ReAR Indicators: Peripheral Cycling Indicators for Rear-Approaching Hazards

Guanghan Zhao
Osaka University
Osaka, Japan
zhao.guanghan@lab.ime.cmc.osaka-u.ac.jp

Xiaodan Hu
Nara Institute of Science and Technology
Nara, Japan

Jason Orlosky
Augusta University
Augusta, USA

Kiyoshi Kiyokawa
Nara Institute of Science and Technology
Nara, Japan

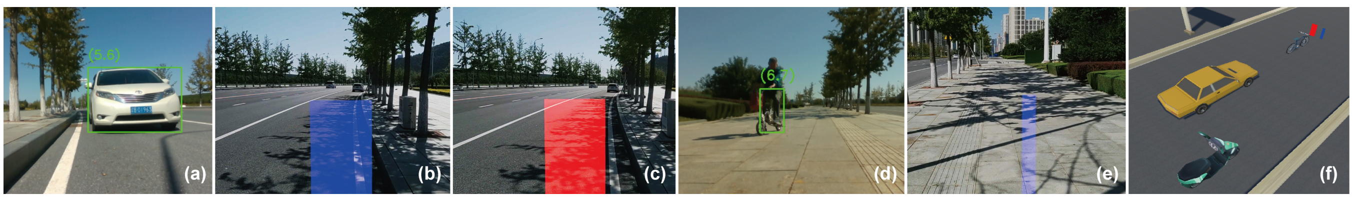

Figure 1: Images showing (a) real-time detection of the vehicle using a bicycle-mounted rear RGB-D camera, (b) the ReAR Indicator, which uses a blue bar to indicate a rear-approaching vehicle, (c) several frames later, where the bar turns red to indicate a potential crash, (d) real-time detection of a cyclist following the user (e) the corresponding ReAR indicator used to visualize the cyclist, and (f) a side-view of the VR experiment interface used to test the ReAR indicator against other information presentation methods.

ABSTRACT

During cycling activities, cyclists often focus on pedestrians, vehicles or road conditions in front of their bicycle. Because of this forward focus, approaching vehicles from behind can easily be missed, which can result in accidents, injury, or death. Although rear information can viewed with handle-mounted mirrors or monitors, looking down can distract the cyclist from other hazards.

To help address this problem, we present the ReAR Indicator, a peripheral information delivery approach that enhances awareness of rear-approaching vehicles and at the same time preserves forward vision. ReAR uses computer vision applied to a rear-facing RGB-D camera and combines it with position data from a head mounted display for real-time vehicle detection and visualization. Our algorithm delivers information to the periphery such that the user can simultaneously view forward information but still use cues that provide information about hazard distance, width, and probability of collision. Results from a virtual reality based experiment with 20 participants showed that the ReAR Indicator helped cyclists maintain a forward focus while still avoiding collisions with rear-approaching vehicles and in some conditions either matched or outperformed 3D arrows and virtual monitors.

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CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; **Visualization design and evaluation methods**.

KEYWORDS

Cycling, User Interface, Safety

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1 INTRODUCTION

As one of the most popular forms of transportation, cycling has several advantages, such as being environmentally friendly and a healthy exercise. However, cyclists often ride through traffic or with a group of other cyclists, so they must pay attention to both the front and rear depending on the situation. Collisions are a significant problem, especially those that come from behind when merging lanes. To detect hazards, cyclists typically make use of rear-view mirrors or monitors, which can be mounted to a bicycle's stem, handlebar, or bar-ends. Although current rear-view methods are able to help cyclists avoid rear-approaching vehicles, the act of looking at the mirror or monitor itself can be a distraction, which is similar to the distractions and accidents caused by bike-mounted cell phones [6, 26, 28].

In addition, cyclists must rotate their heads frequently to integrate information from both their forward and rear views and reduce speed as necessary to avoid collisions [3, 30]. Head mounted displays (HMDs) have commonly been used as augmented reality (AR) devices that provide more accessible information with augmented vision. Considering that cyclists always wear helmets while cycling, HMDs are an excellent candidate for cycling safety since they can easily be integrated into helmets. AR HMDs have the potential to alleviate the problem of cyclists having to look down frequently, and AR approaches have widely been implemented for driving and hazard detection assistance [16, 20]. However, information delivered by AR HMDs may also cause distractions since it is always overlaid in the cyclist's field of view (FoV) [8]. Peripheral cues have the potential to alleviate distractions since information can be delivered without blocking the foveal vision, so they have been widely applied in driving and rear collision avoidance AR approaches [12, 19, 23].

In this paper, we introduce a novel approach called the "ReAR Indicator" that not only provides peripheral indications of rear-located vehicles (e.g. bicycles, motorbikes and cars) but also preserves attention to their frontal view as shown in (b), (c), and (e) of Figure 1. ReAR Indicators are specifically designed to alleviate the danger of rear collisions and distractions that come from looking down at a mirror, monitor, or other rear-view interface by augmenting the user's periphery with color-, size-, and motion-coded visualizations.

Moreover, unlike other existing peripheral indicators, this approach provides indications across the visual areas and can reach to the focal area to draw attention when danger is going to happen. First, to determine the location and width of vehicles, we gather scene data with an RGB-D camera and process scenery behind the bike through a set of computer vision based algorithms. This data is sent to a HoloLens 2 via TCP/IP socket communication. Then, scene data, motion, facing direction, and head position are gathered from the HMD. Using this data as input, we designed an algorithm that detects rear-located vehicles and projects relevant information about them to the periphery.

