"Baby, You can Ride my Bike": Exploring Maneuver Indications of Self-Driving Bicycles using a Tandem Simulator

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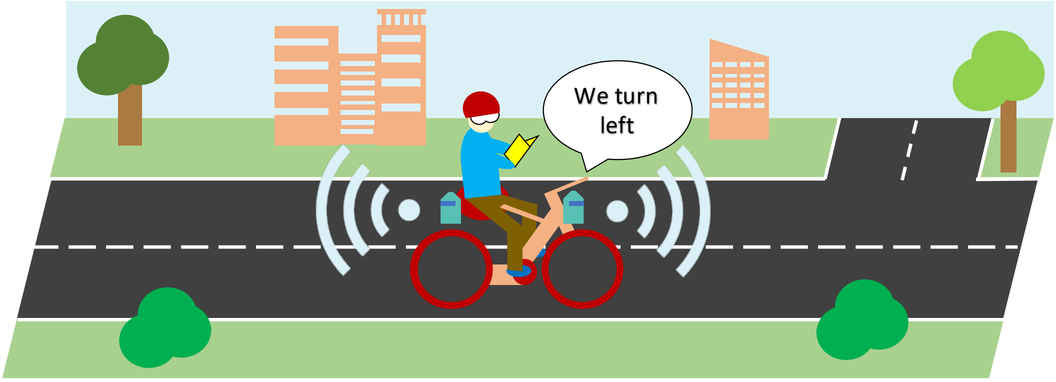

Fig. 1. Self-driving bicycles will enable secondary tasks during cycling. The figure illustrates a cyclist reading a book on a self-driving bicycle equipped with LIDARs to track the surrounding environment and notifications about upcoming maneuvers, e.g., using speech.

We envision a future where self-driving bicycles can take us to our destinations. This allows cyclists to use their time on the bike efficiently for work or relaxation without having to focus their attention on traffic. In the related field of self-driving cars, research has shown that communicating the planned route to passengers plays an important role in building trust in automation and situational awareness. For self-driving bicycles, this information transfer will be even more important, as riders will need to actively compensate for the movement of a self-driving bicycle to maintain balance. In this paper, we investigate maneuver indications for self-driving bicycles: (1) ambient light in a helmet, (2) head-up display indications, (3) speech feedback, (4) vibration on the handlebar, and (5) no assistance. To evaluate these indications, we conducted an outdoor experiment (N = 25) in a proposed tandem simulator consisting of a tandem bicycle with a steering and braking control on the back seat and a rider in full control of it. Our results indicate that riders respond faster to visual cues and focus comparably on the reading task while riding with and without maneuver indications.

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Additionally, we found that the tandem simulator is realistic, safe, and creates an awareness of a human cyclist controlling the tandem.

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

Additional Key Words and Phrases: self-driving bicycles, tandem, maneuver indications

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1 INTRODUCTION

Automation in urban environments is tangentially approaching the state of self-driving vehicles on the road in the near future. To prepare drivers for these upcoming changes in urban automation, researchers have started exploring this future vision using several concepts that communicate different types of information to users in self-driving cars, such as vehicle intentions [52], take-over requests [3, 4, 49], and warning cues [17, 22, 39]. Communication of this information from self-driving cars to the users plays an important role in increasing users' trust in automation [43, 50] and situation awareness [6, 10]. However, their responses to these cues do not have a decisive impact on the driving experience, because users become passive passengers rather than drivers. This situation is changing with the automation of micro-mobility, such as cycling, where riders must pay attention to the assisting cues and balance out the movement of a self-driving bicycle. Therefore, it is unclear how the intentions of self-driving bicycles need to be communicated to riders in order to provide a safe and trustworthy riding experience without additional mental load.

To communicate important information to the users inside self-driving cars, researchers have previously augmented the interior of cars with different types of cues. These included shape-changing interfaces on a steering wheel [3], vibrotactile feedback [4], light and auditory cues [1], speech messages [22, 39], and their combinations [38, 40, 49]. Recently, researchers have also introduced two concepts for visualizing vehicle intentions in a head-up display (HUD) using icon-based and AR visualizations [11]. These concepts have been shown to be effective in communicating vehicle intentions and informing drivers of impending hazards. Therefore, in our work, we build on the previous success in the automotive context of augmenting self-driving cars with additional cues. However, in the context of self-driving bicycles, we do not yet know how these cues can communicate maneuver indications from self-driving bicycles to a rider and how efficient they are. Therefore, we explore maneuver indications as one of the essential elements to prepare a cyclist to compensate for the movements of the bicycle when turning. This is a significant and crucial difference from the self-driving car, where situational awareness might be less important because the actions of the passenger in the car have no or less influence on the self-driving experience. Furthermore, despite a number of technical solutions for self-driving bicycles [47, 48, 55], we still do not know how to provide a safe and trustworthy cycling experience with cyclists on them.

In this paper, we investigate assisting cues for maneuver indications from fully self-driving bicycles to riders as a first step towards exploration of automation in the micro-mobility domain (Figure 1). For this, we designed and evaluated four types of maneuver indications: (1) ambient light integrated in the visor of a cycling helmet, (2) head-up display arrow indications, (3) speech feedback explicitly saying in which direction a bicycle is going, (4) vibration on the handlebar, and (5) no assistance as a baseline. To evaluate these maneuver indications under the conditions of a safe and realistic experience of a fully self-driving bicycle, we proposed a tandem simulator consisting of a tandem bicycle with a steering and braking control on the back seat and a rider fully controlling the bicycle. In this simulator, a person sitting in the front can experience the full experience of cycling without having control over steering, brakes and pedals. With this novel simulator approach, we advance the field of research on self-driving vehicles by creating realistic cycling conditions in terms of acceleration forces and environmental factors. To simulate a possible future scenario in which a self-driving bicycle is responsible for routing and steering, and a person on the bicycle can use the time to do things that are very dangerous in today's reality, we presented participants with a reading task that is mentally demanding and requires visual attention to the point of disengagement. In the controlled outdoor experiment (N=25) based on the proposed tandem simulator, we investigated how efficient the unimodal signals are to provide cyclists a clear understanding of a bicycle intentions, and how they influence trust and the feeling of safety. Additionally, we investigated how applicable the proposed tandem simulator is to replicate the experience on a self-driving bicycle and how successful the participants were in reading while cycling. Our results showed that visual indications of ambient light and HUD lead to the shortest reaction time and lowest rate of missed signals. Furthermore, HUD, ambient light, and speech ensure the highest level of safety and trust towards a self-driving bicycle. Moreover, with ambient light and speech maneuver indications participants answered almost 60% of questions correctly, which is comparable to the baseline. We also discovered that our proposed tandem simulator is suitable for conducting user studies with cyclists, given its high level of safety and realism.

In summary, our research contribution includes:

(1) An empirical evaluation of assisting cues for maneuver indications of self-driving bicycles using our proposed tandem simulator.
(2) A tandem simulator as a safe and realistic approach for conducting user studies with cyclists on self-driving bicycles in physical real-world environments.

