Comparing Unimodal Lane Keeping Cues for Child Cyclists

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ABSTRACT

Child cyclists are at greater risk for car-to-cyclist accidents than adults. This is in part due to developmental differences in the motor and perceptual-motor abilities of children and adults, and missing cycling infrastructure. To address these issues, we examine unimodal and projection-based techniques to support children in maintaining a good lane position in the absence of bicycle lanes. We present safety-relevant information using unimodal cues: vibration on the handlebar, ambient light in a cycle helmet, projected heads-up display indicators, and on-road laser projection. As a first step, we interviewed twelve children about their cycling issues. We then conducted a lab experiment (N=25) in a bicycle simulator using the unimodal cues in the presence of a visual search task, followed by a controlled test-track experiment (N=15). We found that cycling performance with lane keeping cues was comparable to situations without them, however children found them helpful and expressed subjective preferences for the LED helmet and vibration on the handlebar.

CCS CONCEPTS

• **Information interfaces and presentation (e.g., HCI) → Miscellaneous**.

KEYWORDS

child cyclists, unimodal feedback, lane keeping, cycling safety

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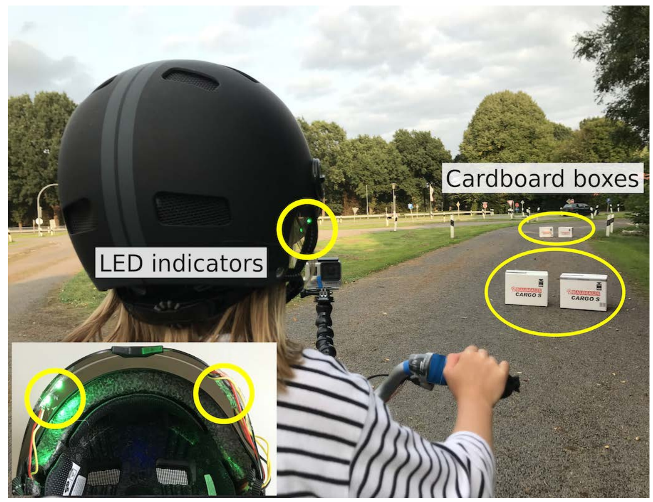

Figure 1: The LED helmet and road obstacles used in the controlled test-track experiment.

1 INTRODUCTION

The number of cyclists in some western countries has increased considerably over recent years [32]. For example, cyclists comprise 26% of the population in the Netherlands, 18% in Denmark and 10% in Germany [31]. However, cyclists in North America are eight to 30 times more likely to be seriously injured than cyclists in the countries of northern Europe [30, 33]. A lack of cycling infrastructure that separates motor vehicles from cyclists is one of the reasons for a higher accident rate in Canada and US compared to the cycling-friendly countries, like the Netherlands, Denmark or Germany.

A closer look at the statistical reports shows that cyclists aged between six and thirteen remain the most vulnerable age group [6, 11]. One of the reasons for the high accident rate among this age group lies in the motor and perceptual-motor developmental differences compared to adults, which affect children's performance of cycling activities. Motor, cognitive, and sensory information processing skills change from childhood to adolescence and influence children's capabilities for navigating complex traffic situations [4, 20].

Recent enhancements to bicycles, such as 360° laser scanners (LIDARs)[1] and ultrasonic sensors[2], allow recognition of traffic and objects around cyclists [3]. This information is necessary for keeping safe distances to the obstacles within a virtual bicycle lane, especially in cities with missing cycling infrastructure [13]. These virtual bicycle lanes (i.e., not visible in the environment) can serve as intermediary solutions while real infrastructure develops. In our work, we focus on how children can be supported to ride safely within these virtual lanes through projected surface assistance and unimodal feedback cues. Our goal is not in the development of these virtual lanes using LIDAR or other sensors, but rather in the technology needed for children to stay within these dynamic virtual lanes.

Our goal is to ultimately increase the mobility of children by providing safety assistance systems on their bicycles and helmets. Multiple Resource theory suggests that usage of multiple modalities can potentially increase cyclists' attention without mental overload [36]. We used this theory as a basis for creating unimodal feedback to present safety-relevant information for child cyclists to support lane keeping. Ultimately, we foresee using lane keeping system with accompanying ultrasound sensors on the side of the bicycle. This way we can correct the trajectories on-the-go in the absence of cycling infrastructure. We acknowledge that there are other solutions, such as making traffic members more aware of cyclists or extra bicycle training courses for children. However, we focus on tractable technological solutions to the problem given our present socio-economic culture. Unimodal cues for lane keeping is one possible approach in this broad research space motivated in part by its prior success in increasing driver awareness and conveying information unobtrusively in the automotive domain [21], motorcycling [35], skiing [25], and cycling with adults [27, 29]. Another possible solution is to use the environment around cyclists as a display for lane keeping assistance. In this case, contextual information can be presented at relevant locations, similarly to the projected surfaces used with adult cyclists for navigation [9].