This system provides simultaneous visual access to information and awareness of the vehicle's location, as well as the likelihood of a collision. Simply put, we provide better rear information access to cyclists without compromising their forward focus. In a VR experiment using a real bicycle with virtual scenes for participant safety as can be seen on the right of Figure 2, we evaluated the ReAR Indicator, a front-fixed virtual monitor, and 3D arrows in order to investigate the following hypotheses, as compared to the other conditions:

- H1: Cyclists using the ReAR Indicator will react more quickly and have fewer collisions with virtual vehicles.
- H2: Reactions to forward information (e.g. button presses) will be faster with the ReAR Indicator.
- H3: The ReAR Indicator will be less distracting and improve the user's feeling of safety.

In the following sections, we discuss related work, detail the design process and implementation of the ReAR Indicator, describe our user study, and provide an analysis of the results. We conclude with a discussion of our findings and observations.

2 RELATED WORK

On urban roads, cyclists can often be at risk of getting hit from the side or rear, especially when they are focused on the road in front of them or if they are checking a bike-mounted interface such as a smartphone or cyclocomputer. To help address these problems, many cycling systems exist to help deliver easily accessible information and hazard alerts. In some systems, peripheral indications have been used as a non-distracting approach, which can be useful for cycling and other mobile use cases. In the following section, we discuss previously proposed AR approaches related to cycling information delivery and peripheral indicators.

2.1 Information Delivery for Cycling Safety

Cycling through traffic is a challenging situation in which cyclists must often navigate through narrow spaces between cars or other bicycles. This often requires high attention to the forward direction, frequent steering, and a reduction in speed [30]. Moreover, using supporting applications such as navigation assistants on a mobile phone or other type of display often cause distractions that can further put the cyclist at risk [26]. To help address this problem, Dancu et al. [5] evaluated a projection-based interface for urban cycling with a head-up display, and Sawitzky et al. [31] investigated the effectiveness of an HUD (Head-Up Display) based augmentation concept for cycling safely. With further consideration for usability, HMDs have been proposed as a viable solution. For example, Berge et al. [1] found that HMDs may fulfill cyclists' needs for recognition, however they may hesitate to use such devices. Lopik et al. [29] demonstrated that handheld devices provide higher perceived usability, while AR glasses improve awareness of hazards. Ginters [9] developed an AR glasses-based interface for providing navigation and other information. With a focus on balancing information access and minimizing distractions during cycling, Zhao et al. [34] implemented a UI snapping method to facilitate synchronized content access while maintaining hazard awareness.

Other than visual cues, audio cues have also been considered as a viable solution to indicate hazards. Kitagawa and Kondo proposed and evaluated a 3D audio based navigation system with wind noise reduction [17, 18]. Similar to Kitagawa and Kondo's studies, a bone conduction based navigation system for cyclists was developed by He and Zhao [11]. For detecting approaching vehicles and providing sound-based feedback, Jeon and Rajamani [14] proposed a low-cost rear-vehicle detection system using a single beam laser sensor mounted on a rotating platform. Moreover, in the work by Schoop et. al. [27], vehicles are detected using machine learning algorithms, and directional audio is provided as a cue.

Current approaches to augment vision mostly use fixed UIs delivered by a HUD or HMD. Since UI textures are fixed in the field of view, they inevitably attract the user's attention, which can cause the user's gaze to move away from the forward direction or from hazards on the road. While using auditory alerts can be useful, we want to avoid distraction and confusion, since cyclists often use auditory input to judge approaching vehicles' directions and distances.

2.2 Peripheral Indication and Visualization

One primary advantage of augmenting peripheral vision is that vision in the foveal region will not be affected, thereby reducing disturbances in the center of a cyclist's field of view. Several prior studies have focused on improving awareness and perception using peripheral augmentations or cues. For example, Gruenefeld et. al.

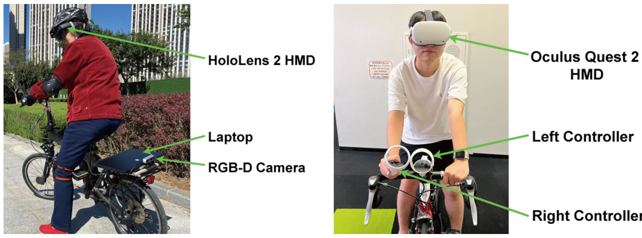

Figure 2: Images of the ReAR bicycle setup, including the HMD, RGB-D camera, and laptop from the rear view (left) and a participant with the bicycle and HMD used for the VR-based experiment (right). For the experimental apparatus, the left-hand controller was mounted to the middle of the handlebar for steering and the right-hand controller was mounted to the right side of the handlebar for input.

[10] implemented a frontal collision warning system for pedestrians using LEDs that are attached to ordinary eyeglasses. For backward collisions, Niforatos et. al. [23] applied LEDs and sensors to a helmet in order to warn the user about approaching skiers. By applying LEDs to HMDs, Qian et. al. [25] proposed an approach for enhancing perception in the region of peripheral vision that is usually blocked by frame of an HMD. Moreover, by combining HMDs and LED light bars, Jones et. al. [15] proposed a displaying method that improves spatial perception in virtual environments.

