on the cyclist's gaze.

Cycling has become more popular in recent years, yet unlike car travel, where major safety improvements have reduced accidents and injuries, cycling safety has seen little progress, leaving cyclists more vulnerable than car passengers. To improve cycling safety, we extend concepts for head-mounted visual bicycle warning systems and integrate eye tracking to adapt warnings based on the cyclist's gaze. Results from a within-subject simulator study ($N = 14$) show that our extended concepts improve road safety perception and user experience. Our study underscores the potential for interactive eye tracking technologies to advance bicycle safety systems. Based on our results, we provide design implications that facilitate the development of advanced bicycle warning systems.

CCS Concepts: • **Human-centered computing** → *Human computer interaction (HCI)*; **Ubiquitous and mobile computing**.

Additional Key Words and Phrases: Bicycle warning systems, interactive eye tracking, head-mounted bike assistance, gaze-adaptive visualizations

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Manuscript submitted to ACM

Manuscript submitted to ACM

ACM Reference Format:

Volker Göhler, Felix Heisel, Florian Eberhard Schierz, and Bastian Pfleging. 2026. Facing Danger Head-On: Eye Tracking-Supported Visualizations for Cyclists to Improve Traffic Awareness at Intersections. In *Proceedings of The 10th ACM International Symposium on Pervasive Displays (PerDis 2026)*. ACM, New York, NY, USA, 14 pages. <https://doi.org/XXXXXXX.XXXXXXX>

1 Introduction

Worldwide, a large number of people are affected by traffic accidents every day with more than one million people dying every year as a consequence of traffic accidents¹. Since the second half of the 20th century, traffic safety research has gained increasing importance, aiming to reduce the risks for passengers and pedestrians involved in car accidents [9]. In contrast, developing safety technology for bicycles is restricted in particular by the bike’s form factor. While modern cars comprise a multitude of active and passive safety technologies, approaches to protect cyclists are limited and mainly relate to infrastructure like separating motorized and bike traffic or passive safety (e.g., helmets). In recent years, cycling has gained popularity as a health-conscious and environmentally sustainable mode of transportation. This growing trend, however, has also been accompanied by a noticeable rise in traffic accidents involving cyclists. According to a study by Statista, participation in various bicycle-based transport activities in the U.S. increased by more than 5 million people between 2018 and 2023².

To assist cyclists’ awareness, we propose two visual augmented reality concepts to improve cyclists’ situation awareness on and around intersections. Based on prior work, we propose adapted visualizations and integrate eye tracking to better highlight unseen cars that are about to reach an intersection. Results from a within-subject study reveal that our proposed concepts enhance both perceived safety and user experience. These positive findings underline the importance of continued efforts to improve cycling safety through assistive technologies. Building on this potential, we advocate for further research and development in this field and offer concrete recommendations for advancing cyclist protection in everyday traffic.

Contribution Statement: Our contributions are threefold: (1) We present an enhanced visual warning system for cyclists that uses eye tracking to adapt warnings based on the cyclists’ gaze behavior along with a proof-of-concept implementation. (2) Through insights gathered from a mixed methods within-subject user study, we demonstrate how our method positively affects perceived safety and user experience. (3) We provide design implications for researchers in the field of cycling technology, offering guidance on developing improved bicycle warning systems.

2 Background and Related Work

This section provides an overview on prior work in the fields of traffic safety with a focus on bicycle assistance and warning systems. In the following, the term *Assistance System* is used when the purpose of the system is to provide general support, for example navigation aids or fall detection, and the term *Warning System* is used when the system has the specific main task of warning the cyclist, in particular of possible collisions. The term *Systems* is used for both types.

2.1 Fundamentals of Bicycle Assistance Systems

Gadsby and Watkins [6] provide an overview of research on bicycles using sensors to assist riders or gather information on user behavior. Since 2007, the number of studies has increased significantly, particularly with the inclusion of e-bikes

¹<https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries>, last access: 2025-08-10

²<https://www.statista.com/statistics/191204/participants-in-bicycling-in-the-us-since-2006/>, accessed at 2025-08-10

from 2012 onwards. Research has predominantly originated from North America and Europe, reflecting better funding and a stronger political focus on sustainable transportation.

