E-ScootAR: Exploring Unimodal Warnings for E-Scooter Riders in Augmented Reality

Andrii Matviienko
matviienko@tk.tu-darmstadt.de
Technical University of Darmstadt
Darmstadt, Germany

Florian Müller
florian.mueller@ifi.lmu.de
LMU Munich
Munich, Germany

Dominik Schön
Régis Fayard
Technical University of Darmstadt
Darmstadt, Germany

Salar Abaspur
Yi Li
Technical University of Darmstadt
Darmstadt, Germany

Max Mühlhäuser
max@tk.tu-darmstadt.de
Technical University of Darmstadt
Darmstadt, Germany

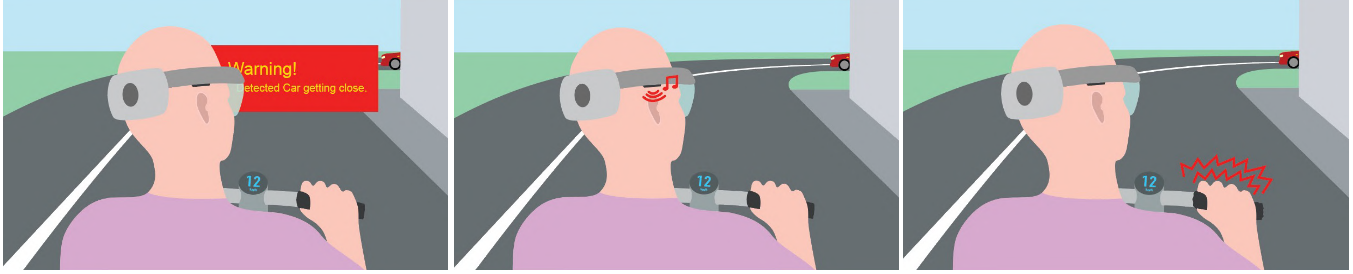

Figure 1: We compared three unimodal warnings for E-Scooter riders to situations with no warnings as a baseline at intersections with approaching vehicles: Augmented Reality warning displays a text "Warning! Detected Car getting close." (left), auditory warning emits beeping signals (middle), and vibrotactile feedback is activated on the grips of the handlebar (right).

ABSTRACT

Micro-mobility is becoming a more popular means of transportation. However, this increased popularity brings its challenges. In particular, the accident rates for E-Scooter riders increase, which endangers the riders and other road users. In this paper, we explore the idea of augmenting E-Scooters with unimodal warnings to prevent collisions with other road users, which include Augmented Reality (AR) notifications, vibrotactile feedback on the handlebar, and auditory signals in the AR glasses. We conducted an outdoor experiment (N = 13) using an Augmented Reality simulation and compared these types of warnings in terms of reaction time, accident rate, and feeling of safety. Our results indicate that AR and auditory warnings lead to shorter reaction times, have a better perception, and create a better feeling of safety than vibrotactile warnings. Moreover, auditory signals have a higher acceptance by the riders compared to the other two types of warnings.

CCS CONCEPTS

• **Human-centered computing** → **Interactive systems and tools**; **Mixed / augmented reality**.

KEYWORDS

E-Scooter, micro-mobility, traffic safety, augmented reality

ACM Reference Format:
Andrii Matviienko, Florian Müller, Dominik Schön, Régis Fayard, Salar Abaspur, Yi Li, and Max Mühlhäuser. 2022. E-ScootAR: Exploring Unimodal Warnings for E-Scooter Riders in Augmented Reality. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '22 Extended Abstracts), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3491101.3519831

1 INTRODUCTION

As a solution to urbanization, its ever-increasing traffic congestion, and global warming, micro-mobility is becoming a popular means of transportation [22, 29]. The trend is being pushed by sharing services of power-standing scooters. Those devices, known as electric scooters or E-Scooters [7], facilitate convenience of mobility and sustainability [4, 5] in cities and replace short-distance driving in urban environments [33]. However, traffic safety regarding E-Scooters is a big concern, as indicated by accident reports [3], which brings the riders and other road users into dangerous situations [14], leading to light and heavy injuries [2, 13, 14, 27]. The

---

CHI '22 Extended Abstracts, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9156-6/22/04…$15.00
https://doi.org/10.1145/3491101.3519831

main circumstances and locations where E-Scooter riders are injured include crashing with moving vehicles while riding on a road, bicycle lane, or a sidewalk [3].