Besides LED based approaches, AR displays are also used as a method for delivering peripheral indications. For example, Fan et. al. [7] developed SpiderVision, a system for extending back view by indicating backward motions on the peripheral area of an HMD's FoV. Janaka et. al. [13] designed an interface that is located on the near-peripheral area and allows the user to access information while keeping eye contact with another person. However, considering the limited FoV that current HMDs have, the range of peripheral area is restricted. Therefore, applying peripheral indications is challenging, as they have to counterbalance accessibility and rendering range. In order to address some of these issues, Chaturvedi et. al. [2] came up with a peripheral navigator using blue color that was inspired by Murch's findings [22]. In our previous work [33], we did an initial exploration of ReAR indicators, which further motivated this work.

3 DESIGN AND IMPLEMENTATION OF REAR INDICATORS

In order to detect vehicles or cyclists behind the bicycle and provide a peripheral indicator that simultaneously represents the width, distance and likelihood of a collision of each vehicle, we first implemented a detection algorithm with Python, which made use of the RGB-D camera and bike-mounted laptop (Figure 2). Then, we designed, developed, and refined peripheral indicators using C# and High Level Shading Language (HLSL), which ran in real time on the HoloLens 2. Asynchronous TCP/IP socket communication was used for data exchange via a smartphone Wi-Fi hotspot. Specific details regarding the recognition algorithm, indicator parameters, and hardware are detailed as follows.

3.1 Equipment

In the outdoor implementation (Figure 2, left), we used a Microsoft HoloLens 2 HMD, Alienware m15 Laptop, Intel Realsense D435i RGB-D camera, iPhone 11 smartphone and Dahon Jetstream P5 bicycle. The HMD's FoV is 43°∗29°. The RGB-D camera can measure distances above 28cm and has a 30 fps frame rate and FoV of 69°∗42°. The real-time indication interface and computer vision detection code were driven by Unity 2021.1.20f1 and Python 3.9, respectively.

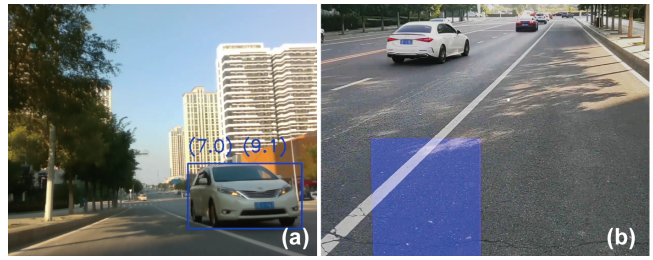

Figure 3: Images showing (a) detection results from the detection algorithm and (b) the corresponding ReAR peripheral indicator that represents the approaching car's position, width, and speed.

3.2 Vehicle and Cyclist Detection Algorithm

For the recognition system, we needed to detect when a car or other cyclist was behind the bike so that we could provide hazard information that would be useful for the rider. To do so, we capture both RGB and depth frames using an RGB-D camera fixed to the back seat of the bicycle, which faces directly backward with respect to the bike frame. We first align these captured RGB frames with the depth frames via the camera's application program interface (API). Next, we apply a Caffe based MobileNet-SSD deep neural network (DNN) model [4] for car and bicycle detection. From this DNN, we can obtain the regions of interest (ROIs), including vertex coordinates, and we calculate the depth of each ROI (Figure 3-a). The available depth range is 0.3 meters to 20 meters due to the RGB-D camera, which covers a relatively wide range of vehicles and reaction times. For example, for an urban speed limit of 60km/h with a cyclist riding at an average speed of 20km/h, the reaction time is approximately two seconds, a similar allowance to other state-of-the-art notification systems [27]. After obtaining the vertex coordinates and depth, the world coordinates (x, y, z) of each vertex are defined as:

$$z = depth \tag{1}$$
$$x = (u - cx) * z / fx \tag{2}$$
$$y = -(v - cy) * z / fy \tag{3}$$

where (u, v) is the pixel coordinate of each vertex, and cx, cy, fx, fy are from the intrinsic matrix of the RGB-D camera. To convert the v value on the top down v axis in pixel coordinates to the y axis in projection coordinates, we calculate $-(v - cy)$. This set of equations are originally from the 2D-3D coordinate transformation models of SLAM. Since we only focus on the front view, and the camera is always considered to be the origin in this study, the rotation and transformation matrices are not applied. Further, we rotate the world coordinates to the rear by converting x to $-x$ and z to $-z$.

Once the world coordinates of the ROIs are defined, we pass them through an asynchronous TCP/IP socket running in another thread. In this socket, we set the laptop to be the host with a sending interval set to 0.05 seconds in order to mitigate jitter and packet sticking of the network.

3.3 Peripheral Indication

Our peripheral indicator is developed in Unity and deployed on the HoloLens 2. Moreover, the indicator is driven by a shader script that is applied to a camera canvas in the environment. The visual recognition data is received via Socket client as messages and are cut based on a header in order to further avoid packets getting stuck. From the data, world coordinates were projected to a u-v coordinate in a customized Unity shader. The scale relation was defined as:

$$ul = -xl * 0.1 + 0.5 \tag{4}$$

$$ur = -xr * 0.1 + 0.5 \tag{5}$$

$$vmax = 0.5 - z * 0.0125 \tag{6}$$

where the xl and xr are the X-axis values of the left and right vertex and the ul and ur are the projected u-axis values of xl and xr. In addition, the xl and xr are flipped to make ul and ur match the real direction and the indicator is rendered between ul and ur. The z is the depth but also represents the distance between the detected vehicle and the bicycle and the $vmax$ is the maximum height for rendering the indicator. Regarding the scale ratio of z, since the shader is designed to match the HMD's aspect ratio, we defined it as: $0.5/2/20$.