Many studies rely on only one or a few sensor types, primarily GPS, cameras, accelerometers, gyroscopes, and speed sensors. However, GPS and cameras often present challenges in data processing. Gadsby and Watkins [6] classify 75 articles into eight main research areas, including the impact of e-bikes on behavior and safety, and the role of infrastructure in cycling. Kapousizis et al. [14] reported similar findings in their review of bicycle warning systems, noting a growing number of publications on collision avoidance technologies. Although many of the examined systems remain at the prototype stage, their results indicate a positive impact on cycling safety. The authors further emphasize the rising integration of network technologies to enhance safety, particularly in scenarios involving multiple vehicles.

Smart bicycles can be categorized into six levels of *smartness* or automation [14], similar to autonomous driving. These levels range from traditional bikes with no assistance (level 0) to fully connected systems where bicycles can communicate with other vehicles and infrastructure (level 5). Current research focuses on level 2 systems, which include warning systems and monitoring systems, with systems in development or prototype stages.

Progress towards level 5 requires substantial political, infrastructural, and societal changes, as well as technological advancements [21]. Kapousizis et al. [14] assess the technology readiness levels (TRL) for each stage, with smartness levels 0 and 1 having reached TRL 9 and 8, while smartness level 2 is at TRL 6 and level 3 at TRL 4. This classification places level 2 systems in the demonstration stage, implying that development is still ongoing, though early prototypes are beginning to reach the market.

2.2 Assistance Systems on the Market

There are various bicycle assistance systems available on the market, most of which can be classified as level 1 or 2. The Garmin Edge 1040 Solar³, for example, offers navigation assistance, emergency notifications, and fitness tracking, which places it as a level 1 and 2 monitoring system. Other monitoring systems include the Smarthalo 2, the Karoo 2 by Hammerhead⁴, and the Engo 2⁵, smart glasses with a micro-OLED projector that displays real-time fitness data and supports gesture control.

As for warning systems, Garmin's Varia Rearview Bike Radar⁶ detects vehicles via radar and provides alerts via a handlebar display and a flashing rear light. The ESub Tracks Helmet⁷, developed by WertelOberfell, goes a step further: it is energy-autonomous, warns the rider of approaching vehicles through directional vibrations, and allows voice control and audio playback via bone conduction. However, it is not commercially available at the time of writing.

Overall, passive level 1 systems dominate the market. These include for example the FARO Smart Helmet⁸ with turn signals and brake lights, which aims to prevent accidents.

This underscores the relevance of active level-2 warning systems. Kapousizis et al. [14] likewise highlight their importance, noting that 15 of the 36 reviewed studies fall into this category. The system presented in this paper can similarly be classified as a level-2 warning system.

³<https://www.garmin.com/en-GB/p/731136>, last access 04-10-2025

⁴<https://www.eu.hammerhead.io/products/karoo>, last access 04-11-2025

⁵<https://engoeyewear.com/>, last access on 04-11-2025

⁶<https://www.garmin.com/en-GB/p/518151>, last access 04-10-2025

⁷<https://www.werteloberfell.com/projects/prestige-esub-tracks-helmet>, last access 04-11-2025

⁸<https://unit1gear.com/>, last access on 04-11-2025

2.3 Bicycle Warning Systems in Research

This section provides an overview of scientific work on bicycle warning systems, similar to the warning system developed in this study. As mentioned earlier, monitoring and navigation systems also belong to this level. Since this work focuses on the development of a bicycle warning system, it only briefly mentions related works on other systems and motor vehicle-based systems [1, 4, 13, 24, 25, 33, 34].

The literature review revealed that some studies focus on the real-world implementation of warning systems and sensor technology, while others concentrate on the user perspective, assuming the technical implementation is already in place. Most systems rely on connected traffic (Bicycle to Everything - B2X), assuming wide availability of nearby vehicle information. These studies mainly investigate how warning signals should be designed.

2.3.1 Research Focused on Sensors. Green et al. [8] developed a prototype of a warning system as part of the SEBRA project⁹. It uses four radar sensors (two front and two rear) to create a 360° object detection around the bicycle, aiming to enhance safety and provide a good user experience. Six test scenarios were developed and tested under controlled field conditions. The study explored if automotive technologies and toolchains could be adapted to bicycles with minimal adjustments, with a focus on radar technology. Green et al. [8] found that radar could work well but highlighted limitations caused by bike instability and the sole use of radar.

Schoop et al. [29] also utilized 360° surround vision, using cameras with 2D images for object detection. Their system, *Hindsight*, focused on bone conduction speakers to keep the hearing channel open for traffic sounds while presenting warnings in a prominent and limited manner to avoid overwhelming the user. The system increased users' sense of safety and awareness of nearby vehicles.