2 RELATED WORK

Although there has not been much work on the interaction with self-driving bicycles, researchers have designed and investigated several concepts for communicating intents of self-driving cars. In this section, we first discuss the importance of communicating vehicle intentions and their influence on trust and situational awareness, followed by an overview of existing work in the area of self-driving vehicles and assistance systems for cyclists.

2.1 Conveying Vehicles' Intentions

Transparency in the communication of vehicle intentions, and thus better predictability of vehicle behavior, plays an important role in automation trust and situational awareness, which has been shown to be viable in the context of automation [36] and self-driving cars [13]. Moreover, the transparency of the system state and its communication with users implies cooperation between the driver and the vehicle in takeover requests [25] and trust [2]. Therefore, it is critical for a user to establish an appropriate level of trust and transparency toward an automated system. It has already been shown that participants who received more transparent information had higher trust in the autonomous robotic agent [5]. In the experiment with drivers conducted by Helldin et al. [15] it was shown that the participants with uncertain information trusted the automated system less than the participants without such information. This implies that information has to be presented precisely and clearly to create a trusted environment. To justify the level of trust, it is also necessary for the user to have a sufficient understanding of the state of the system to gain correct situational awareness [12]. Both the human user and the vehicle agent perform a situation awareness process to plan their next actions, such as braking or taking over a steering task. Thus, the communication of vehicle intentions is directed toward increasing each other's situational awareness, which improves the user's assessment of the vehicle's decisions and leads to successful vehicle-driver cooperation [51]. In our work, however, we focus explicitly on the communication of the bicycle's future actions and the concepts that these intentions convey to the cyclist. In this way, we aim to increase cyclists' confidence in the self-driving bicycle and their situational awareness.

2.2 Situation Awareness in (Self-driving) Cars

To increase situational awareness in self-driving cars and communicate to passengers what the vehicle is doing, researchers have previously looked at presenting take-over requests (TORs), warnings, and directions for movement. For example, to represent efficient take-over requests, Sadeghian et al. [3] employed shape-changing interfaces and vibrotactile feedback on a steering wheel to convey contextual information as a TOR and found that vibration cues were preferred in urgent takeover situations because of their higher alertness and urgency. Similarly, researchers used additional cues to warn drivers in vehicles [14, 18, 38, 40, 45]. For example, Ho et al. [16] have shown that participants initiate their braking responses to audiotactile warning cues significantly faster than to unimodal auditory or unimodal vibrotactile cues. Warning cues can also provide spatial guidance [17] using verbal messages [22, 39]. For example, Beattie et al. [1] investigated spatial auditory feedback to improve driver perception and found that spatial auditory warnings inform drivers of self-driving vehicles' intended actions much more efficiently than other methods. In addition, Koo et al. [22] found that messages providing only "how" information about upcoming actions (e.g., "the car is braking") led to poor driving performance, while "why" information describing the reasons for actions (e.g., "obstacle ahead") led to better driving performance and was most preferred by drivers. More recently, Detjen et al. [11] introduced icons (planar HUD) and augmented reality (contact analog HUD) to increase the transparency of vehicle intentions to the driver, and have shown that both visualizations increase user experience and confidence in an automated system. In terms of directions of movement, many in-car displays show what the car detects and transform the car's actions into more understandable intentions [7, 24]. For instance, Wintersberger et al. [53] investigated the applicability of augmented reality (AR) to indicate upcoming maneuvers in automated vehicles in foggy weather and demonstrated that AR can increase trust, technology adoption, and a positive driving experience when participants are informed of the vehicles' intentions. Löcken et al. [26] examined ambient lighting concepts to highlight an automated vehicle's future trajectory and potential conflicts with other road users. They found that displaying both facilitated clear information presentation to users. In another approach, an avatar was placed on the vehicle's dashboard to display the system's actions [56], with the rotation of its head indicating which direction the vehicle will travel next.

In summary, multimodal approaches and voice-based messages have been studied for self- and non-self-driving cars, but we do not know much about these approaches for self-driving bicycles. Therefore, in this paper, we build on the success of these approaches, such as ambient light, vibrotactile feedback, head-up display indicators, and speech.

2.3 Cyclists' Assistance Systems

With a focus on cyclists, previous works presented many systems that assist them while having a full control over a bicycle [31]. These systems primarily include warning signals, navigation cues, and traffic behavior recommendations. Given safety-related issues for cyclists, both commercial and research sides have contributed to the designs of warnings signals. For example, Garmin presented Varia Rearview radar [1] that warns the rider about vehicles approaching from behind via an on-screen visual notification mounted on the handlebar. Other commercial products explored cycling

[1]https://road.cc/content/review/246451-garmin-varia-rtl510

navigation, which utilized on-bicycle visual systems, such as Smarthalo [2] and Hammerhead [3]. TactiCycle was one of the first works to employ vibration motors in the handlebar for turn-by-turn navigation [37, 41], which was later on commercialized by SmartGrips [4]. To better indicate road obstacles and cyclists' visibility, existing commercial systems have also used projected interfaces to visualize potholes [5] or projected a bicycle sign in the front [6]. However, it has been shown that projected surfaces were limited to dark environments and were difficult to see during daytime [8, 28]. Alternatively, Everysight developed glasses with an integrated head-up display [7] to show all necessary information in front of a cyclist's eyes using OLED technology. Similarly, the newly introduced helmet SKULLY AR-1 [8] displays detailed information about speed, navigation, and nearby vehicles in the corner of the helmet's visor. Moreover, researchers used head-up displays for trajectory adjustment [28] and reminding about safety gestures [30] in experiments with children and have shown their efficiency. More recently, it has been shown that navigation cues represented as vibration, auditory cues, and ambient light integrated into helmets are also sufficient for child cyclists [29]. To warn about approaching out-of-view vehicles, Schopp et al. [44] augmented a helmet with a bone conductive speaker. They found that in this way they could increase cyclists' situational awareness and that cyclists were able to better identify dangerous situations. Jones et al. [21] augmented a cycling helmet with both input and output, which allowed tracking head tilts and thus estimate cyclists' intentions. As an output, the turn signal was shown on the back of a helmet to notify other traffic members about cyclists' intentions. Moreover, it was recently shown that an immediate action of braking is more efficient to perceive when it is represented as a combination of visual, vibrotactile, and auditory signals [27]. Researchers have recently investigated Augmented Reality (AR) for cyclists and e-Scooter riders for both input [23] and output [33, 34]. They have shown that AR is sufficient to augment cyclists' surroundings to increase situational awareness.