With these width and height values, we render bar-shape indicators (the number of bars corresponds to the number of detected vehicles) (Figure 3-b), where width represents the width of the oncoming vehicle and height represents the distance between the bicycle and vehicle. In addition, if a vehicle is just behind the bicycle, the bar will be positioned just below the foveal area, and as it is approaching, the bar's height will increase towards central vision in order to better notify the user of the oncoming hazard.

Considering HMDs with limited FoVs, the shape was designed to be simple and easy to understand [21], and the color was set to blue since the peripheral area is more sensitive to blue compared to the foveal area [2, 13]. Furthermore, since the DNN model is not able to calculate speed between frames, we record depth values of the vehicle behind the bicycle (if present) and compare frames them to detect the vehicle's approach. If there is an approaching vehicle that becomes a hazard, the indicator will flicker red in order to draw attention, which should not cause significant distraction in the foveal region [32].

4 EVALUATION OF DETECTION ACCURACY AND LATENCY

To get a better understanding of the system's end-to-end capabilities we conducted two initial evaluations of technical performance, including an evaluation of detection accuracy and the system's end-to-end latency.

To set up this test, we biked in two environments for approximately 16 minutes each, recording data for the duration of each trip. We then gathered the every 10th frame from the data and set up a frame pool of 2000 frames. Figure 12 shows a set of representative images and detection results. From the frame pool, we picked the every second frame for testing in terms of true and false positives and negatives. The result revealed 97.67% precision, 92.2% recall, and 2.2% false-positive rate. While this performance can be satisfying, it's important to note that factors in the complicated road environments, such as noise caused by shadows and signboards, were observed to contribute to the errors.

We tested the end-to-end latency of the system by printing timestamps in each step of the system process with 10 iterations and averaged the results. In the test, we found that the latency was on average 371ms the time a vehicle is detected until a bar is rendered. The average latency of each step was: 100.6ms from detection until sending a socket message (with the 50ms sending interval), 262.8ms from sending a socket message until it is received, and 7.6ms from receiving a socket message until a bar is rendered.

5 USER STUDY

In the experiment, we compared the ReAR Indicator to a front-placed virtual monitor and 3D arrow indicators in a virtual reality (VR) environment. Participants sat on a stationary bicycle, and interactions in the VR environment were driven by controller, one of which was attached to the bicycle's handlebar (Figure 2, right). The other was used to record responses to experiment tasks. In addition, participants were asked to avoid approaching vehicles from behind while maintaining a forward focus. We examined their task performance, riding behavior and subjective preferences with the three UI conditions.

5.1 Equipment

For the experiment, we used an Oculus Quest 2 HMD, a PREC Ovation 2014 bicycle and a PC with Intel Core i7-9750H processor (16GB RAM) and NVIDIA GeForce RTX 2070 graphics card. The VR program was developed in and driven by Unity 2021.1.20f1.

5.2 Experiment Design

In order to preserve safety in bicycle-related work, a widely accepted study design is to conduct experiments with virtual reality environments and a stationary bicycle [5, 31]. Therefore, we decided to implement our experiment with a similar setup. In addition, a controller was mounted on the middle of the bicycle's handlebar to detect steer actions, and the other controller was mounted on the right side of the handlebar for task-related inputs.

Two primary tasks were designed to test participants' performance with the three conditions and included forward focus and backward collision avoidance. For the forward focus task, participants had to quickly press the button that is shown in front of them within two seconds, which is a common interaction in video games, also known as a quick time event (QTE) (Figure 4-c). In order to prevent the participant from randomly pressing buttons to accumulate successful QTEs, we limited the input interval to 0.5s. At the same time, participants were asked to avoid collisions with incoming vehicles from behind by steering left or right as necessary.

The user study used a within-subjects design that tested the ReAR Indicator against two other UI conditions, a front-placed virtual monitor and 3D arrow interface, which were both fixed in the forward direction just below the horizon (a preferred position for easy access and low distraction during mobile tasks [24]) (Figure 4). In addition, the front-placed virtual monitor was set at 1.2 meters width and 0.72 meters height in size, six meters forward, and matched the average aspect ratio of mobile phone screen. The

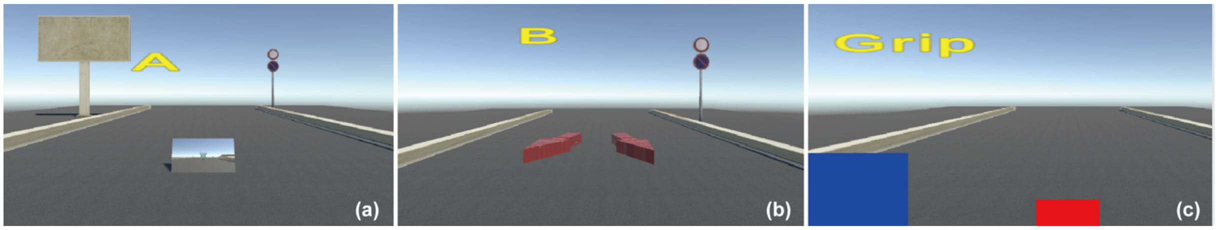

Figure 4: Images showing the three UI conditions in the experiment, including (a) the virtual rear-view monitor, (b) 3D arrows, and (c) the ReAR Indicators. Letters or words that specified a target controller button were displayed in front of the user to simulate cycling tasks such as following landmarks or observing road signs.