Previous research aimed to address the issue of safety in micromobility, which was primarily focused on cyclists [15–19]. Several works have shown that the safety of riding bicycles can be elevated by augmenting vehicles and drivers with additional signals. For instance, a warning system on the helmet has been implemented to avoid accidents for bicycle riders [26] and intelligent driving assistants by mobile applications for car drivers [10], which have significantly improved the safety of traffic participants. Furthermore, studies were made in the bicycle subject area, where riders perceived the signals of warning through different interaction ways, such as physical vibration [25] or by a signal on the road [6]. Also, the researchers compared the reaction time of riders perceiving a warning signal via visual, auditory, and vibrotactile modalities, intending to improve the safety of child cyclists [15]. Given that safety for cyclists and E-Scooter riders poses similar challenges, such as lower protection compared to motorized vehicles, comparable speed, the danger of being overseen, we hypothesize that unimodal warning signals can assist E-Scooter riders. Therefore, in this work, we aim to answer an open question of whether unimodal warnings can be applied to the safety requirements of riding E-Scooters, and, if yes, how effective they are.

In this paper, we explore the idea of augmenting E-Scooters with unimodal warning signals to facilitate the safety of E-Scooter riders on the roads with intersections [1, 8], where cars can appear from both sides, as one of the most dangerous situations. For that, we conducted an outdoor experiment (N = 13) in an Augmented Reality (AR) simulation to examine the effectiveness of the proposed warning signals: (1) AR notifications, (2) vibrotactile feedback on the handlebar, and (3) auditory signals in the AR glasses (Figure 1). The AR simulation facilitates riding on a real E-Scooter in a safe physical environment, e.g., on a restricted outdoor test track, through a purely virtual world shown in the AR glasses, and supports mimicking of hazardous situations without putting participants into danger. The results from our experiment indicate that auditory and AR warnings induced the shortest reaction time to a hazard, created a higher feeling of safety, and were perceived and accepted better than vibrotactile. With this work, we contribute an empirical evaluation of unimodal warning signals for E-Scooter riders.

2 RELATED WORK

Although there has not been much research done on the exploration of warning signals for E-Scooter riders, researchers have investigated assistance systems for other groups of micro-mobility. In this section, we outline related work related to (1) the current state of assistance for E-Scooter riders and (2) warning systems for cyclists as one of the closest groups to E-Scooter riders in terms of speed and lack of protection.

2.1 Current State of E-Scooter Riders

The analyses of the reasons for injuries of E-Scooter riders have indicated that the most severe accidents have previously happened on sidewalks (58%) and roads (23%) [3]. Moreover, only 5% of the riders wear helmets and have most injuries in the head region [13, 27], and most severe injuries happen due to the high travel speed [3]. In their attempts to assist E-Scooter riders, Maiti et al. [14] collected data on encounters between E-Scooters and pedestrians and found that 58% of pedestrians were interested in a mobile application that would warn them about encounters with E-Scooters. To overcome the lack of turning signals on some E-Scooters, Löcken et al. [12] investigated the feeling of safety for participants when they show safety signals using hands. Their results indicated that every participant performed the test using hand gestures without any accident and felt overall safe. Our work makes the first step towards a better understanding of assistance systems for E-Scooter riders by exploring unimodal warning signals integrated into the scooters and glasses. We build on the previous work related to warning assistance for cyclists, which we outline in the following.

2.2 Warning Assistance for Cyclists

Safety for cyclists and E-Scooter riders poses similar challenges, such as lower protection compared to motorized vehicles, comparable speed, the danger of being overseen by car drivers. Therefore, we hypothesize that unimodal warning signals can assist E-Scooter riders. In this subsection, we outline warning systems for cyclists with an aim to extend them to E-Scooter riders.

Most of the existing warning systems for cyclists have explored the use of on-bicycle assistance systems. One prominent example includes an off-the-shelf Garmin Varia Rearview radar [1], which warns of vehicles approaching from behind using a visual notification on the screen fixed to the handlebar. Vibrotactile feedback was also previously employed for collision prevention between cyclists and pedestrians. For example, Yoshida et al. [32] proposed a system that warns both pedestrians and cyclists through their smartphones about an impending collision at a blind corner. They showed that collisions could be prevented by using their GPS-based algorithm and vibrotactile feedback. A helmet is perhaps the most common bicycle safety accessory. Researchers have previously augmented helmets with both visual and auditory signals to notify riders and other traffic participants. For instance, Schopp et al. [24] augmented a cyclist's helmet with a bone conduction speaker to warn cyclists of approaching vehicles outside their field of view. Their results showed that participants perceived an increase in situational awareness and could easier identify hazardous situations. Jones et al. [9] enhanced a cyclist's helmet for both input and output. Additional lights placed on the back of a helmet were used to indicate turn signals through head-tilting and a microphone to communicate the location to other drivers. Similarly, Blink Helmet [2], utilized manual buttons on the sides of the helmet to indicate stop and turn signals. Von Sawitzky et al. [30] have investigated three head-up concepts to improve road safety for cyclists, which include seeing through walls, a smart path for crossing, and warning signs. More recently, a combination of signals integrated into both bicycles and helmets has been investigated to warn child cyclists [15].