As can be seen from the previous work, researchers and industrial designers have previously developed several support systems for cyclists based on augmentation of existing cycling accessories, e.g., helmets, bicycles, and areas around cyclists, e.g., via projected surfaces. Given that the later approach is limited to dark environments, in this work, we look into augmentations of helmet and bicycles to represent maneuver indications of self-driving bicycles. With this, we aim to explore the applicability of existing methods not only for situations, when cyclists have a full control over cycling, but also when they have no control at all. In the context of self-driving bicycles, this is a key difference to self-driving cars, where situational awareness might be of less importance, since the actions of the passenger in the car have no influence on the self-driving experience, and a cyclist still has to balance out the bicycle's movement. In the following sections, we first describe a tandem simulator for self-driving bicycles, followed by the evaluation of maneuver indications using augmentations in helmet and bicycles.

3 TANDEM AS A SIMULATOR FOR SELF-DRIVING BICYCLES

To simulate a cycling experience on a self-driving bicycle, we created a simulation, which consisted of (1) a tandem bicycle and (2) a cycling person sitting in the back seat of it. The design of the tandem bicycle allows a person who sits in the back to control the steering, braking and pedaling

[2] https://www.smarthalo.bike/
[3] https://www.theregister.com/2015/07/12/review_hammerhead_satnav_for_cyclists/
[4] http://smrtgrips.com/
[5] https://newatlas.com/lumigrids-led-projector/27691/
[6] https://thexfire.com/products-page/lighting-system/bike-lane-safety-light
[7] https://everysight.com/
[8] https://wearabletech.io/skully-fenix-ar-helmet/

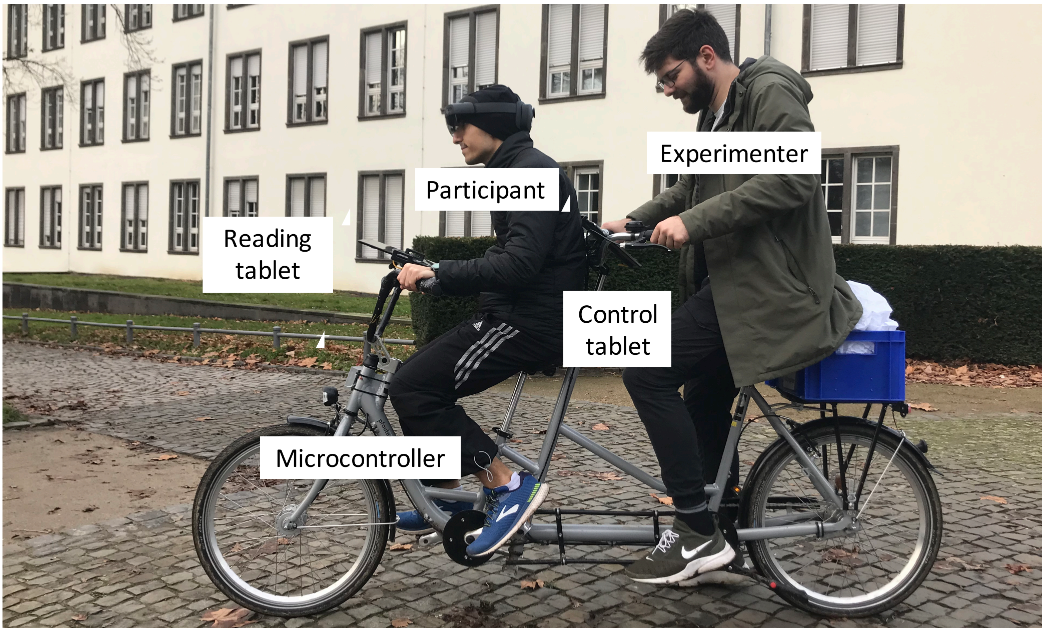

Fig. 2. Tandem simulator consists of a tandem bicycle and a person in control of steering, braking, and pedaling sitting in the back.

of the tandem. The person in the front, i.e., participant, has no control over steering or braking, and can optionally pedal, however, the option of braking and steering can be enabled on demand. This allows to explore different levels of cyclist's engagement into a cycling activity, e.g., by providing cyclists with an option to pedal, brake or steer. With this, the tandem simulator further facilitates different levels of automation, similar to ones introduced for cars [19]. Cyclists can partially or fully take over the steering, pedaling, and braking control in complicated situations, when a self-driving bicycle experiences difficulties on the road. To create a feeling of a self-driving bicycle, the person cycling in the back of the tandem ensures smooth and safe cycling by pedaling evenly and avoiding additional noise and conversation. With this low cost approach we aim to bring a close-to-reality cycling experience on self-driving bicycles prior to the technological advances, which would enable self-balancing, speed control, and automated braking on the bicycles.

Within the scope of this paper, we explored the cycling experience of a fully self-driving bicycle, in which participants did not have to pedal. With this we aimed to investigate the feasibility of the proposed tandem simulator for situations, where cyclists did not have to do anything related to the primary task of cycling. We aimed to explore the highest point within the range of automation, leaving the in-between stages for future investigations. In the following sections, we report on the evaluation based on the proposed tandem simulator for the situation of a fully autonomous cycling experience.

4 EVALUATION

To investigate unimodal signals for maneuver indications of self-driving bicycles, we conducted an outdoor experiment using the proposed tandem bicycle approach. Therefore, for this experiment we had the following research question: *Which feedback modalities are the most suitable to communicate maneuver indications of self-driving bicycles in terms of safety, trust, and perception?*

4.1 Participants

We recruited 25 participants (3 female, 22 male) aged between 19 and 46 years ($M = 27.6, SD = 5.32$) using social networks and personal contacts. Thirteen participants experienced automated vehicles before, such as buses, metro, trams, and airport trains. Nine of the participants cycle everyday, six – once a week, five – once a month, and five at least once a year. All of the participants had no hearing problems and had normal or corrected vision without color blindness. Participants did not receive any compensation for their participation.

4.2 Study design

The study was designed to be within-subject with one independent variable: *type of a maneuver indication*. We explored four types of maneuver indication: (1) ambient light, (2) head-up display, (3) vibrotactile feedback, (4) speech (Figure 3), and no maneuver indication as a baseline. We explored these types of indications motivated in part by their success in the automotive domain and cycling assistance systems, particularly in conveying navigation information [29, 32] and warning cues [27, 38]. Given that indication of moving direction is one of the essential elements of self-driving vehicles, we encoded two types of signals using the aforementioned maneuver indications: (1) turning left and (2) turning right. The ambient light signals consisted of three consequent vibrations (500 ms each), the head-up display showed an blinking arrow indicating a direction of movement, and the vibrotactile feedback included three consequent blinking signals (500 ms each). The speech-based method notified cyclists via the following messages: *"We turn right/left"*. Each message lasted about 1 second. About 10 meters before a turn participants received a signal, indicating which direction a bicycle is about to turn.

We conducted the experiment in the city park with occasionally passing cyclists and pedestrians without motorized vehicle for safety reasons. The park consists of a network of asphalt routes with multiple intersections. We designed five unique routes, where a bicycle turned five times left and five times right. About ten meters prior to a turn, participants received an indication of whether the bicycle turns left or right issued by an experimenter sitting in the back of a tandem bicycle using a tablet (control tablet). Participants' task was to press a button as fast as possible when they perceived signal and understood in which direction the bicycle is turning.