Jeon and Rajamani [12] focused on crash risks during overtaking by motor vehicles and intersection-related collisions, developing a prototype with sonar sensors and a rotating laser sensor to measure distance to other vehicles. They aimed for low cost, small size, low weight, and low power consumption to ensure the system's practicality, although this made algorithm development challenging.

2.3.2 Research Focused on User Perspective. While previous work focused mainly on sensor implementations, the following studies emphasize the user perspective. Kreißig et al. [16] developed a system that collects information on dangerous situations via connected traffic (B2X) and evaluated user trust, acceptance, workload, and safety perception in a simulated environment. They created a multimodal warning system by combining visual and haptic signals with adaptive intensity, which proved effective in enhancing perceived safety and reducing workload.

Von Sawitzky et al. [35] examined *Dooring*-scenarios using AR glasses and audio cues to warn cyclists. Although AR use increased perceived competence rather than safety or workload, participants supported helmet-based AR concepts and further research on warning modalities. Earlier, von Sawitzky et al. [36] proposed AR-based solutions for vulnerable road users using connected traffic and GPS technologies; while questionnaires showed limited effects, interviews highlighted potential benefits of clearer signal design.

Similarly, Matviienko et al. [20] tested AR systems simulating cyclists at unsignalized intersections, visualizing incoming vehicles or showing a countdown to the next gap. Both approaches improved confidence and perceived safety, with the countdown proving most effective. Overall, these studies indicate that AR, combined with 5G-enabled B2X systems, holds strong potential to enhance cyclist safety once the technologies become affordable and widespread.

⁹SEBRA = SEnsor for Bicycle's impRoved Awareness, <https://www.ri.se/en/expertise-areas/projects/sebra-sensor-for-bicycles-improved-awareness>, last access on 08-26-2025

2.4 Eyetracking in the Context of Cycling

Eyetracking captures eye movements and fixations, offering insights into visual attention and enabling gaze-based interaction. During fixations (short pauses between saccades) new visual information is processed [26]. As the fovea perceives only about 2° of the visual field sharply, gaze shifts continuously; tracking these points reveals attention distribution [3]. Wearable devices such as the Tobii or Pupil Labs glasses^{10 11} use video-based infrared tracking and have become increasingly accessible, broadening applications in research and beyond [3].

In cycling research, eyetracking has primarily served analytical purposes. Matviienko et al. [19] examined children's gaze in hazardous scenarios, showing reduced accident rates with warning systems. Springer-Teumer et al. [32] linked gaze and braking behavior to subjective safety perceptions. However, the real-time application of gaze data for adaptive warnings remains rare. Examples include an automotive prototype [17] and a smart helmet that records but does not process gaze data for assistance [22].

Studies on cyclists' gaze in traffic [15, 18, 27] have revealed correlations between experience, traffic complexity, and visual workload, with higher workload associated to greater risk. Building on these insights, practical implementations of gaze-responsive bicycle assistance systems remain scarce. This paper addresses this gap by introducing a real-time warning system that adapts to cyclists' current focus of attention, aiming to minimize distraction while emphasizing relevant threats.

3 Concept, Research Question & Hypotheses

We developed and evaluated a concept for an interactive bicycle warning system that incorporates eye tracking as an active (implicit) input. The motivation arises from the increasing popularity of cycling and the corresponding rise in accidents involving vulnerable road users. While prior research has demonstrated the effectiveness of visual warning systems, eye tracking has so far been used only diagnostically in this context – to analyze user behavior post hoc without influencing the system in real time. This work addresses the research gap by embedding gaze data directly into the warning logic, allowing the system to dynamically adapt its signals based on where and whether the user is actively looking, thus making gaze an integral, interactive component of the warning mechanism.

Research Question: How can interactive eye-tracking improve traffic safety and user experience when integrated into bicycle warning systems?

To answer this, we developed two concepts: a visual warning system (Bicycle Warning System (BWS)) using the X-Ray Vision System introduced by prior work [20] and an extended system using eye tracking (Bicycle Warning System with Eye Tracking (BWS-ET)). These were implemented in a virtual reality environment using realistic urban intersection scenarios based on real-world traffic dynamics. We also compared both warning systems to a session without any warning system assistants.