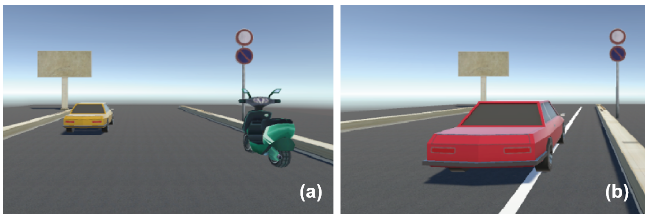

Figure 5: Images showing the scenes in which experiment participants experienced (a) moving traffic, i.e. the *traffic scene*, and (b) roadside obstacles, i.e. the *roadside scene*.

3D arrows were set to keep pointing to the approaching vehicles and the number of them was correspond to the number of vehicles within 20 meters backward. Considering conventional usage and the ease of understand, we set these two conditions for evaluation. The order of conditions was assigned based on a balanced Latin-Square in order to minimize ordering effects.

5.3 Experimental Environment

To test the three conditions, we utilized a VR environment that made use of virtual cars and bikes to ensure that participants would not be at risk of crashing into real hazards. Instead of detecting real vehicles, we adapted our method to react to the virtual vehicles within the VR environment for the experiment as shown in Figure 5. We also provided two different scenes to better simulate actual cycling situations, including a *traffic scene* (left) and *roadside scene* (right). These scenes mimic the cases in which a cyclist may be in a center lane and experience significant traffic or be on the side lane and just need to avoid cars to one side, respectively. The participant encountered these scenes in randomized order for each trial.

In the traffic scene, we rendered a road with three lanes, a bike and a car. In addition, the vehicles were set to move on one of two random lanes and repeatedly pass the participant on the road. This was done to ensure that there was always an empty lane that the participant could use to avoid the vehicles. In the roadside scene, we rendered a cycling lane and a car which repeatedly and slightly move into the lane, and participants had to avoid the car without moving too far away from the lane. In both scenes, the lanes were set to 60 meters long and the vehicles were set to move with a random speed from 1m/s to 16m/s when they spawned at the beginning of the lane. The maximum speed was set approximately to a common urban speed limit of 60km/h.

In addition, the participant's position was set to 30 meters ahead of the start line, and only passive forward movements of the virtual bicycle were provided in the virtual environment. Since the ReAR Indicator's detection range was set to align with the RGB-D camera's depth range (0.3-20 m) in the VR experiment, newly spawned virtual vehicles in the distance would not immediately be rendered with the indicator until they came within this range. To improve presence, we also implemented traffic signs and billboards. The participant moved at a constant speed of 6m/s, resembling an average cycling speed of 20km/h, so the participants perceived that they were passing these objects at that speed. Moreover, the size of each object in the VR environment resembled the size of its real-world counterpart.

5.4 Participants

20 naive individuals (5 female, mean age 26.1, SD 2.73, range 23-31) were recruited for the experiment. All participants had normal or corrected-to-normal vision and at least some experience with bicycles. They were informed that they were allowed to discontinue the experiment at any time. The experiment was conducted under approval of a university ethics committee.

5.5 Measurements

As performance measurements, we gathered data and information from the participants with the following approaches: Regarding forward focus task performance, number of correct QTEs, missed QTEs (i.e. failed to press the correct button within two seconds for a QTE) and total QTEs were recorded by button inputs. In addition, if a participant is able to correctly and quickly react to the QTEs, he/she will get a higher number of total QTEs within the time limit (3 minutes) of each trial. Regarding backward collision avoidance task performance, number of collisions (i.e. hit by a vehicle) and time of staying in front of vehicles were gathered. Besides, total angle of head rotation and subjective ratings were gathered. For subjective ratings, post-trial questionnaires were implemented with the following subjective preference questions on 7-point rating scales from 1 ("Strongly disagree") to 7 ("Strongly agree"):

- I had a clear perception of the backward vehicles' positions and speeds while looking forward.
- I could react to the approaching vehicles quickly.
- I felt safe while riding.
- The interface disturbed me.

5.6 Procedure

As each participant joined our experiment, we briefly introduced the experiment, and we informed the participants about the tasks

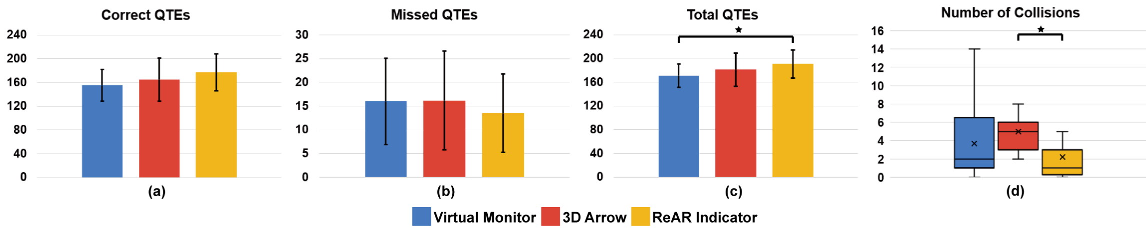

Figure 6: Analysis of the data collected from the *traffic scene* including (a) correct quick time events (QTEs), (b) missed QTEs, (c) total QTEs, and (d) number of collisions.