4.2.1 Secondary task. Except for reacting to maneuver indication signals, participants were asked to do a secondary task of reading an article shown on a second tablet (reading tablet) in front of them. The articles were taken from the "Twenty passages written at the one thousand word level" by Quinn et al. [42] and included the following articles: "Life in the Pacific Islands", "Jainism", "Fa Hien", "Willem Iskandar", and "The Inuit". The articles were fully displayed on the reading tablet as one page (ca. 500 words) without a need to scroll through. The grammar of these articles has been restricted by limiting the number of relative clauses, passives and difficult time references. In empirical test slow reading speed is up to five minutes. For each ride participants were assigned a different article and were asked ten questions, which they could answer using a multiple choice answering options or mark a question as "I don't know". With the secondary task, we aimed to distract participants from the primary task of cycling to investigate how effective the signals are to bring their attention back to cycling. The reading task is one of the possibly activities cyclists can do on self-driving bicycles, which require a high level of concentration and visual channel. With this we also wanted to demonstrate the feasibility of safely performing visually demanding secondary activities on a bicycle, compared to the reading on a bicycle with a full control causing a higher risk. The articles presented for the secondary task were randomly assigned to the cycling routes. The order of all five conditions and routes was counterbalanced using a Balanced Latin square.

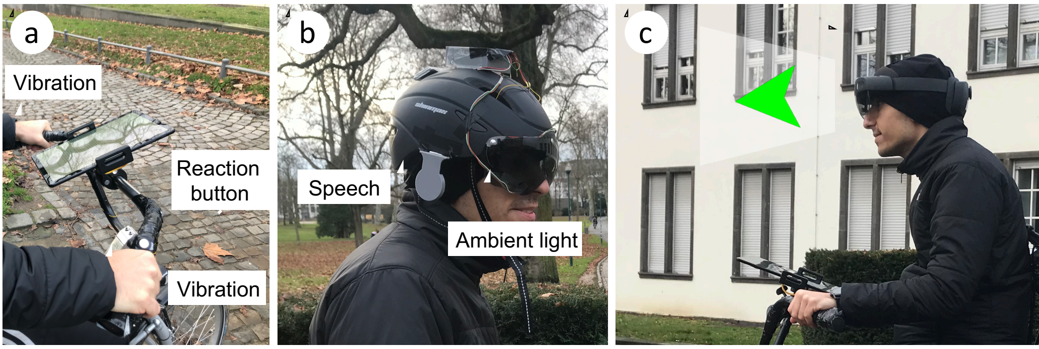

Fig. 3. Overview of maneuver indications investigated in the experiment: (a) vibration on the left and right sides of the handlebar (and a reaction button), (b) helmet with ambient light feedback integrated in the visor of a bicycle helmet and auditory feedback (as speech) on the right and left sides of the helmet, (c) a head-up display with arrows shown in Microsoft HoloLens 2.

4.3 Apparatus

To create a realistic and safe automated cycling experience, participants sat in the front seat of a two-wheeled Collettivo Tandem bicycle (24-inch, 226.82 x 101.6 x 51.82 cm, 26,5 kg) and were driven outdoors by a person sitting in the back (Figure 2). To convey the vibrotactile feedback on the handlebar of the bicycle, we augmented the grips of the handlebar with two vibration motors (1000 RPM M20 Mini Micro Vibration Motors with Eccentric Rotary Wheel) one on each side. To measure reaction time to the presented signals, we placed a button on the right side of the handlebar. The vibration motors and the reaction button were directly connected to the NodeMCU microcontroller, enclosed in a 3D-printed housing and placed on the bicycle frame under a handlebar. We augmented a bicycle helmet with NeoPixels stripes on the sides of the visor to present the signals in the periphery of participants' vision for the ambient light condition. Additionally, we integrated two speakers on both sides of the helmet to convey speech-based instructions about bicycle's intentions. Both speakers and NeoPixels stripes were directly connected to the NodeMCU, enclosed in a 3D-printed box placed on top of the helmet. To simulate the head-up display experience, we used a Microsoft HoloLens 2 Augmented Reality (AR) glasses. Both NodeMCU boards and the HoloLens AR glasses were connected to the control tablet placed in back of the tandem to activate maneuvering signals in a Wizard-of-Oz manner. For the secondary task of reading, we placed a second tablet on the handlebar in front of participants.

4.4 Measures

To compare the signals for maneuver indications of self-driving bicycle, we measured the following dependent variables:

- *Reaction time (in ms):* The time between the occurrence of a maneuvering signal and a button press. We started a timer when a signal was emitted and stopped after a button press. Participants were asked to press a button, when they perceived a signal and understood in which direction the bicycle is going.
- *Rate of missed signals:* For each maneuver indication, we calculated the rate of missed signals, i.e., situations when participants did not press a button to confirm a reaction.
- *Error rate on a secondary task:* For each maneuver indication signal, we calculated a rate for correct, wrong, and "I don't know answers" answers asked after reading a text.

	Reaction Time, s		**Missed Signals, %**		**Answers to the reading task, %**		
	M	SD	M	SD	Correct	Wrong	IDK
Ambient Light	0.93	0.40	0.4	0.2	55.2	14.8	30
HUD	1.09	0.68	0.4	0.2	38.6	19	42.4
Speech	1.40	0.79	1.6	0.37	56.2	17.6	26.2
Vibration	1.35	0.75	8	0.91	37.6	25.7	36.7
No assistance	–	–	–	–	59	18.1	22.9

Table 1. Summary of results: means and standard deviation for reaction time, percentage of missed signals, and percentage of correct, wrong, and "I don't know"answers to the reading task.

- *Understandability, safety, trust, distraction, and ease of perception:* for each condition, we asked participants to specify how understandable the signals were, their level of safety, trust, and distraction, as well as the ease of perceiving the signals using a 5-point Likert scale. The statements were the following: *"I could easily understand in which direction the bicycle is going."*, *"I felt safe cycling with this type of assistance."*, *"I could trust the self-driving bicycle with this type of assistance."*, *"I found this type of assistance distracting."*, and *"I perceived a signal regarding the bicycle's maneuver without any problem."*.
- *Safety, realism, awareness of a cyclist, and the overall experience of the tandem simulation:* at the end of the study, we asked participants to specify how safe and realistic the tandem simulation was perceived by them, whether they were aware of a cyclist sitting behind them, and whether it was a positive experience cycling without control over a bicycle using a 5-point Likert scale.