The evaluation focused on several key metrics, including road safety, measured through collisions, crossing times, and proactive gap acceptance, as well as perceived safety, usability, user experience, and subjective workload. To examine these aspects systematically, the study was guided by the following hypotheses:

- *H1a*: BWS-ET leads to fewer collisions than the Baseline / No System (BL) and BWS.
- *H1b*: BWS-ET enables faster crossing of intersections.

¹⁰<https://www.tobii.com/de/products/eye-trackers/wearables>, last access 2025-08-27

¹¹<https://pupil-labs.com/>, last access 2025-08-20

- *H1c*: BWS-ET increases perceived safety.
- *H2a*: BWS-ET improves usability over BWS.
- *H2b*: BWS-ET leads to higher user experience scores.
- *H2c*: BWS-ET does not negatively impact perceived workload.

4 Implementation and Experimental Setup

The warning systems were implemented in Unity¹² and tested with a high-fidelity VR setup that combined real cycling hardware with a virtual urban traffic scenario.

4.1 Bicycle Simulator

The simulator used authentic cycling hardware to capture realistic riding input (see Figure 1a). A Garmin Tacx Neo 2¹³ trainer recorded pedaling speed, while an Elite Sterzo Smart¹⁴ steering unit provided handlebar input. Braking was measured with pressure sensors mounted on the V-brakes. Participants experienced the simulation through a Varjo Aero headset¹⁵. This includes a built-in 200 Hz eye-tracking system that uses dual cameras to compute precise gaze direction in real time with low latency.

4.2 VR Simulation

The virtual environment was designed as an urban intersection embedded in a dense inner-city environment, with exclusively large, multi-storey buildings enclosing the intersection area. Each trial began with cyclists approaching from a minor road, approximately 100 m away. The intersection was controlled by a yield sign rather than a stop sign, allowing participants to approach freely without mandatory stopping. Traffic on the main road consisted exclusively of cars travelling at a constant speed of 36 km h⁻¹, appearing from randomized directions, either from the left or the right. This speed was chosen because distances and velocities are perceived differently in virtual reality compared to the real world, and a speed of 10 m s⁻¹ is well supported in the literature as an appropriate value [20]. To prevent visual “pop-in” and ensure a natural traffic approach, vehicles were spawned 100 m away from the intersection in each respective direction. The simulated cars did not adapt their behavior to that of the cyclist. To increase ecological realism, static visual obstructions such as parked cars, pedestrians, and street furniture were placed to reduce visibility, although none of these objects moved during the simulation. The simulation was implemented in Unity and included a trigger zone placed directly on the intersection to start vehicle movement and synchronize data collection precisely.

4.3 Implemented Warning System Prototypes

Both warning system prototypes were based on a two-level classification of approaching vehicles using distance thresholds and braking trajectories. An *attention warning* was issued when the distance to a vehicle fell below 80 m, while a *critical warning* was triggered below 8 m. These values were calibrated during prototyping and judged to provide intuitive and non-intrusive feedback. In all cases, *all* vehicles within the attention zone were highlighted to ensure situational awareness. In contrast, in the gaze-adaptive prototype, the peripheral glow was restricted to the nearest threatening vehicle, focusing attention on the most imminent hazard while preventing distraction from multiple

¹²<https://unity.com/>, last accessed 2025-04-11

¹³<https://www.garmin.com/de-DE/p/690886>, accessed 2025-04-10

¹⁴<https://www.elite-it.com/de/produkte/heimtrainer/zubehor-fur-das-okosystem/sterzo-smart>, accessed 2025-04-10

¹⁵<https://varjo.com/products/aero/>, accessed 2025-04-10



Fig. 2. Color-coded warning overlays used in both Bicycle Warning System to indicate the perceived threat level of approaching vehicles based on distance and visibility.

simultaneous glows. The dynamic behavior of both warning systems, including gaze interaction and the transition between attention and critical warnings, is illustrated in the supplementary videos.

Two prototypes were realized: the Bicycle Warning System, which displays overlays over the approaching cars, and the Bicycle Warning System with Eye Tracking, which adapts warnings based on gaze interaction. In the BWS prototype, vehicles were highlighted in a gradient between yellow and red depending on their assigned warning level and distance (see Figures 1b and 2). The BWS-ET prototype further introduced directional cues and gaze adaptation. When a threatening vehicle approached, a peripheral glow appeared on the left or right side of the cyclist’s visual field to indicate the direction of the next threat. If the cyclist then looked directly at this vehicle, its overlay gradually became transparent and the glow faded, confirming that the system had registered user awareness (see Figure 1c).