Although multimodal warnings have proven to be the preferred way to efficiently inform about impending hazards, in this work, we investigate unimodal warnings as a first step towards safety

---

[1] https://buy.garmin.com/en-GB/GB/p/518151, last accessed 22nd February 2022
[2] https://www.wired.com/2011/04/blink-touch-sensitive-bike-lights-built-into-helmet/, last accessed 22nd February 2022

Figure 2: A first person perspective in the AR-based simulation (left) and AR simulation shown through the AR glasses (right).

and their applicability for E-Scooter riders. With this, we aim to investigate whether unimodal signals are sufficient enough to warn E-Scooter riders and increase their safety before adding multiple simultaneous signals.

3 STUDY

To investigate the warning signals for E-Scooter riders, we conducted an experiment on an outdoor test track. Given that the real-world traffic conditions can put participants into dangerous situations, we simulated a virtual world and traffic conditions, which were shown in Augmented Reality glasses. This experiment aimed to identify the warning signals that lead to the shortest reaction time, lowest accident rate, and create a high feeling of safety. Therefore, for this experiment, we had the following research question: *Which unimodal warning signals are the most applicable to increase the safety of E-Scooter riders in terms of reaction time to a hazard, accident rate, and feeling of safety?*

3.1 Participants

We recruited 13 participants (2 female and 11 male) aged between 19 and 60 ($Mean = 27.9, SD = 10.1$). All participants received no compensation and had normal or corrected vision.

3.2 Study design

The study was designed to be within-subject with one independent variable: *type of warning signal*. The type of warning contained four levels and reflected four experimental conditions, which included riding an E-Scooter with (1) Augmented Reality (AR), (2) vibrotactile, (3) auditory warning, and (4) without warning as a baseline (Figure 1). The AR warning appears in front of the rider as a text message *"Warning! Detected car getting close."* (Figure 2 left), the vibrotactile feedback was presented on both sides of the handlebar with a sequence of three vibrations with a delay of 500 ms, and the auditory signal was emitted from the AR glasses as a sequence of three beeping signals also with a delay of 500 ms. All three types of warnings lasted 2.5 seconds in total.

During the experiment, participants were wearing AR glasses, which showed a virtual city (Figure 2), and were physically riding on the empty restricted parking lot. We used AR simulation to ensure visibility of the real world for safety reasons, e.g., to avoid riding against objects in the real world, unlike Virtual Reality simulation that shows only the virtual world, as introduced by Matviienko et al. [21]. We designed four unique routes with six T- and six X-crossings, where one car per intersection was randomly coming four times from the left, four times from the right, and four times from both sides. Due to the differences of speed perception between virtual and real world [11, 31], the speed of the cars was 15 km/h. The maximum speed of 50 km/h for urban environments in a virtual environment is perceived higher, and riding without accidents is practically impossible, given the smaller sizes of the surrounding buildings and cars. The conditions and trajectories were counterbalanced with the Balanced Latin Square to avoid learning effects. Each condition was assigned to one of the four trajectories for each participant in a counterbalanced way. Upon approaching an intersection, participants were provided with a warning about an upcoming car.

Figure 3: The E-Scooter was equipped with four vibration motors on the left and right sides of the handlebar and the reaction button on the left to measure reaction time to the warnings. The vibration motors and the reaction button were directly connected to a NodeMCU microcontroller for communication with a HoloLens.

	Reaction Time, ms		**Accident rate (%)**		**Acceptance**		**Perception**		**Safety**	
Warning	M	SD	M	SD	Md	IQR	Md	IQR	Md	IQR
AR	645	386	21.1	0.29	3	1	5	1	4	2
Auditory	769	478	18.2	0.2	4	2	5	0	4	1
Vibration	1392	1072	35.6	0.22	3	2	3	1	3	1
No assistance	-	-	39.4	0.23	-	-	-	-	-	-

Table 1: Overview of the descriptive results. M = mean, SD = standard deviation, Md = median, IQR = interquartile range.

3.3 Apparatus

Participants rode on a commercially available XIAOMI Mi Scooter 1S (Figure 3) while wearing Augmented Reality glasses. The E-Scooter had two mechanical brakes and could be accelerated with a throttle on the right side of the handlebar. The virtual environment was implemented using Unity game engine and shown in Microsoft HoloLens 2 Augmented reality glasses. To create a virtual city, we used a set of four tiles (4.5m x 4.5m): (1) corner, (2) straight street, (3) T-intersection, and (4) intersection. We detected the rider's position using invisible checkpoints and rearranged the tiles to create a new road, facilitating a continuous ride for each condition. The glasses were used off the shelf without additional tracking support from the hardware side. To specify the origin of the virtual city, the glasses had to be placed at the designated location on the ground prior to an experimental condition. To reduce the influence of vibrations caused by the road surface, we conducted a study on a restricted parking lot with asphalt pavement without other vehicles.