4.5 Procedure

For this study, we adhered to our universities health department's guidelines for user studies during the COVID-19 pandemic. All testing equipment was disinfected for each participant and the experiment was conducted outside in the fresh air. After obtaining informed consent, we collected participants' demographic data. Afterward, we provided a brief overview of the procedures, which included explanations of the signals and the tandem simulator. Participants familiarized themselves with the tandem bicycle and all four types of signals prior to a test ride. Once the participants felt comfortable, we started experimental conditions with cycling on the tandem in city park. During the experiment, participants had to read a text shown on a tablet in front of them and press a button every time they perceived a maneuver indication from a bicycle as a confirmation. After each ride, participants received a number of questions about the text they were reading during a ride. With this, we aimed to increase their concentration on the secondary task and distract them from the primary activity of cycling. At the end of the study, we interviewed the participants about their preferences for the different signals and the tandem simulator. The cycling part of the study took about half an hour and the entire study lasted approximately one hour. The study was conducted with approval from the ethical review board at our university.

5 RESULTS

We discovered that riders react faster to visual signals (ambient light and HUD) than vibration and speech. Moreover, participants had more difficulties perceiving vibration while cycling compared to all other signals, which also led to a higher number of missed signals. Additionally, we found that participants could comparably concentrate on the reading task while cycling, based on the number of correct, wrong, and "I don't know" responses. Finally, based on the Likert responses of

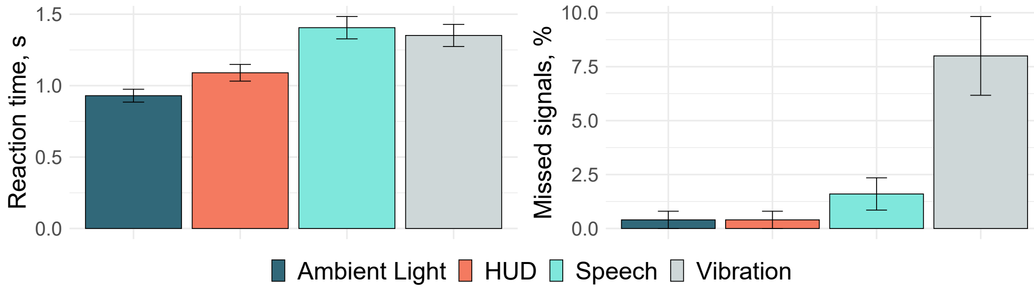

Fig. 4. Overview of the results: reaction time (left) and number of missed signals (right) per type of maneuver indication.

the participants, our results indicated that the tandem simulation is realistic, safe, and creates a high awareness of a human cyclist in control of the tandem. 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 Tables 1 and 2. We outline these findings in detail in the following.

5.1 Reaction time

We discovered that participants react the fastest to the visual maneuver indications encoded via ambient light ($M = 0.93sec, SD = 0.4$) and HUD (Head-up Display) ($M = 1.09sec, SD = 0.68$), followed by vibrotactile ($M = 1.35sec, SD = 0.75$) and speech ($M = 1.40sec, SD = 0.79$) indications. These differences were supported by a statistically significant Friedman test ($\chi^2(3) = 45, p < 0.001, \eta^2 = 0.6$). The pairwise comparisons have shown that it took participants a shorter time to react to ambient light indicators compared to vibrotactile ($p < 0.001$) and speech ($p < 0.001$). The same applies for the comparisons of the HUD to vibrotactile ($p < 0.05$) and speech ($p < 0.001$) indications. However, we did not observe statistically significant differences for the following two pairs: ambient light – HUD ($p > 0.05$) and vibration – speech ($p > 0.05$).

5.2 Number of missed signals

As for the number of missed signals, we found that participants missed most of the vibrotactile signals ($M = 8\%, SD = 0.91$), followed by speech ($M = 1.6\%, SD = 0.37$), HUD ($M = 0.4\%, SD = 0.2$), and ambient light ($M = 0.4\%, SD = 0.2$). Using the Friedman test we revealed that this difference was statistically significant ($\chi^2(4) = 24.58, p < 0.001, \eta^2 = 0.33$). With the pairwise analyzes we discovered that vibrotactile signals were missed more frequently than speech ($p < 0.001$), HUD (($p < 0.001$), and ambient light (($p < 0.001$). However, we did not observe statistically significant differences among the remaining pairs ($p > 0.05$).

5.3 Concentration level on the reading task

As for the number of correct answers to the reading task, we found that participants could give the highest number of correct answers while cycling with no assistance ($M = 59\%, SD = 23.43$), speech ($M = 56.2\%, SD = 27.5$) and ambient light ($M = 55.2\%, SD = 32.8$), followed by HUD ($M = 38.6\%, SD = 22.42$) and vibration ($M = 38.6\%, SD = 19.5$). Although we found that this difference was statistically significant ($\chi^2(4) = 17.54, p < 0.01, \eta^2 = 0.21$) using a Friedman test,

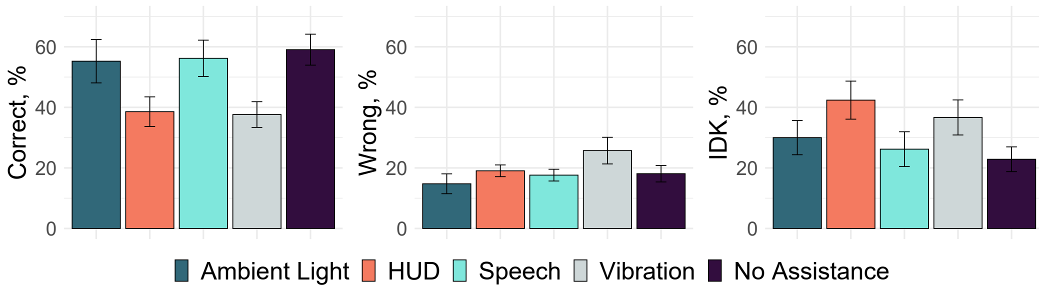

Fig. 5. Overview of the results about the reading task: percentage of correct (left), wrong (middle), and "I don't know" answers.

after the Bonferroni correction none of the pairwise comparisons were statistically significant ($p > 0.05$), except for no assistance and HUD ($p < 0.05$).

As for the wrong answers to the reading task, we discovered that participants had the highest percentage of wrong answers while cycling with a vibrotactile maneuver indication ($M = 25.7\%, SD = 20.1$), followed by HUD ($M = 19\%, SD = 8.9$), no assistance ($M = 18.1\%, SD = 12.5$), speech ($M = 17.6\%, SD = 8.9$), and ambient light ($M = 14.8\%, SD = 15$). However, using a Friedman test we found that these differences were not statistically significant ($\chi^2(4) = 4.46, p > 0.05, \eta^2 = 0.05$).

Finally, as for the "I don't know" answers, riders with the HUD ($M = 42.4\%, SD = 28.8$) maneuver indication had the highest percentage of not knowing the answer to questions, followed by vibration ($M = 36.7\%, SD = 25.5$), ambient light ($M = 30\%, SD = 25.9$), speech ($M = 26.2\%, SD = 26.36$), and no assistance ($M = 22.9\%, SD = 18.75$). Similarly to the percentage of the correct answers, we discovered that these differences were statistically significant using a Friedman test ($\chi^2(4) = 15.75, p < 0.01, \eta^2 = 0.19$). However, based on the pairwise comparisons only the pair of no assistance and HUD was shown to be significantly different ($p < 0.01$) and all the remaining pairs were not ($p > 0.05$).