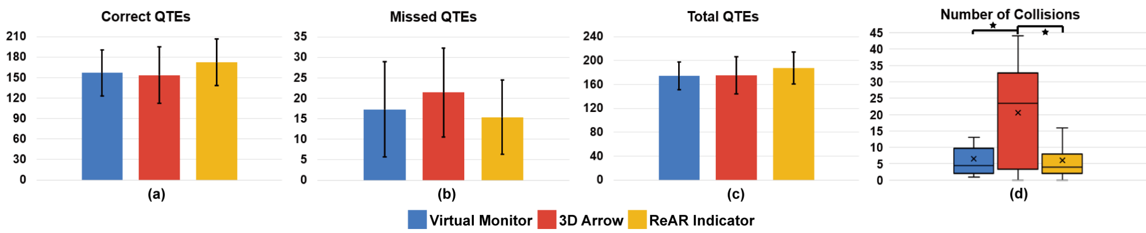

Figure 7: Analysis of the data collected from the *roadside scene* including (a) correct quick time events (QTEs), (b) missed QTEs, (c) total QTEs, and (d) number of collisions.

and requirements. Then, the participant rides on the bicycle and puts on the HMD with help from an experimenter. Before the first trial started, the participants were asked to complete a quick tutorial for practicing inputs of QTEs. Each trial lasted 3 minutes. After each trial, the experimental environment was reset and the participant was asked to fill in a questionnaire.

6 RESULTS

Here, we describe the results of our experiment with respect to the three conditions and two scenes, differences in performance, and subjective preferences. We first tested the data of each measurement with Q-Q plots and Shapiro tests to determine whether the data is normally distributed. Then, we use analysis of variance (ANOVA) with Tukey's HSD post-hoc tests and Friedman tests with Wilcoxon post-hoc tests with a level of 0.05 for determining significance.

6.1 Task Performance

Our significant results included a reduction in the number of collisions as well as an increase for correct QTEs for the ReAR Indicator and Virtual Monitor, which varied in degree between the traffic and roadside scenes. These results are summarized in Figure 6 and Figure 7.

6.1.1 Traffic Scene. Regarding correct QTEs, ANOVA test revealed no significance between the three conditions ($F(2, 57) = 2.298, p = 0.11$) (Figure 6-a). Regarding missed QTEs, no significance was found ($F(2, 57) = 0.487, p = 0.617$) (Figure 6-b). Regarding total QTEs, significance was found ($F(2, 69) = 5.62, p < 0.01$) (Figure 6-c) and post hoc tests showed that there was a significant effect in the ReAR Indicator vs. the virtual monitor ($d = 0.88, p < 0.05$), indicating that when using the ReAR Indicator, participants were more likely to react to the QTEs faster than the virtual monitor.

Regarding number of collisions, a significance was found by Friedman test ($\chi^2 = 15.39, p < 0.001$) (Figure 6-d) and further Wilcoxon post-hoc tests revealed a significant effect in the ReAR Indicator vs. the 3D arrow ($V = 136, p < 0.01$), which showed that the ReAR Indicator were able to help participants to collide less than using the 3D arrow. Regarding time of staying in front of vehicles, significance was found ($F(2, 57) = 9.33, p < 0.001$) (Figure 8-a) and post-hoc tests showed that there were significant effects in the ReAR Indicator vs. the 3D arrow ($d = 0.93, p < 0.01$) and the virtual monitor vs. the 3D arrow ($d = 1.51, p < 0.001$). These results indicated that participants averagely reacted to the approaching vehicles from right behind quicker with the ReAR Indicator and the virtual monitor.

6.1.2 Roadside Scene. Regarding number of collisions, a Friedman test revealed a significance of condition ($\chi^2 = 16.92, p < 0.001$) (Figure 7-d), and further significant effects were observed in the virtual monitor vs. the 3D arrow ($V = 193, p < 0.01$) and the ReAR Indicator vs. the 3D arrow ($V = 181.5, p < 0.001$), indicating that participants were more likely to collide with approaching vehicles when using the 3D arrow.

No significance between the three conditions was found by ANOVA regarding correct QTEs ($F(2, 57) = 1.42, p = 0.25$) (Figure 7-a), missed QTEs ($F(2, 57) = 1.63, p = 0.21$) (Figure 7-b), or total QTEs ($F(2, 57) = 1.44, p = 0.25$) (Figure 7-c).Regarding time staying in front of vehicles, no significance was found ($F(2, 57) = 2.547, p = 0.09$) (Figure 9-a).

6.2 Head Behavior

To determine whether the methods affected participants' head rotation, Friedman tests were applied to the non-normally distributed total angle of head rotation data. In the traffic scene, no significance was found ($\chi^2 = 0.38, p = 0.83$) (Figure 8-b).

In the roadside scene, a significance was found between the three conditions ($\chi^2 = 7.3, p < 0.05$) (Figure 9-b) and post-hoc tests showed that there were significant effects in the ReAR Indicator vs. the virtual monitor ($V = 158, p < 0.05$) and the ReAR Indicator vs. the 3D arrow ($V = 182, p < 0.01$). These results indicated that the ReAR Indicator helped participants to averagely rotate their head less compared to the virtual monitor and the 3D arrow.

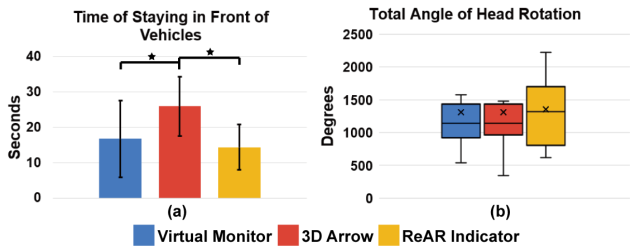

Figure 8: Analysis of the data collected from the *traffic scene* including (a) time of staying in front of vehicles and (b) total angle of head rotation.