The auditory warning assistant uses the speakers of the HoloLens, where a beeping sound was played three times upon the arrival of danger. For the tactile warning assistant, four vibration motors[3] connected to a NodeMCU ESP8266 microcontroller for communication with a HoloLens were placed on each side of the handlebar (Figure 3). To measure the reaction time of participants, we added a button on the left side of the handlebar, also connected to the NodeMCU ESP8266 (Figure 3). To facilitate communication between the vibration motors and the button with the Hololens, we used a Wi-Fi access point via a NodeMCU.

3.4 Measures

To compare the warning signals for E-Scooters riders, we measured the following dependent variables:

- *Reaction time (in ms):* The time between the occurrence of a warning signal and a button press. We did not measure the reaction time for conditions without warnings since our study aims to compare warning signals and not the reaction time to the appearance of a car.
- *Accident Rate:* We counted the number of times participants had a collision with a virtual car.
- *Warning acceptance:* for each condition, we asked participants to specify the level of acceptance of the warning when riding in real traffic conditions using a 5-point scale.
- *Perception of a signal and safety*: for each condition, we asked participants to specify how well they could perceive the waning signal and how safe they felt riding on an E-Scooter using the warning signal using a 5-point scale.

3.5 Procedure

For this study, we adhered to our universities health department's guidelines for user studies during the COVID-19 pandemic, and all testing equipment was disinfected for each participant. After obtaining informed consent, we collected participants' demographic data and provided a brief overview of the procedures, including explanations of warning signals. Participants familiarized themselves with an E-Scooter, augmented reality simulation, and warning signals during a test ride. Once the participants felt comfortable, we started experimental conditions with riding in the simulation while wearing the Augmented Reality glasses. Participants had to ride straight during the experiment or follow the road course on an E-Scooter through a virtual city shown in the AR glasses. Their task was to safely ride through the city and press a button on the handlebar whenever they perceived a warning. The reaction time was measured only for the conditions with warning signals. The speed of the E-Scooter was restricted to a maximum of 15 km/h for safety reasons. At the end of the study, we interviewed the participants about their preferences for the warnings. The riding part of the study took about half an hour, and the entire study lasted approximately one hour.

4 RESULTS

We found that it takes longer to perceive and react to vibrotactile than AR and auditory warnings. However, the accident rate remained consistent for all types of warning signals. Given that the collected data was not normally distributed according to the Shapiro-Wilk test, we used the Friedman test and Wilcoxon-signed rank test for post-hoc analysis of the non-parametric data. For pairwise comparisons, we used a Bonferroni correction. The summary of results is shown in Table 1. We outline these findings in detail in the following.

4.1 Reaction time

We found that reaction time to AR ($M = 645ms, SD = 386$) and auditory ($M = 769ms, SD = 478$) warnings was shorter compared to vibrotactile ($M = 1392ms, SD = 1072$). Using the Friedman test we revealed that this difference was statistically significant ($\chi^2(2) = 7.54, p < 0.05, \eta^2 = 0.26$). The pairwise comparisons have shown that it took participants a longer time to react to vibrotactile warnings compared to AR ($p < 0.001$) and auditory ($p < 0.001$). However, the reaction time for AR and auditory warnings was comparable ($p > 0.05$) (Figure 4 left).

---

[3] https://www.adafruit.com/product/1201

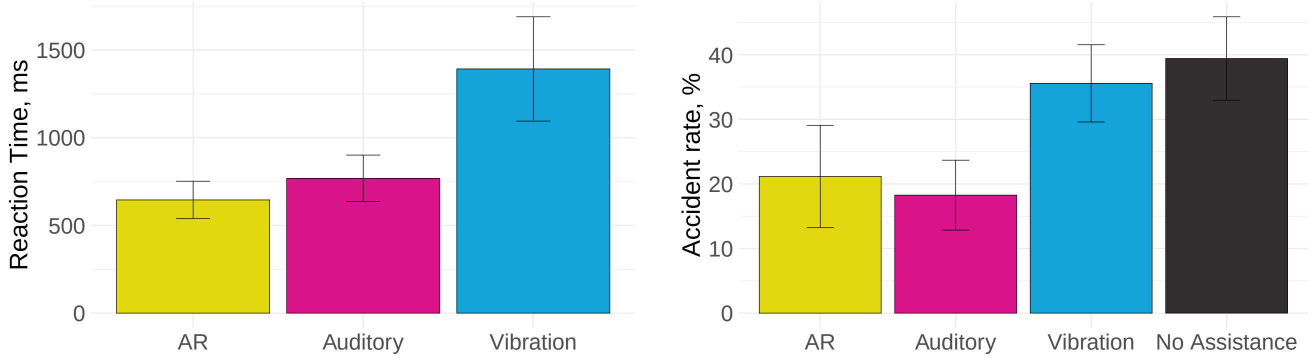

Figure 4: Overview of the results: reaction time (left) and accident rate (right) per type of warning.