5.4 Understandability, safety, trust, distraction, and ease of perception

5.4.1 Understandability. Maneuver indications via speech ($Md = 5, IQR = 1$), ambient light ($Md = 5, IQR = 0$), and HUD ($Md = 5, IQR = 1$) were the most understandable to the riders compared to vibration ($Md = 3, IQR = 1$) and no assistance at all ($Md = 2, IQR = 2$). These differences were shown to be statistically significant using a Friedman test ($\chi^2(4) = 43.37, p < 0.001, \eta^2 = 0.52$). The post-hoc analyzes have revealed that it was less understandable for riders where a bicycle is turning with no indication at all than with ambient light ($p < 0.001$), HUD ($p < 0.001$), and speech ($p < 0.001$), but it was comparable for the vibration and no indication ($p > 0.05$). Moreover, vibration was shown to be less understandable than ambient light ($p < 0.01$) and speech ($p < 0.05$). However, the remaining pairs were not statistically significant ($p > 0.05$).

5.4.2 Safety. As for the feeling of safety, we found that participants felt the safest with maneuver indications – vibration ($Md = 4, IQR = 1$), speech ($Md = 4, IQR = 1$), ambient light ($Md = 4, IQR = 2$), and HUD ($Md = 4, IQR = 1$) – than no indication ($Md = 3, IQR = 1$) at all. However, we did not observe statistical differences for the feeling of safety using a Friedman test ($\chi^2(4) = 7.16, p > 0.05, \eta^2 = 0.09$).

5.4.3 Trust. Similar to the feeling of safety, participants could comparably trust to all four maneuver indications – vibration ($Md = 4, IQR = 0$), speech ($Md = 4, IQR = 1$), ambient light ($Md =$

	Understand.		Safety		Trust		Distraction		Perception	
	Md	IQR	Md	IQR	Md	IQR	Md	IQR	Md	IQR
Ambient Light	5	0	4	2	4	1	3	2	5	1
HUD	5	1	4	1	4	0	3	2	5	1
Speech	5	1	4	1	4	1	2	2	5	1
Vibration	3	1	4	1	4	0	2	2	3	1
No assistance	2	2	3	1	3	2	1	1	–	–

Table 2. Summary of Likert results: Medians and interquartile ranges for the level of understandability, safety, trust, distraction, and perception using a 5-point Likert scale (1 – difficult to understand, unsafe, non-trustworthy, distracting, difficult to perceive, 5 – easy to understand, safe, trustworthy, non-distracting, easy to perceive).

$4, IQR = 1$), and HUD ($Md = 4, IQR = 0$) – more than with no assistance ($Md = 3, IQR = 2$) at all. We observed a statistically significant difference for the feeling of trust using a Friedman test ($\chi^2(4) = 13.99, p < 0.01, \eta^2 = 0.17$). The post-hoc analysis revealed that riding a bicycle with no indication is less trustworthy than with ambient light ($p < 0.05$) or speech ($p < 0.05$). However, the remaining pairs were not statistically significant ($p > 0.05$).

5.4.4 Distraction. As for the distraction, we found that visual signals were perceived as more distracting – ambient light ($Md = 3, IQR = 2$) and HUD ($Md = 3, IQR = 2$) – than vibration ($Md = 2, IQR = 2$), speech ($Md = 2, IQR = 2$), and no assistance ($Md = 1, IQR = 1$). Using a Friedman test we discovered that these differences were statistically significant ($\chi^2(4) = 17.95, p < 0.01, \eta^2 = 0.21$). The post-hoc analysis have indicated that cycling with no maneuver indication is statistically less distracting than with ambient light ($p < 0.01$). However, the remaining pairs were not statistically significant ($p > 0.05$).

5.4.5 Ease of perception. As for the ease of perception of the maneuver indications, we found that speech ($Md = 5, IQR = 1$), ambient light ($Md = 5, IQR = 1$), and HUD ($Md = 5, IQR = 1$) were the ones easier to perceive than vibration ($Md = 3, IQR = 1$). We discovered that this difference was statistically significant using a Friedman test ($\chi^2(3) = 28.97, p < 0.001, \eta^2 = 0.46$). The post-hoc analysis indicated that vibration was the most difficult to perceive compared to ambient light ($p < 0.001$), HUD ($p < 0.001$), and speech ($p < 0.001$). However, the remaining pairs were not statistically significant ($p > 0.05$).

5.5 Tandem Simulation

We estimated the applicability of the tandem simulation to mimic self-driving bicycles in terms of safety, realism, awareness of a person behind, and the overall experience of the tandem simulation. Based on the participants' responses using a 5-point Likert scale, we discovered that participants found the simulation rather realistic ($Md = 4, IQR = 1$) and safe ($Md = 5, IQR = 1$). However, they remained rather aware of a human behind them being in control of the bicycle ($Md = 2, IQR = 2$) and were neutral regarding the point of whether the overall cycling experience without control over a bicycle was positive ($Md = 3, IQR = 1$).

5.6 Qualitative Feedback

5.6.1 Problems and preferences. After the study, participants' preferences regarding the most suitable maneuver indication were diverse, starting from the highest rank for the HUD (N = 8), speech (N = 7), and ambient light (N = 5), and ending with no assistance at all (N = 3), and vibration (N = 2). Only four (out of 25) participants mentioned that they did not need any signals at all, because

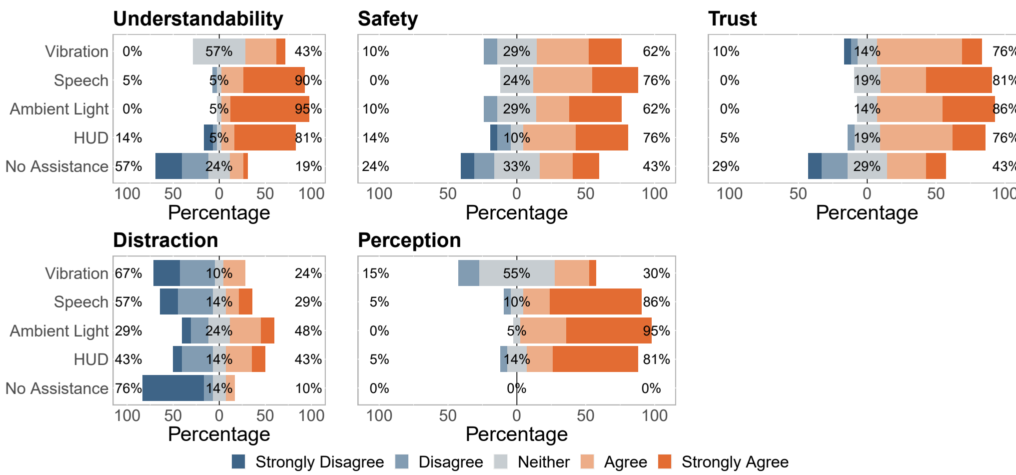

Fig. 6. Overview of the Likert scale results regarding the understandability of the maneuver indication, safety, trust, distraction, and ease of perception.

they were experienced cyclists. The main arguments for having signals were safety, awareness, and predictability of movement. As some participants commented: *"The ride felt more secure and predictable. During turns one could shift his focus away from the activity to follow where the bike is going."* (P23) and *"Feel more secure and know where I am going"* (P6). While participants preferred having signals to indicate maneuvers of the self-driving bicycle, they had different reasons for their preferences in terms of understandability and distraction. We outline the advantages and disadvantages for each type of maneuver indication in the following.