To better understand children's issues while cycling, we first conducted an interview with twelve children, where they explored how they would react to different cycling situations using Legos. We then conducted a lab and controlled test-track experiment to explore how vibration on the handlebar and ambient light in the helmet can assist child cyclists in maintaining a good lane position compared to projected surfaces, such as projected heads-up display (HUD) indicators and on-road laser projection. For the lab experiment, we developed an indoor bicycle simulator and investigated the efficiency of lane keeping cues in the presence of a visual search task. In the subsequent controlled test-track experiment, we examined the generalizability of our findings in conditions closer to the real world in an outdoor test track using a mid-size tricycle. Our main contribution is an empirical evaluation of unimodal lane keeping cues for child cyclists in both lab and test-track evaluations. Furthermore, we provide potential solutions for lane keeping, which can be easily and cheaply integrated into safety equipment (e.g., helmets) and bicycles (e.g., vibration in grips and projected laser guidance in the frame).

[1]https://www.borealbikes.de/wp-content/uploads/2018/09/Holoscene_JDE_Brochure.pdf
[2]https://interaktiv.tagesspiegel.de/radmesser/

2 RELATED WORK

A variety of technological interventions have been developed for supporting cyclists, however, the evaluations of these systems have been conducted with adults. These systems have typically been used to assist cyclists with navigation, warning signals, traffic behavior, and lane keeping, which has been previously done in the automotive domain. In the following subsections, we discuss previous work through the prism of these four areas and highlight challenges in designing safety systems for children.

Navigation cues. Navigation cues have been previously integrated on the handlebar, in a helmet, or projected in front of a cyclist. One of the earlier works in on-bicycle systems was Tacti-Cycle [27, 29] which integrated vibration motors in the handlebar for turn-by-turn navigation. SmartGrips [3] further commercialized this idea and released two vibrotactile grips for the consumer market. Another on-handlebar LED-based navigation product, called Smarthalo [4], indicates distance and direction via different light patterns. Hammerhead [5] is a bike accessory that also can be fixed to the handlebar and indicates turn-by-turn navigation cues through directional LEDs. Both navigation devices, however, require pairing with a smartphone to receive routing information.

Tseng et al. [35] utilized peripheral light cues located inside the helmet, particularly above the eyes, to navigate riders without introducing additional distraction. Matviienko et al. [24] further explored this idea and showed through the lab and test-track evaluations that navigation cues presented with ambient light integrated into a helmet were applicable for children. We continue this line of work and investigate the use of ambient light (integrated in the helmet) for keeping a good lane position. Another inspiring approach is the use of projection to indicate navigation cues and improve visibility. Dancu et al. [9] augmented a bicycle with a map projection in front of the bicycle to show navigational cues.

Warnings signals. A range of research and commercial systems have explored the use of visual feedback integrated into the bicycle and a helmet to warn cyclists about upcoming danger. For example, Garmin Varia Rearview radar [6] warns the rider about vehicles approaching from behind using an on-screen visual notification mounted on the handlebar. Other warning systems for cyclists [16] and motorcyclists [14] employed a buzzer, beeper, or lighted bulb to warn about approaching vehicles and possible collisions. Massey [22] has introduced technology for tracking location and motion of multiple vehicles, which warns drivers about possible collisions at the same time.

Schopp et al. [34] integrated a bone conductive speaker into a helmet to warn cyclists about approaching, out-of-view vehicles. The cyclists showed increased situational awareness and were better able to identify dangerous situations. Jones et al. [18] augmented a cyclist's helmet with both input and output methods. They tracked head tilts and utilized them to indicate turn signals on the back of a helmet. Similarly, a commercial product, Blink Helmet, utilized manual buttons on the sides of the helmet to indicate stop and turn signals. More recently, Matviienko et al. [23] investigated multimodal feedback to represent warning signals for child cyclists.

[3]http://smrtgrips.com/
[4]https://www.smarthalo.bike
[5]https://www.dragoninnovation.com/customer-projects/hammerhead
[6]https://buy.garmin.com/en-GB/GB/p/518151

They showed that a combination of vibration, light, and sound on both handlebar and helmet can efficiently warn cyclists about upcoming hazards.