4.2 Accident Rate

We found that participants had the lowest number of accidents with virtual cars using auditory ($M = 0.18, SD = 0.2$) and AR ($M = 0.21, SD = 0.29$) warnings, followed by vibration ($M = 0.36, SD = 0.22$, and no assistance ($M = 0.39, SD = 0.23$). Although we found that this difference was statistically significant ($\mathcal{X}^2(3) = 8.4, p < 0.05, \eta^2 = 0.16$), after the Bonferroni correction none of the pairwise comparisons were statistically significant ($p > 0.05$) (Figure 4 right).

4.3 Acceptance, perception, and safety of warnings

We discovered that participants found auditory warnings the most *acceptable*, i.e., appropriate to use, in the real traffic conditions ($Md = 4, IQR = 2$), followed by AR ($Md = 3, IQR = 1$) and vibrotactile ($Md = 3, IQR = 2$). Using the Friedman test we revealed that this difference was statistically significant ($\mathcal{X}^2(2) = 8.6, p < 0.05, \eta^2 = 0.33$). The pairwise comparisons have shown that participants found it more acceptable to ride with auditory warnings in the real traffic conditions compared to AR ($p < 0.001$) and vibrotactile warnings ($p < 0.001$). However, the acceptance of AR and vibrotactile warnings was comparable ($p > 0.05$).

As for the *perception of warnings*, we found that auditory ($Md = 5, IQR = 0$) and AR ($Md = 5, IQR = 1$) warnings were easier to perceive compared to the vibrotactile ($Md = 3, IQR = 1$) ones. Using the Friedman test we revealed that this difference was statistically significant ($\mathcal{X}^2(2) = 20.7, p < 0.001, \eta^2 = 0.8$). The pairwise comparisons have shown that participants found it more challenging to perceive vibrotactile warnings compared to auditory ($p < 0.001$) and AR ($p < 0.001$). However, the perception of AR and auditory warnings was comparable ($p > 0.05$).

As for the *feeling of safety* with warnings, we found that auditory ($Md = 4, IQR = 1$) and AR ($Md = 4, IQR = 2$) warnings facilitated a higher feeling of safety compared to the vibrotactile ($Md = 3, IQR = 1$) ones. This difference was statistically significant, as shown by the Friedman test ($\mathcal{X}^2(2) = 14.8, p < 0.001, \eta^2 = 0.57$). The pairwise comparisons have shown that participants felt less safe with vibrotactile warnings compared to auditory ($p < 0.001$) and AR ($p < 0.001$). However, the feeling of safety with AR and auditory warnings was comparable ($p > 0.05$).

4.4 Problems and preferences

Concerning participants' preferences for warnings, we found that most of the participants (N = 8) preferred the auditory warnings, followed by AR (N = 3), vibrotactile (N = 1), and none (N = 1).

As for the *AR* warnings, the opinions of the participants diverged. While some participants mentioned that the signal took too much space in the field of view, e.g., *"Bad view because of the signal. You can not see the car"* (P10) or *"The signal takes space of your sight"* (P9), others mentioned that *"the visual signal was very good to receive"* (P3) and *"easy too see"* (P4). P2 also remarked that he was not distracted from riding an E-Scooter with this kind of warning: *"I have my eyes most of the time at the street where I drive, and I can't oversee a warning"*. Additionally, some participants said that they had *"no time to read"* (P1, P4) the warning and *"Visual appearance is irritating"* (P13) due to the simultaneous presentation of the warning signal and the arriving car.

The *auditory* warning was rated primarily positive. The sound of the warning signal was *"clear"* (P9, P13) and made the participants more *"concentrated"* on the imminent danger situation (P5, P11). Furthermore, it was mentioned that hearing the warning signal was not as *"irritating"* (P12) as the other signals. However, participants questioned the perception of audio warnings in real traffic situations: *"How will it work with high traffic density?"* (P5, P6).

Participants' opinions regarding the vibrotactile warnings were predominantly negative. Most participants were not sure whether the vibration was caused by the surface or the vibration of the handlebars (P11, P13), which led to situations in which the signal was not *"that much noticeable"* (P6), or felt *"irritating"* (P3, P9). Only two participants gave positive feedback about vibration, mentioning that they perceived it *'good"* (P12) and it was a *'strong signal"* (P8).

5 DISCUSSION AND FUTURE WORK

In general, we discovered that unimodal warnings can facilitate safety for E-Scooter riders. Our results indicate that with simple unimodal signals E-Scooter riders could quickly react to an upcoming hazard and avoid accidents.