The main reasons for preferring the *HUD* indications were due to the fact that it was *"easy to understand"* (P7), *"non-distracting"* (P9), and "fun" (P18). As some of the participants noted, *"The arrows (HUD) were easiest for me to understand. "* (P25) or *"Prefer visual assistance over audio. Have a head up display in the car."* (P5). As for the disadvantages, participants mentioned that *"arrows look too similar"* (P2) and can be *"distracting"* (P11).

Regarding the *speech* assistance, participants mentioned that it was not distracting and easy to remember. For instance, as some of the participants mentioned: *"Speech was the least distracting, did not require hands and did not impair line of sight"* (P15), *"It was easier to remember which way the bicycle was turning with the help of speech and it wasn't that distracting while reading"* (P8), and *"I found that any kind of assistance was better than no assistance. If i looked up during the ride when there was no assistance, I felt a little unsafe knowing that i have no control over turns and avoidance of obstacles."* (P10). On the other side, sometimes *"the speech was to distracting and loud"* (P9).

The main advantage of the *ambient light* was its subtle (peripheral) nature, it required no attention from the participants, it was less distracting and easy to perceive. As our participants mentioned: *"Ambient light requires no attention at all."* (P2), *"Ambient light is subtle and clear at the same time"* (P12), *"Ambient light and HUD are the least distracting and most perceivable"* (P23). Only one participant mentioned that ambient was *"distracting"* (P20).

Some of the participants enjoyed cycling with *no additional signals*. The cyclists felt bicycle's intentions from its movement and were indifferent to signals, since no action was required from them. For instance, they noted that *"I felt safe without any information about turns, since the is no action needed from me anyway."* (P11) and *"No need for directional assistance"* (P1).

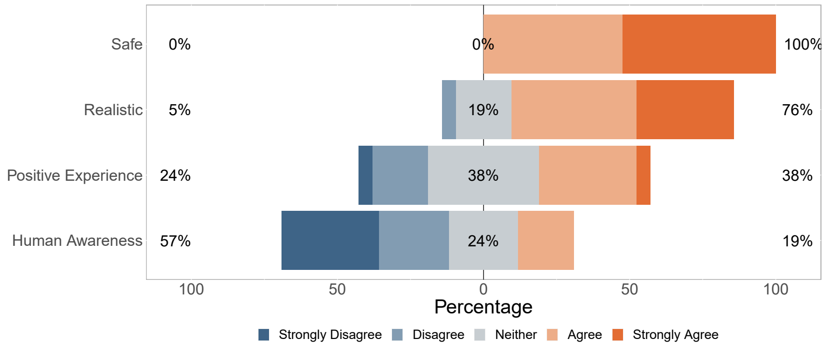

Fig. 7. Overview of the Likert scale results regarding the safety, realism, awareness of a cyclist, and the overall experience of the tandem simulation.

Finally, participants who preferred *vibrotactile* feedback mentioned that they enjoyed it due to its non-distracting nature and preferred feeling signals rather than hearing or seeing them. For instance, they mentioned that vibrotactile signals were *"Understandable and non-distracting"* (P17) and *"It is just about feelings"* (P22). Confirming the quantitative results, participants also mentioned that *"vibrotactile signals are sometimes not very perceivable."* (P22).

5.6.2 Usage of self-driving bicycles. As for the self-driving bicycle usage, participants opinions were split in the half. While the first half of the participants (N = 12) mentioned that they would like to use it, because *"you can do other stuff meanwhile"* (P2), *"can drive home drunk"* (P5), *"you don't have to worry about driving and can concentrate on your work"* (P7), and *"they could potentially be quite helpful for disabled people"* (P8), the other half noted that *"A bike feels like an extension of the body in terms of control. Letting someone else control the steering and speed feels more intrusive than in a car."* (P4), *"I see riding a bike as an exercise"* (P6), and *"I use my bike for short to medium distances only and I find it hard to concentrate on any other activities during the ride. I would consider self driving vehicles only when it decreases risk of accidents significantly"* (P23). However, all participants could easily imagine several secondary activities while riding a self-driving bicycle, such as texting, watching videos, browsing, listening to audio content, reading, or even working. Finally, we asked participants what they lacked in the self-driving bicycle and they mentioned that an indication of braking, intercept before a collision, and the possibility to take over the control would enrich their experience of self-driving on a bicycle.

5.6.3 Reading experience. Based on the feedback from the post-study questionnaire, we collected diverse opinions about experiencing reading as a secondary task while cycling. Four participants explicitly mentioned that they would enjoy reading a book while riding on a self-driving bicycle. For example, P17 noted *"[I can imagine] reading while holding a book in my hand"* and P16 commented that *"I could imagine reading or even working"*. However, the negative experiences were related to annoying vibrations caused by a road surface. Therefore, participants mentioned that they would rather watch videos, text friends, or listen to audio. For instance, P4 noted that *"[I would prefer] listening to audio or watching the news. Unless the medium and I are stabilized, reading is too annoying."* and added in the general comments that *"An alternative to reading would have been nice. Like a video or a small (puzzle) game"*. Thus, despite difficulties experienced while reading on a bicycle, most participants (23 out of 25) were generally positive about secondary tasks on self-driving bicycles and could imagine many alternatives.

6 DISCUSSION AND FUTURE WORK

In general, cyclists preferred having maneuver indication signals on self-driving bicycles. They facilitated a feeling of safety, situation awareness, and predictability of bicycle's movements. However, we discovered differences regarding the presentation of the maneuver indications, levels of concentration on the reading task, and perception of self-driving bicycles via a Tandem Simulator, which we discuss in the following.

6.1 Maneuver indications – What should they be?

As for the question of how maneuver indications should be represented, we discovered differences among the evaluated unimodal signals. We found that despite the visual nature of reading as a secondary task, visual signals were found the most effective, i.e., ambient light integrated in the visor of a cycling helmet and head-up display indications. Not only did cyclists prefer these encodings, but they also performed better in terms of reaction time. The more obtrusive nature of visual signals most likely led to a higher level of distraction and therefore was more effective in guiding cyclists' attention. However, we could not measure this higher distraction in the reading task. This highlights the dominance of vision in perception, which is indeed special both psychologically and epistemically, and was found more dominant than other senses, such as audition and touch [46]. However, riders had more difficulties perceiving vibration than other signals, which also led to a higher number of missed signals. This can be explained by a low level of perception of vibrotactile signals outdoors due to the vibration of the bicycle while riding, despite the flat surface of paved tracks. Although speech-based notifications led to the longest reaction time, it had a comparable number of missed signals and had a similar level of safety and trust compared to ambient light and the head-up display. This can be explained by the fact that participants wanted to listen to the audio message until the end (duration of the message was 1 second + reaction time) before pressing a button and by implicit movement cues of a bicycle, e.g., slowing down or changing a trajectory. Therefore, in the future designers might consider shortening the message or combine it with other modalities and account for implicit cues of cycling. Moreover, since we used speech as a rather sophisticated version of audio cues, in future designs it might be a beeping signal coming from left or right.