Traffic behavior recommendations. Different commercial systems have presented recommendations for safe behavior on the road using helmet and projected interfaces. Newly introduced helmets with augmented reality look promising for representing information in a subtle and non-distracting way. For example, the SKULLY AR-1 [7] shows detailed information about speed, navigation, and nearby vehicles in the corner of a helmet's visor. Another example is the Livemap helmet [8], which augments the environment with routing information, speed and safety features. However, it is unclear whether augmented reality helmets can enhance safe cycling and lane keeping for children. Additionally, we were inspired by VRscout project [9] that explores DIY solutions for building AR glasses, and decided to extend the functionality of a helmet with a similar HUD display in our evaluations.

Commercial systems have also focused on the detection of obstacles on the road, such as potholes [10], and project a bicycle sign in the front to indicate visibility [11]. Flashy Blinky Lights introduced a projected bicycle lane on the sides of the bike to increase the visibility of cyclists in the dark and assist car drivers in keeping a safe distance [12]. However, it is unclear how effective these systems are, due to the lack of empirical evidence. For instance, previously, researchers discovered that projected surfaces were harder to use and perceived as less safer than heads-up displays [9]. However, from the perspective of child cyclists it is valuable to have a system which can be usable in both day and nighttime. Therefore, in our evaluations we investigated both HUD display and a laser-based projection to support child cyclists with keeping a good lane position.

Lane keeping cues. Lane keeping assistance has been previously explored in the automotive domain. For example, Pohl and Ekmark [28] explored a torque feeling in the steering wheel, which mediated the correct lane position. They suggest that multimodal assistance, specifically a combination of haptic feedback and HUD display might work better to increase driver awareness. However, Kidd et al. [19] showed that driver trust for active lane keeping was the lowest among driver assistance technologies. Research has yet to explore how to support child cyclists in safe lane keeping, especially where cycling infrastructure is missing, and therefore we focus on this aspect in our work.

3 INTERVIEW

Before starting the design and evaluation of lane keeping cues, we wanted to better understand any safety-related issues child cyclists faced and their behavioral patterns when encountering particular traffic situations, following a user-centered design approach [7]. As can be seen from the related work, we lack empirical evaluation of lane keeping mechanisms for child cyclists. Therefore, we needed a deeper understanding of children's perceptions of road hazards and the way they deal with dangerous situations on the road.

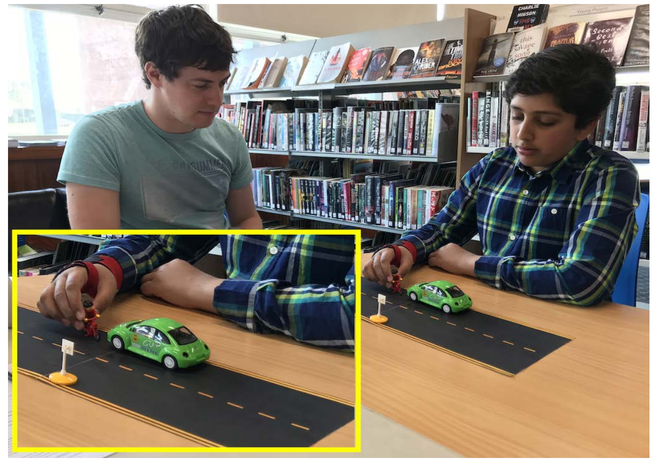

Figure 2: One of the participants is showing his cycling actions using Lego figures during the interview.

3.1 Participants

We recruited twelve children (7 female, 5 male) aged between seven and twelve (M = 9.3, SD = 1.8) years. They had between two to eight years of cycling experience (M = 4.3, SD = 2) and the majority cycled two-four times per month. Eight children attended a bicycle training course as a part of their school education, where they learnt how to use hand signals for navigation, safety accessories, such as helmets and lights, and how to control a bicycle, i.e., balancing, braking, and steering.

3.2 Procedure

After obtaining informed consent from participants' parents, we explained the purpose of the interview to children. We started by asking demographic questions followed by a brief semi-structured interview on any problems they experienced while cycling. Afterwards, children were presented with two situations: cycling on a road without cycling infrastructure with *static* obstacles, e.g., parked cars, trash containers, and *dynamic* obstacles, e.g., a dog, a ball, or a pedestrian on the street in front of them. For these situations, children were asked to describe verbally and demonstrate using a Lego cyclist the actions they would perform to avoid the obstacles (Figure 2). The entire interview lasted approximately 15 minutes.

3.3 Results & Discussion

We found that most children (N=8) avoid main roads without cycling infrastructure, i.e., without bicycle lanes, due to the high accident risk. Instead, they preferred to cycle in the safe areas within their neighborhoods or in the parks with their parents. *"We don't go to the busy areas, we go to the parks and avoid busy roads. We don't take a right turn (UK), because it's too complicated. If we want to turn right, we go off the bike and cross the street as a pedestrian."* [P3, 9 years old].