6.3 Subjective Preference

In the traffic scene, by analyzing the data from post-trial questionnaires, significant differences were found between the three conditions for “rear perception” ($\chi^2 = 25.65, p < 0.001$) (Figure 10-a), “reaction” ($\chi^2 = 12.69, p < 0.01$) (Figure 10-b), “safety” ($\chi^2 = 16.09, p < 0.001$) (Figure 10-c) and “disturbance” ($\chi^2 = 10.03, p < 0.01$) (Figure 10-d). Post-hoc paired tests revealed significance: For “rear perception”, significant differences were located in the virtual monitor vs. the 3D arrow ($V = 176.5, p < 0.01$) and the ReAR Indicator vs. the 3D arrow ($V = 190.5, p < 0.01$). For “reaction”, a significant difference was found in the ReAR Indicator vs. the 3D arrow ($V = 143, p < 0.01$). For “safety”, significant differences were located in the virtual monitor vs. the 3D arrow ($V = 150, p < 0.01$) and the ReAR Indicator vs. the 3D arrow ($V = 138, p < 0.01$). For “disturbance”, a significant difference was found in the virtual monitor vs. the 3D arrow ($V = 124, p < 0.01$).

In the roadside scene, significant differences were found between the three conditions for “rear perception” ($\chi^2 = 20.51, p < 0.001$) (Figure 11-a), “reaction” ($\chi^2 = 20, p < 0.001$) (Figure 11-b), “safety” ($\chi^2 = 20.63, p < 0.001$) (Figure 11-c) and “disturbance” ($\chi^2 = 8.03, p < 0.001$) (Figure 11-d). Further post-hoc paired tests revealed significant effects: For “rear perception”, significant differences were located in the virtual monitor vs. the 3D arrow ($V = 166, p < 0.001$) and the ReAR Indicator vs. the 3D arrow ($V = 207, p < 0.001$). For “reaction”, significant differences were located in the virtual monitor vs. the 3D arrow ($V = 149, p < 0.001$) and the ReAR Indicator vs. the 3D arrow ($V = 153, p < 0.001$). For “safety”, significant differences were located in the virtual monitor vs. the 3D arrow ($V = 150.5, p < 0.001$) and the ReAR Indicator vs. the 3D arrow ($V = 147.5, p < 0.001$). For “disturbance”, a significant difference was found in the virtual monitor vs. the 3D arrow ($V = 110, p < 0.01$).

7 DISCUSSION

Regarding H1, our analysis of the number of collisions data revealed that participants encountered fewer collisions from behind when using the ReAR Indicator as compared to the 3D arrow in both scenes. Moreover, the virtual monitor was able to help participants to encounter fewer collisions as compared to the 3D arrow in the roadside scene. Besides, there was no significant difference between the ReAR Indicator and virtual monitor in both scenes.

These results suggested that the 3D arrow or similar pointers cannot help users perceive approaching vehicles as efficiently as virtual monitors or peripheral indicators. In addition, the ReAR Indicator was able to deliver enough information for avoiding rear-approaching vehicles as well as a monitor in the field of view. Furthermore, by analyzing the time participants stayed in front of vehicles, we found that using the ReAR Indicator and virtual monitor was more effective than the the 3D arrow when cycling through traffic, indicating that participants were able to more quickly react to approaching vehicles, even when there were multiple vehicles approaching from behind. For the roadside scene, we found no significant difference in reaction times. While cycling on a narrow cycling lane, participants likely paid much more attention to accurate control of the bicycle to keep themselves within the lane.

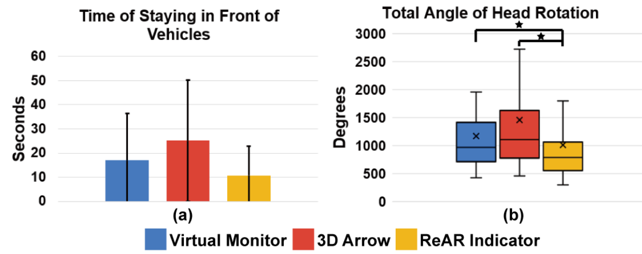

Figure 9: Analysis of the data collected from the *roadside scene* including (a) time of staying in front of vehicles and (b) total angle of head rotation.

In terms of subjective rating results, participants felt both the ReAR Indicator and virtual monitor could better enhance their perception of approaching vehicles in both scenes as compared to the 3D arrow. Moreover, participants felt that they were able to react faster to approaching vehicles with both the ReAR Indicator and virtual monitor in the roadside scene as compared to the 3D arrow. Both the ReAR Indicator and virtual monitor were able to straightly deliver location information of approaching vehicles without requirements of understanding, this feature is likely to positively affect participants’ feeling of perception.

In H2, we hypothesized that our ReAR Indicator may positively affect the participants’ reaction to forward information. Therefore, we investigated correct QTEs, missed QTEs, and total QTEs. However, the statistical results did not reveal any significance in correct QTEs and missed QTEs for both scenes, indicating that the three conditions did not affect participants on the number of correctly inputted QTEs or missed QTEs. Besides, analysis of total QTEs revealed that in the traffic scene, participants were able to react to the QTEs faster with the ReAR Indicator as compared to the virtual monitor. In addition, compared with the ReAR Indicator, there was a larger information flow of multiple approaching cars being displayed on the monitor, therefore participants had to access and process the location and speed of each vehicle with longer duration, thus they had less time to react to the forward located QTEs.