Given the scope of this paper, we focused on the exploration of only unimodal maneuver indications, and it is necessary to explore a multimodal approach in future work for multiple reasons. Firstly, the secondary reading task was purely visual and did not account for tasks of multimodal nature, e.g., visual and auditory channels while watching a video. Secondly, the cycling activity requires multiple information channels to stay aware of the surroundings. Therefore, to decrease the chance of missing maneuvering indications, it would be necessary to avoid potential perceptual conflicts caused by, for example, background noise, a vibration of a road surface, or very bright days.

Interestingly, participants had a comparable level of correct, wrong, and "I don't know" answers to the secondary task of reading, based on the statistical analyses. However, we observed that ambient light and speech notifications led to a comparable number of correct answers with no assistance at all (almost 60%). This indicates that distraction based by both ambient light and speech does not affect the quality of reading. Therefore the question for the future research is whether extending signal notifications to a multimodal approach would enrich the cycling experience on self-driving bicycles, and more importantly would make it safer.

6.2 Is a Tandem Simulator a good way to simulate self-driving bicycles?

Based on participants' Likert responses, our results showed that the tandem simulator felt realistic, safe, and created a high awareness of a human cyclist steering the tandem. The main reason for the high perception of safety may be due to the fact that participants knew that the bicycle was controlled by a human rider who was proficient in cycling. Moreover, participants were still aware that a human cyclist was steering the tandem, even though they were focused on the secondary task of reading. We also assume that the human driver automatically provides cyclists with a sense of safety and most likely implicitly conveys cues to turn, such as slowing down and changing lanes. In the future, we should have a closer look at these implicit cues to convey the direction changes to riders without actively telling them. Thus, riding an AI-controlled bicycle could reduce participants' confidence and sense of safety, primarily due to the novelty effect and lack of predictability compared to a human driver. However, trust in a system can be built quickly, especially if the cyclist has the opportunity to take control of the cycling experience. Therefore, future research must also address methods for communicating take-over requests for self-driving bicycles and different levels of automation, similar to self-driving cars. Most importantly, participants found the tandem simulator to be a realistic approach to cycling without control of the bike, i.e., self-driving cycling. This will allow this simulation to be used in future work without the need for fully functional systems such as automatic brakes and built-in sensors to balance and steer bicycles. Furthermore, similarly to the stationary bicycle simulators [35, 54], motion sickness should be addressed in future research about self-driving bicycles, especially in the presence of a secondary task.

6.3 Where do we go with self-driving bicycles?

Although experienced cyclists of our experiment mentioned that they would not like to have self-driving bicycles and maneuver indications, because they do not want to lose the cycling experience and are experienced enough to need additional indications, we envision self-driving bicycles in areas of service and private use. For example, self-driving bicycles can promote micro-mobility for people, who commute by cars, given that self-driving bicycles facilitate safe working activities on-the-go, e.g., reading, writing. As we have shown in our experiment, cyclists of self-driving bicycles can focus on visually demanding tasks, e.g., reading, which is very dangerous in current cycling situations. This, in turn, would enable multitasking while cycling, especially on long distance rides.

Although the results of our study showed that participants were successful in reading and processing information while cycling, there is a need to investigate active input by a rider, such as writing or typing, in future studies. In the fully automated mode, riders can spend more time enjoying the surroundings on recreational tours, take videos or pictures without fearing to fall off, or simply take a break without stopping. It will also allow cyclists to switch pedaling and steering off and stretch without stopping. However, from the safety perspective, it also implies that there might be situations when cyclists can unintentionally drop their tablet or book caused by additional distractions during texting [9, 20], which can put them or other road users into danger. Therefore, the future designers of self-driving bicycles should account for these safety measures by, for example, creating integrated dashboards or smartphone holders. Moreover, self-driving bicycles can facilitate inclusion of people with physical disabilities, who cannot cycle, but would like to experience cycling, and be extended to tricycles if needed. Delivery services, such as post couriers or food delivery, can rely on self-driving bicycles for navigation and quicker routes, which would save time and avoid traffic jams compared to cars. This will facilitate concentration on the delivery details and can potentially reduce delivery mistakes. Finally, cycling on self-driving bicycles in rainy weather would allow the riders to hold an umbrella.

7 LIMITATIONS

When evaluating the cycling experience on self-driving bicycles, we encountered several limitations. First, our bike was not automated by technology, such as self-balancing or collision tracking, but by a proposed tandem simulator with a human rider on it. Moreover, experience and cycling style of an experimenter might have an influence on the cycling experience, which is unavoidable, but still can be reduced by acquiring an experienced cyclist for an experiment. The secondary reading task in our experiment was only limited to the visual channel and did not account for other modalities. Therefore, including a secondary task that facilitates multi-modality and additionally requires auditory demands, such as having a phone call or watching a movie, would potentially increase the ecological validity of the experimental setup, which needs to be explored in the future. However, with the reading task, we aimed to explore the cycling experience that is utterly hazardous on a non-self-driving bicycle compared to a phone call, which is still possible on a bicycle with full control. Furthermore, our results showed that participants perceived the tandem simulator as realistic and safe, which could be explained by the fact that they perceived a human behind the wheel of the vehicle. Our test environment was a city park with pedestrians and other cyclists on paved paths, which excluded environments with car traffic flows. But with this experiment, we wanted to create a safe environment for cyclists. Since the experiment spanned several days, we were faced with different weather and lighting conditions that could have an impact on the perception of the visual signals.

8 CONCLUSION

In this paper, we investigated unimodal signals for maneuver indication of self-driving bicycles and proposed a tandem simulator to facilitate a safe and realistic cycling experience without control of a cyclist. From the conducted evaluation, we discovered that riders react faster to visual signals, i.e., ambient light integrated in the visor of a cycling helmet and head-up display indications, than vibration and speech. Riders had more difficulties perceiving vibration than other signals, which led to a higher number of missed signals. Moreover, based on the number of correct, wrong, and "I don't know" responses to the secondary reading task, we found that participants could comparably concentrate on the reading task while cycling with and without maneuver indicating signals. Based on the Likert responses of the participants, our results have shown that the tandem simulation is realistic and safe, and creates a high awareness of a human cyclist in control of the tandem. Finally, our experiment has demonstrated that self-driving bicycles may have a future but have to be researched further and thoroughly.

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