5 User Study

To evaluate the presented prototypical concept, we used the hard- and software implementation described above as apparatus and conducted a lab-based simulator experiment that we describe in the subsequent sections.

5.1 Study Design

We conducted a controlled within-subject experiment ($n=14$) to evaluate the two systems and compared them to a no-warning baseline (BL), i.e., we had one independent variable with 3 levels (BL, BWS, and BWS-ET). Each participant completed five trials per condition in counterbalanced order, encountering dynamically generated traffic scenarios at urban intersections without traffic lights. Traffic arrival timing was adjusted through five trigger-point variations, with cars approaching at 36 km/h to simulate realistic and progressively more demanding crossing decisions. The study was submitted to and approved by the local ethics committee.

We collected the following quantitative measures:

Accident count (including near-collisions): An accident was recorded whenever the bicycle came within 30 cm of a car, marking a collision event. To ensure participant safety and comply with ethical guidelines, the simulation automatically paused at this threshold, freezing the scene before any impact occurred. Consequently, both collisions and near-collisions within this safety margin were uniformly classified as accidents.

Time to cross the intersection: Intersection crossing time was measured via trigger zones in Unity, which recorded entry and exit timestamps; their difference defined the crossing duration.

Number of successful crossings before the first car arrival: The simulation followed a controlled traffic pattern in which cars approached the intersection at predictable intervals after spawning. By synchronizing the participant’s ride onset with the scheduled arrival of the first car, the system determined whether the participant successfully completed a crossing before the first car reached the intersection.

To collect subjective data, participants completed a series of questionnaires at defined points throughout the study: After each of the three conditions (BL, BWS, and BWS-ET), they filled out the Perceived Safety Questionnaire (PSQ) [23] and the NASA Task Load Index (NASA-TLX) [11]. Following the two blocks that included a warning system (BWS and BWS-ET), participants also completed the System Usability Scale (SUS) [7] and the User Experience Questionnaire Short (UEQ-S) [30]. Upon completing all simulation blocks, they provided demographic information, completed the Affinity for Technology Interaction (ATI) scale [5], and gave an open-ended final evaluation of their experience.

5.2 Participants

We recruited 14 participants, mainly through advertising the study on an institution-internal mailing list. Nine of the participants self-identified as male and five as female. With regard to the highest educational qualification achieved, one participant has no higher education qualification, six participants have a high school diploma, six a bachelor’s degree, and one person a doctorate. Most participants had a university background. Participants were aged between 18 and 40 years ($M = 24.5$ years). 3/7 of the participants use their bike almost daily, two participants 1–3 times a week, one participant 1–3 times per month, while the remaining participants use a bike even less frequently (2/7) or almost never (1/7). 6/7 of the participants had used VR glasses in the past (but less than monthly) while one participant already had experiences in using a driving simulator. Four participants (2/7) already had experiences with passive assistance systems.

5.3 Procedure

Upon arrival, participants were informed about the study’s purpose and the option to withdraw at any time without penalty. Written informed consent was obtained prior to participation. Participants were then introduced to the VR bicycle simulator and completed several practice rides to familiarize themselves with the controls and environment.

The experiment comprised three blocks, each corresponding to one system condition. Block and scenario order were counterbalanced using a Latin Square design to control for order effects. Each block consisted of five rides, resulting in a total of 15 experimental rides per participant. This number was chosen to ensure sufficient data collection while minimizing the risk of motion sickness. Each ride lasted approximately 30–60 seconds, yielding an overall simulation time of 10–20 minutes. Between blocks, participants could rest and remove the headset while completing the questionnaires. The session could be paused or discontinued at any time upon request. Following the final block and questionnaire, a short semi-structured interview was conducted to capture qualitative impressions and provide additional insights not reflected in the standardized measures. Participants were compensated with €15.

6 Results

This section presents the findings of the user study conducted to evaluate the developed bicycle warning systems. The results are structured according to the main focus areas of the study: objective traffic safety metrics, perceived safety, and user-centered aspects such as usability, user experience, stress, and workload.