Although we could not significantly reduce the accident rate of E-Scooter riders with unimodal warning signals, we showed that both auditory and AR warnings lead to about two times fewer accidents than vibrotactile feedback and baseline without any support. One of the reasons for this result could be that vibrotactile feedback is hardly perceived outdoors due to the vibrations of the road surface while riding. Moreover, we ensured that vibrotacile feedback was easy to perceive and distinguish between left and right in a stationary position from the hardware side. While AR auditory warnings were barely influenced by the AR environment and external noise, the vibration caused by the road surface affected the perception of vibrotactile signals. This finding does not necessarily mean that vibrotactile feedback should be excluded from signals on E-Scooters, but it can be possibly combined with auditory and visual feedback to enhance attention through multiple sensory channels, as has been done for cyclists [15] and car drivers [23]. The second reason for an increased accident rate may be related to the AR simulation, which was perceived as a harmless experience without fatal consequences in a "miniature" city compared to real traffic situations and led to the riders' careless behavior. However, this was unavoidable, given that a 1:1 mapping of the virtual environment would lead to unstable AR outdoor tracking. Moreover, with our experiment, we have shown that the proposed AR environment for conducting user experiments can not only be used indoors for cyclists [21] but also outdoors for E-Scooter riders. Given that AR warnings were found to be distracting, in future, they need to be redesigned to a more abstract visualization without textual information. Alternatively, the visual type of warnings can be moved to the periphery of the visual field [20], similar to helmets for cyclists [17] and motorcycles [28].

The shorter reaction time for auditory and AR warnings of 600-800 ms further indicates that they were perceived faster than vibrotactile signals. This finding is in line with previous works about warnings for cyclists, which led to comparable results [15]. Although cycling on a regular bicycle differs from riding an E-Scooter that requires standing and leads to higher speeds, we can observe similarities in our results between both types of micro-mobility. However, future designers will have to consider the duration of warning signals more carefully, given the reaction time of 600-800 ms for AR and auditory warnings, to avoid lengthy signals of over 1.5-2 seconds. In addition, auditory signals have higher acceptance by riders and generate a higher sense of safety. This can be explained by the more subtle nature of auditory signals compared with AR warnings, which were displayed more explicitly in front of drivers and partially covered the field of view. Both signals can be integrated into helmets for E-Scooter riders, especially when they will be introduced as a recommended or mandatory safety element for E-Scooter riders.

All in all, this shows that AR and auditory warnings can increase the safety of E-Scooter riders and bring advancement compared to the baseline without any assistance at all. The next step for future work could be to explore a combination of warning signals [15, 23] for different hazard levels or traffic densities, such as rush hour in the city versus 30 km/h in the neighborhood. Finally, we tested a limited number of participants to obtain initial results in this area of research in the simulation-based nature of the experiment, which made them feel safer in the virtual city than in real-world conditions. However, this was unavoidable as our goal was to conduct the experiment under controlled, reproducible, and, most importantly, safe conditions.

6 CONCLUSION

In this paper, we evaluated three types of unimodal warnings in augmented reality simulation to improve the safety of E-Scooter riders. We found that AR and auditory warnings lead to shorter reaction times when a dangerous situation happens, higher perception and acceptance of the signals, and create a better feeling of safety compared to vibrotactile warnings. Moreover, the multimodal solution via a combination of AR and auditory signals might be a suitable solution for more complex traffic situations, which requires further investigation.

ACKNOWLEDGMENTS

We would like to thank all participants who took part in our experiment. This work has been co-funded by the LOEWE initiative (Hesse, Germany) within the emergenCITY center and the Humane AI Net from the European Union's Horizon 2020 research and innovation program under grant agreement No 761758.

REFERENCES

[1] Bjorn Anderson, Jonathan D. Rupp, Tim P. Moran, Lauren A. Hudak, and Daniel T. Wu. 2021. The Effect of Nighttime Rental Restrictions on E-Scooter Injuries at a Large Urban Tertiary Care Center. *International Journal of Environmental Research and Public Health* 18, 19 (2021). https://doi.org/10.3390/ijerph181910281

[2] Austin Badeau, Chad Carman, Michael Newman, Jacob Steenblik, Margaret Carlson, and Troy Madsen. 2019. Emergency department visits for electric scooter-related injuries after introduction of an urban rental program. *The American Journal of Emergency Medicine* 37, 8 (2019), 1531–1533. https://doi.org/10.1016/j.ajem.2019.05.003

[3] Jessica B. Cicchino, Paige E. Kulie, and Melissa L. McCarthy. 2021. Severity of e-scooter rider injuries associated with trip characteristics. *Journal of Safety Research* 76 (Feb. 2021), 256–261. https://doi.org/10.1016/j.jsr.2020.12.016

[4] Regina Clewlow, Fletcher Foti, and Toshi Shepard-Ohta. 2018. *Measuring equitable access to new mobility: A case study of shared bikes and electric scooters.* Technical Report.