Regarding H3, based on the total angle of head rotation data, participants rotated their head less when using the ReAR Indicator as compared to the virtual monitor and 3D arrow in the roadside scene, suggesting that peripheral indications are able to help users to rotate their head less frequently and keep their view more stable when cycling on roadside. On the other hand, when riding through traffic, the three methods will likely affect head behavior similarly. With further analysis on the subjective ratings of “disturbance”, we found that participants on average felt the virtual monitor was

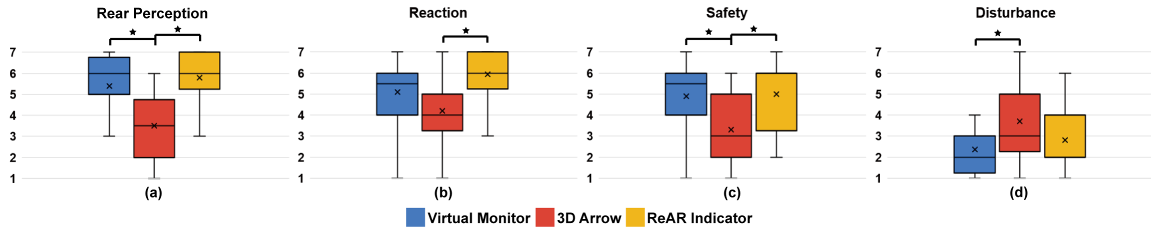

Figure 10: Analysis of the subjective ratings collected from the *traffic scene* including (a) rear perception, (b) reaction, (c) safety, and (d) disturbance.

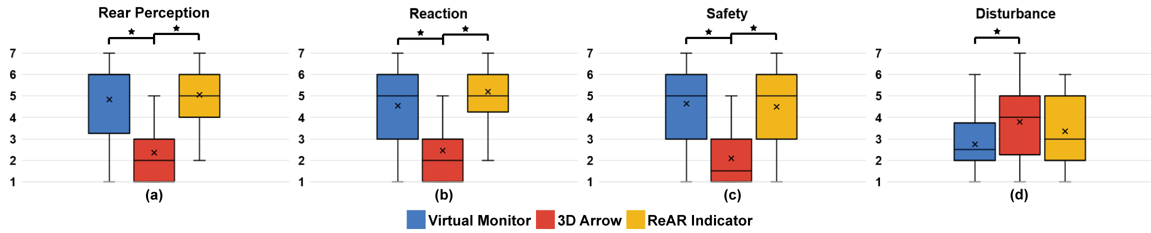

Figure 11: Analysis of the subjective ratings collected from the *roadside scene* including (a) rear perception, (b) reaction, (c) safety, and (d) disturbance.

less disturbing than the 3D arrow in both scenes. Although both of the methods were placed in the same location of the view, this result is still reasonable since the virtual monitor provides a realistic rearview and no learning cost for them. Besides, the subjective ratings of "safety" indicated that participants considered using the ReAR Indicator and virtual monitor to be safer than using the 3D arrow. We believe that in this user study, feeling of safety is correlated with the feeling of rear perception vehicles, as participants rated "rear perception" low, they would feel less safe.

The results indicated that the peripheral indications were subjectively satisfying to the participants, consistent with findings from previous works ([19, 23]). However, they were not observed to have a stronger effect on task performance than the virtual monitor, in contrast to the findings by Kunze et al. ([19]). During the user study, several participants reported that they have driving experience and felt the virtual monitor is similar to rear monitors in cars but larger, therefore they were able to take advantage of the experience without hesitation. This familiarity may have influenced results, particularly as participants juggled dual tasks.

8 CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a novel augmented reality-based peripheral indicator designed to help cyclists access information about vehicles approaching from behind in a safe and easy manner. To accomplish this, we integrated real-time vehicle detection from a rear-facing camera and peripheral rendering techniques. Vehicle information can then be converted into a bar format in the cyclist's peripheral area, which allows the cyclist to both pay attention to forward obstacles and perceive information about rear vehicles. We then conducted a VR based within-subjects user study with 20 participants to determine how participants would perform with the ReAR Indicator, a virtual monitor, and 3D arrows. In addition, the participants were asked to avoid vehicles that were approaching from the rear while inputting forward-located quick time events in traffic and roadside virtual cycling scenes.

Results from this study showed that both our proposed approach and a virtual rear view mirror effectively reduced the number of collisions with vehicles in comparison to 3D arrows. Moreover, the ReAR Indicator enabled users to maintain better head stability without a significant decrease in forward reaction time. In addition, since the participants were not familiar with peripheral rendering methods, the indicator may prove to be more effective when the peripheral rendering techniques along with AR HMDs are more common and broadly accepted in the future. A current limitation of our work is that vehicles approaching from afar can not be detected until they reach the 20-meter limit of the RGB-D camera. The user may not have enough time to react when a vehicle is approaching quickly. However, longer-range RGB-D cameras may solve this problem in the future. The implementation of our approach differed slightly between AR and VR, particularly in terms of the FoV of the HMDs, display resolution, and render transparency. Additionally, it's worth noting that AR glasses like the HoloLens 2 offer a limited field of view, which may not be optimal for presenting a wide range of UI information simultaneously. In future studies, we plan to conduct experiments testing combinations of forward and backward hazard indicators when cycling.

The main contributions of this work are as follows: proposing a novel peripheral rendering technique to improve awareness of rear-approaching vehicles while cyclists focus on the forward direction. Experimental results confirm that it effectively helps cyclists maintain focus on their forward view while avoiding collisions with virtual vehicles from the rear. We hope that this work will encourage the development of other peripheral information delivery techniques for cyclists that can improve riding safety and maintain attention to the forward view as well as the exploration of augmented reality-based peripheral indicator designs that allow for high accessibility and low disturbance.

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