6.1 Number of Accidents / Near-Accident Situations

Across all conditions, a total of 8 accidents with cars were observed. The distribution of accident counts was not normal, as indicated by a Shapiro–Wilk test ($p < .05$). To test for differences across conditions, a Friedman test was conducted. The mean number of accidents decreased from BL ($M = 0.50$), to BWS-ET ($M = 0.36$), to BWS ($M = 0.29$), but this trend did not reach statistical significance, $\chi^2(2) = 1$, $p = 0.601$.

6.2 Time to Cross Intersection

We measured the time required to cross an intersection as an objective indicator of situational awareness and decision-making efficiency. This measure reflects how effectively the BWS helps cyclists perceive traffic, reduce uncertainty, and act safely. Participants needed on average 17.4 s in the BL condition, 16.0 s with BWS, and 18.5 s with BWS-ET. The shortest observed times were 10.4 s (BL), 3.7 s (BWS), and 4.8 s (BWS-ET). We conducted a one-way repeated-measures ANOVA to test for differences across conditions. We found no extreme outliers, the data met the assumption of normality (Shapiro–Wilk $p > .05$), and sphericity (Mauchly’s test). Crossing times did not differ significantly between conditions, $F(2, 26) = 0.734$, $p = .49$.

6.3 Perceived Safety

We used a Friedman test to analyze perceived safety, measured with the PSQ survey, across all three conditions. The test showed statistically significant differences ($\chi^2(2) = 16.77$, $p < .001$). We then performed pairwise comparisons with a Bonferroni correction. Participants reported significantly higher perceived safety with BWS compared to BL ($p = .006$) and with BWS-ET compared to BL ($p = .007$). The comparison between BWS and BWS-ET was not statistically significant. As shown in Figure 3, participants attributed greater perceived safety to both proposed warning systems compared to their baseline rides.

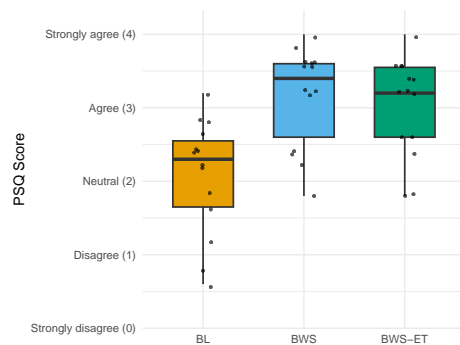


Fig. 3. Perceived Safety Questionnaire scores across system variants (Baseline/No System (BL), Bicycle Warning System (BWS), and Bicycle Warning System with Eye Tracking (BWS-ET))

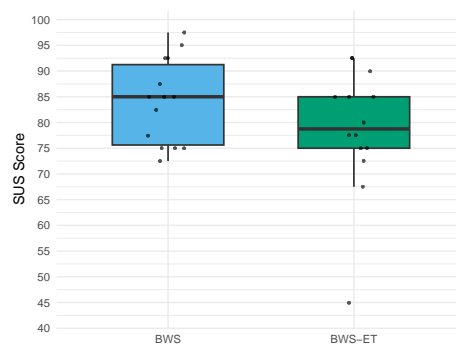


Fig. 4. System Usability Scale scores across system variants (Bicycle Warning System (BWS), and Bicycle Warning System with Eye Tracking (BWS-ET))

6.4 Usability and User Experience

We assessed usability with the SUS survey. As shown in Figure 4, participants rated BWS higher ($M = 84.1$) than BWS-ET ($M = 78.6$). A Wilcoxon signed-rank test confirmed this difference as statistically significant ($p = 0.0311$,

$r = 0.584$). For user experience, Figure 5 displays the overall, pragmatic, and hedonic scores. Participants rated BWS-ET slightly higher overall ($M = 2.06$) than BWS ($M = 1.96$), but this difference was not statistically significant ($p = 0.356$). On the pragmatic dimension, BWS scored marginally higher ($M = 2.11$) than BWS-ET ($M = 1.96$), with no significant difference ($p = 0.473$). On the hedonic dimension, however, participants rated BWS-ET significantly higher ($M = 2.16$) than BWS ($M = 1.82$), $p = 0.0117$, $r = 0.701$.