[5] Regina R Clewlow. 2019. *The micro-mobility revolution: The introduction and adoption of electric scooters in the united states.* Technical Report.

[6] Alexandru Dancu, Velko Vechev, Adviye Ayça Ünlüer, Simon Nilson, Oscar Nygren, Simon Eliasson, Jean-Elie Barjonet, Joe Marshall, and Morten Fjeld. 2015. Gesture Bike: Examining Projection Surfaces and Turn Signal Systems for Urban Cycling. In *Proceedings of the 2015 International Conference on Interactive Tabletops and Surfaces* (Madeira, Portugal) *(ITS '15)*. Association for Computing Machinery, New York, NY, USA, 151–159. https://doi.org/10.1145/2817721.2817748

[7] SAE International. 2021. J3194: Taxonomy and Classification of Powered Micromobility Vehicles. https://www.sae.org/standards/content/j3194_201911/

[8] Junfeng Jiao, Shunhua Bai, and Seung J. Choi. 2021. Understanding E-Scooter Incidents Patterns in Street Network Perspective: A Case Study of Travis County, Texas. *Sustainability* 13, 19 (2021), 10583. https://doi.org/10.3390/su131910583

[9] Eric M. Jones, Ted Selker, and Hyemin Chung. 2007. What You Said about Where You Shook Your Head: A Hands-Free Implementation of a Location-Based Notification System. In *CHI '07 Extended Abstracts on Human Factors in Computing Systems* (San Jose, CA, USA) *(CHI EA '07)*. Association for Computing Machinery, New York, NY, USA, 2477–2482. https://doi.org/10.1145/1240866.1241027

[10] Joni Jämsä and Heidi Kaartinen. 2015. Mobile applications for traffic safety. In *2015 6th IEEE International Conference on Cognitive Infocommunications (CogInfoCom)*. 19–24. https://doi.org/10.1109/CogInfoCom.2015.7390557

[11] Markus Löchtefeld, Antonio Krüger, and Hans Gellersen. 2016. DeceptiBike: Assessing the Perception of Speed Deception in a Virtual Reality Training Bike System. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (Gothenburg, Sweden) *(NordiCHI '16)*. Association for Computing Machinery, New York, NY, USA, Article 40, 10 pages. https://doi.org/10.1145/2971485.2971513

[12] Andreas Löcken, Pascal Brunner, and Ronald Kates. 2020. Impact of Hand Signals on Safety: Two Controlled Studies With Novice E-Scooter Riders. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. ACM, Virtual Event DC USA, 132–140. https://doi.org/10.1145/3409120.3410641

[13] Olivia Mair, Markus Wurm, Michael Müller, Frederik Greve, Sebastian Pesch, Dominik Pförringer, Peter Biberthaler, Chlodwig Kirchhoff, and Michael Zyskowski. 2020. E-Scooter-Unfälle und deren Folgen. *Der Unfallchirurg* (Oct. 2020). https://doi.org/10.1007/s00113-020-00910-7

[14] Anindya Maiti, Nisha Vinayaga-Sureshkanth, Murtuza Jadliwala, Raveen Wijewickrama, and Greg P. Griffin. 2020. Impact of E-Scooters on Pedestrian Safety: A Field Study Using Pedestrian Crowd-Sensing. *arXiv:1908.05846 [cs]* (July 2020). http://arxiv.org/abs/1908.05846

[15] Andrii Matviienko, Swamy Ananthanarayan, Shadan Sadeghian Borojeni, Yannick Feld, Wilko Heuten, and Susanne Boll. 2018. Augmenting Bicycles and Helmets with Multimodal Warnings for Children. In *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Barcelona, Spain) *(MobileHCI '18)*. Association for Computing Machinery, New York, NY, USA, Article 15, 13 pages. https://doi.org/10.1145/3229434.3229479

[16] Andrii Matviienko, Swamy Ananthanarayan, Stephen Brewster, Wilko Heuten, and Susanne Boll. 2019. Comparing Unimodal Lane Keeping Cues for Child Cyclists. In *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia* (Pisa, Italy) *(MUM '19)*. Association for Computing Machinery, New York, NY, USA, Article 14, 11 pages. https://doi.org/10.1145/3365610.3365632

[17] Andrii Matviienko, Swamy Ananthanarayan, Abdallah El Ali, Wilko Heuten, and Susanne Boll. 2019. *NaviBike: Comparing Unimodal Navigation Cues for Child Cyclists*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300850

[18] Andrii Matviienko, Swamy Ananthanarayan, Raphael Kappes, Wilko Heuten, and Susanne Boll. 2020. Reminding Child Cyclists about Safety Gestures. In *Proceedings of the 9TH ACM International Symposium on Pervasive Displays* (Manchester, United Kingdom) *(PerDis '20)*. Association for Computing Machinery, New York, NY, USA, 1–7. https://doi.org/10.1145/3393712.3394120