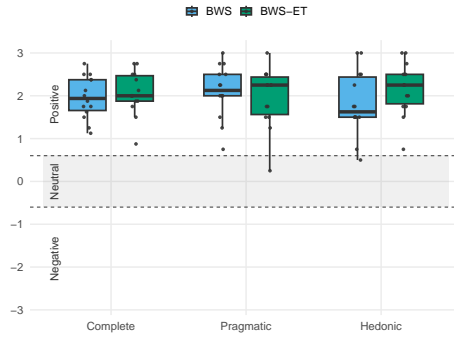


Fig. 5. User Experience Questionnaire Short complete score and hedonic/pragmatic subscores across system variants (Bicycle Warning System (BWS), and Bicycle Warning System with Eye Tracking (BWS-ET)). Neutral zone from -0.6 to 0.6 is marked in light grey.

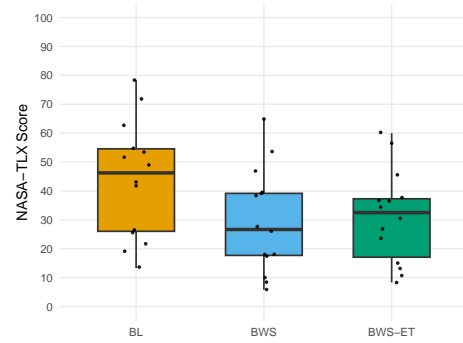


Fig. 6. Subjective workload ratings NASA Task Load Index (Raw) across system variants (Baseline/No System (BL), Bicycle Warning System (BWS), and Bicycle Warning System with Eye Tracking (BWS-ET))

6.5 Subjective Workload

We measured perceived cognitive workload with the NASA-TLX, administered after each condition. Figure 6 shows the distribution of workload scores across conditions. The mean workload score was highest in the BL condition ($M = 43.8$), lower in BWS-ET ($M = 31.1$), and lowest in BWS ($M = 29.5$). A Friedman test identified significant differences across conditions, $\chi^2(2) = 16.00$, $p < .001$, Kendall's $W = 0.571$, indicating a large effect size. Post-hoc Wilcoxon signed-rank tests with Bonferroni correction showed that participants reported significantly lower workload with BWS than with BL ($p < .001$). The difference between BWS-ET and BL approached significance ($p = .051$), while the two warning systems did not differ significantly. We further explored this trend with a repeated-measures ANOVA on the NASA-TLX scores, acknowledging their ordinal nature. The analysis revealed a significant effect of condition, $F(2, 26) = 7.49$, $p = .003$, $\eta^2 = 0.12$. Post-hoc comparisons confirmed significantly lower workload in both BWS ($p = .004$) and BWS-ET ($p = .012$) compared to BL. These findings suggest that the introduction of a visual warning system, even with additional gaze-based interactivity, does not increase and may even reduce perceived mental workload during cycling in complex urban scenarios.

6.6 Additional Qualitative Feedback and Ranking

For perceived safety, BWS-ET received the highest average ranking score with 36 points, followed by BWS (31 points), and BL (17 points). Regarding stress perception, BWS was ranked best (37 points), while BWS-ET (27 points) and BL (20 points) followed. In terms of overall impression, BWS-ET again scored highest with 35 points, slightly ahead of BWS (32 points) and well above BL (17 points). Rankings were point-weighted, assigning 3 points for a first-place vote, 2 for

second, and 1 for third. In follow-up semi-structured interviews, participants confirmed the positive impact of both warning systems. The peripheral visual alert in BWS-ET, in combination with its adaptive transparency, was perceived as particularly intuitive and useful. Despite some concerns about potential visual overload (especially due to the limited field of view of the VR headset) many participants stated they could imagine using such systems in daily cycling. This aligns with the technology affinity score measured using the ATI scale, which showed an average of $M = 3.97$ (on a 1–6 scale), indicating a rather high openness toward technology among participants.

7 Discussion

The findings of this study show several encouraging outcomes regarding the effectiveness and user reception of the developed bicycle warning systems, particularly the version enhanced with eye tracking. Participants rated both systems positively across a range of metrics, including perceived safety (PSQ), usability (SUS), user experience (UEQ-S), and subjective workload (NASA-TLX), suggesting that interactive visual warnings have the potential to significantly contribute to cyclist safety and user experience.

From a safety standpoint, both BWS and BWS-ET slightly reduced the number of collisions compared to the baseline. As the differences between the systems were not statistically significant, we cannot fully confirm *H1a*, but the trend clearly favors the implementation of any form of visual warning. Notably, the systems increased the number of proactive crossings—defined as successful street crossings completed before the arrival of the first oncoming vehicle (*H1b*) in the simulation—which indicates that participants felt more confident in interpreting safe traffic gaps. Furthermore, subjective safety perception was significantly improved in both bicycle warning system variants, confirming hypothesis *H1c*.