[19] Andrii Matviienko, Florian Heller, and Bastian Pfleging. 2021. *Quantified Cycling Safety: Towards a Mobile Sensing Platform to Understand Perceived Safety of Cyclists*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3411763.3451678

[20] Andrii Matviienko, Andreas Löcken, Abdallah El Ali, Wilko Heuten, and Susanne Boll. 2016. NaviLight: Investigating Ambient Light Displays for Turn-by-Turn Navigation in Cars. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Florence, Italy) *(MobileHCI '16)*. Association for Computing Machinery, New York, NY, USA, 283–294. https://doi.org/10.1145/2935334.2935359

[21] Andrii Matviienko, Florian Müller, Dominik Schön, Paul Seesemann, Sebastian Günther, and Max Mühlhäuser. 2022. BikeAR: Understanding Cyclists' Crossing Decision-Making at Uncontrolled Intersections using Augmented Reality *(CHI '22)*. Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3491102.3517560

[22] Giulia Oeschger, Páraic Carroll, and Brian Caulfield. 2020. Micromobility and Public Transport Integration: The Current State of Knowledge. *Transportation Research Part D: Transport and Environment* 89 (Dec. 2020), 102628. https://doi.org/10.1016/j.trd.2020.102628

[23] Ioannis Politis, Stephen Brewster, and Frank Pollick. 2013. Evaluating Multimodal Driver Displays of Varying Urgency. In *Proceedings of the 5th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Eindhoven, Netherlands) *(AutomotiveUI '13)*. Association for Computing Machinery, New York, NY, USA, 92–99. https://doi.org/10.1145/2516540.2516543

[24] Eldon Schoop, James Smith, and Bjoern Hartmann. 2018. HindSight: Enhancing Spatial Awareness by Sonifying Detected Objects in Real-Time 360-Degree Video. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173717

[25] Haska Steltenpohl and Anders Bouwer. 2013. Vibrobelt: Tactile Navigation Support for Cyclists. In *Proceedings of the 2013 International Conference on Intelligent User Interfaces* (Santa Monica, California, USA) *(IUI '13)*. Association for Computing Machinery, New York, NY, USA, 417–426. https://doi.org/10.1145/2449396.2449450

[26] Yoshiaki Taniguchi and Hiroyuki Hisamatsu. 2017. A Road Surface Condition Monitoring System Using Bicycle-Mounted Laser Light. *International Journal of Simulation: Systems, Science & Technology* (Jan. 2017). https://doi.org/10.5013/IJSSST.a.17.35.01

[27] Tarak K. Trivedi, Charles Liu, Anna Liza M. Antonio, Natasha Wheaton, Vanessa Kreger, Anna Yap, David Schriger, and Joann G. Elmore. 2019. Injuries Associated With Standing Electric Scooter Use. *JAMA Network Open* 2, 1 (Jan. 2019), e187381–e187381. https://doi.org/10.1001/jamanetworkopen.2018.7381

[28] Hung-Yu Tseng, Rong-Hao Liang, Liwei Chan, and Bing-Yu Chen. 2015. LEaD: Utilizing Light Movement as Peripheral Visual Guidance for Scooter Navigation. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Copenhagen, Denmark) *(MobileHCI '15)*. Association for Computing Machinery, New York, NY, USA, 323–326. https://doi.org/10.1145/2785830.2785831

[29] Sylvaine Tuncer and Barry Brown. 2020. *E-Scooters on the Ground: Lessons for Redesigning Urban Micro-Mobility*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376499

[30] Tamara von Sawitzky, Philipp Wintersberger, Andreas Löcken, Anna-Katharina Frison, and Andreas Riener. 2020. Augmentation Concepts with HUDs for Cyclists to Improve Road Safety in Shared Spaces. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3334480.3383022

[31] Veronica U. Weser, Joel Hesch, Johnny Lee, and Dennis R. Proffitt. 2016. User Sensitivity to Speed- and Height-Mismatch in VR. In *Proceedings of the ACM Symposium on Applied Perception* (Anaheim, California) *(SAP '16)*. Association for Computing Machinery, New York, NY, USA, 143. https://doi.org/10.1145/2931002.2947701

[32] Hiroyuki Yoshida, Atsushi Hoshina, Miyuki Nakano, and Midori Sugaya. 2015. Collision Detection for Bicycle and Pedestrian Exchange GPS Location in Smartphone. In *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers* (Osaka, Japan) *(UbiComp/ISWC'15 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 1583–1586. https://doi.org/10.1145/2800835.2801638

[33] Zhenpeng Zou, Hannah Younes, Sevgi Erdoğan, and Jiahui Wu. 2020. Exploratory Analysis of Real-Time E-Scooter Trip Data in Washington, D.C. *Transportation Research Record* 2674, 8 (2020), 285–299. https://doi.org/10.1177/0361198120919760