Regarding usability and user experience, participants rated BWS higher in terms of usability (SUS), which is why we cannot confirm hypothesis *H2a*. While there are no significant differences regarding overall user experience, BWS-ET scored better on hedonic dimensions of user experience (UEQ-S), which partly confirms hypothesis *H2b*. This indicates a trade-off: while eye tracking may not enhance basic usability, it does contribute to a more engaging and potentially enjoyable interaction. Both systems maintained a low workload, with no significant increases in stress or cognitive effort reported, contributing to a confirmation of *H2c*.

7.1 Limitations

This study has several limitations. We conducted it in a VR simulator with a relatively small sample of young academics, which limits the generalizability of the findings. This sample choice reflects the typical availability of participants in exploratory research and ensures sufficient technical familiarity for VR-based experiments. Technical constraints may also have influenced the results. The VR setup imposed a restricted field of view, and the Tacx Neo sensor introduced a measured input lag of about 300 ms. Furthermore, we relied on Varjo Aero-based eye tracking with simplified gaze-event detection, which may not capture the full richness of visual behavior.

While VR cannot fully reproduce all sensory and contextual cues of on-road cycling, evidence from simulator validation studies suggests that well-designed virtual environments can elicit behavioural responses and perceptual judgments that are comparable to real-world behaviour for relative evaluations of design alternatives [10, 37]. Therefore, although absolute measures should be interpreted with caution, the comparative effects observed between the warning system variants in this study are likely to generalise to real cycling contexts and serve as a strong basis for future field validation. Nonetheless, the VR environment enabled us to create a safe and controlled setting for exploratory testing. This approach made it possible to systematically manipulate conditions that would be difficult or unsafe to investigate

in real traffic. Such exploratory studies represent an essential first step before transferring findings into real-world cycling contexts, where ecological validity can be evaluated [2, 28, 31].

7.2 Future Work

Accordingly, future work should address these limitations. In particular, we envision a follow-up real-world cycling study with a larger and more diverse sample to validate the findings in a real-world context. The warning system could be integrated into a helmet-mounted augmented reality display or a lightweight see-through head-up display. Such a form factor would allow gaze-aware visual overlays to be presented directly in the cyclist's field of view without obstructing situational awareness. However, translating the current prototype into a wearable system introduces several design challenges, including constraints on weight, ergonomics, battery life, data availability, and heat dissipation, as well as the need to ensure robustness against vibrations, lighting conditions, and outdoor motion artifacts. Moreover, integration of multimodal feedback, such as auditory or haptic signals, might improve awareness without overloading the visual channel. The design and testing of intelligent fusion algorithms, leveraging real-time gaze data, could also further personalize and optimize warnings. Lastly, while the current implementation of BWS-ET shows promise, the study underscores the need for iterative user-centered design. The addition of eye tracking introduced novel interaction possibilities, but also posed usability challenges. The design of peripheral alerts and the use of gaze-dependent transparency modulation were generally well-received, but further refinements are required to ensure clarity and prevent overload.

8 Conclusion

This study investigated the integration of eye tracking into head-mounted bicycle warning systems and evaluated its impact on traffic safety and user experience using a controlled, VR-based experiment. Two systems were developed and tested: a baseline visual warning system and an extended gaze-adaptive variant that responded dynamically to the user's line of sight. While both systems (BWS, BWS-ET) outperformed the not assisted baseline (BL) in terms of perceived safety and user experience, the gaze-based system showed particular promise in enhancing perceived situational awareness.

To our knowledge, few studies have investigated gaze-aware bicycle warning systems in real time. Our findings provide initial evidence that such systems can enhance cyclists' perceived safety and user experience. While the prototype was positively received, several challenges remain before real-world deployment, including eye-tracking reliability in outdoor conditions, hardware costs, calibration demands, and field-of-view limitations. Addressing these issues will be essential for translating the promise of gaze-adaptive assistance into everyday cycling contexts.

The study makes a compelling case for the inclusion of gaze-aware interaction in safety-critical mobility systems. Eye tracking offers a pathway to more context-sensitive and user-tailored warnings, yet future research should move beyond VR simulations and explore longitudinal usage, multimodal feedback integration, and broader demographic representation. Ultimately, while the prototype demonstrates conceptual viability, translating its benefits into real-world cycling scenarios will require significant technological and methodological refinement.

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