[7] https://skullytechnologies.com/fenix-ar/
[8] https://livemap.info/
[9] https://vrscout.com/projects/diy-ar-device-hololens/
[10] https://newatlas.com/lumigrids-led-projector/27691/
[11] https://thexfire.com/products-page/lighting-system/bike-lane-safety-light
[12] https://www.youtube.com/watch?v=6cstdEpmKLM

Two children reported that they never cycle alone and their parents or older siblings assist them with cycling. For example, one child mentioned that she always cycles in a group, typically between her mother (behind) and older sister (in front), and receives instructions regarding speed, keeping safe distances, and braking from her mother. *"My mom helps me to make my decision behind me."* [P4, 7 years old].

In the scenario with the *static* objects on the road, such as parked cars or trash containers, five children tended to keep close to the side of the road, and the other five motioned cycling in the middle of the road after overtaking an obstacle. Two children mentioned that they would get off their bike and walk around the cars using the pavement for safety reasons. *"I would usually get off my bike before every obstacle and walk around it on the pavement."* [P12, 8 years old]. In the scenario with the *dynamic* obstacles on the road, children said they would stop completely and continue cycling when the obstacle was gone (N=11). Only one child mentioned overtaking the upcoming object. *"I would cycle around the dog to avoid him."* [P4, 7 years old]. As for the safety measures, children mentioned checking the upcoming cars behind and in front of them (N=6), keeping close to the side of the road (N=3) and maintaining a safe distance to the obstacles on the road (N=2), and braking (N=1).

We observed that almost half of the interviewed children (N=5) forgot to return to the side of the road after overtaking an obstacle, or were unsure about the safe distance to the side of the road. Since children usually avoid dynamic objects and wait until the danger is gone, we focus on lane keeping mechanisms around static objects with missing infrastructure for the rest of the paper. Our focus is not on the generation of the lane with LIDAR or ultrasonic sensors but rather on lane keeping feedback cues. We therefore assume there is an already existing system that tracks surrounding objects.

4 LAB EXPERIMENT

To address some of the issues discovered from the semi-structured interview, we began our investigation in an indoor bicycle simulator. This allowed us to provide a safe environment to collect first insights regarding children's performance with lane keeping cues. The idea was to provide path correction cues to guide children on streets with parked cars, as in the scenario from the interview. We developed four lane keeping mechanisms based on previous works.

For the tactile lane keeping aid, we used vibro-tactile motors on the left and right side of the handlebar grips. This was based on the previous work on vibrotactile navigation and warnings for cyclists [23, 24, 27], which utilized similar vibration cues. For the ambient light lane keeping aid, we used a green flashing light on the left and right side of the helmet to indicate direction. We used the location above the eyes to take advantage of peripheral vision [35]. For the heads-up display cues, we used a green blinking arrow on the left and right, projected in front of the helmet to indicate a direction. Vibration, ambient light and HUD arrows consisted of three 500 ms pulses. As soon as a cyclist went too far left, a signal was presented on the right side, and vice versa. If a cyclist remained within the safe distance area, a signal was not shown. For the laser-based projection lane keeping cues, we used a laser beam mounted in the front of the bicycle. Since the laser beam projected on the screens was not visible, it was projected on the cardboard paper placed at the bottom of the screens, simulating a projection on the road in the simulation. The line turned left or right to indicate the direction to turn, and was always visibly persistent. Across all mechanisms, the direction a cyclist had to go was shown on the corresponding side : signal on the left – go to the left, signal on the right – to the right. The summary of the conditions is shown in Figure 3.

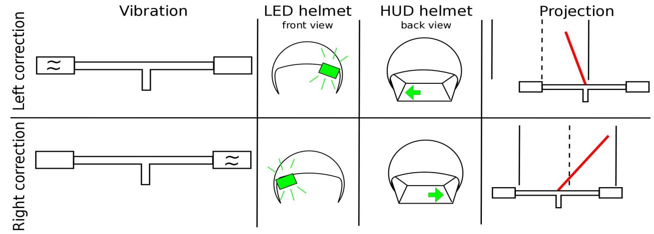

Figure 3: Overview of encodings for the lane keeping cues used for trajectory corrections. Children experienced each cue via vibration on the handlebar, blinking light in the LED helmet, blinking arrows in the HUD helmet, and a projected laser line indicating left and right in front of the cyclist.

Two external factors compete for a cyclist's attention while cycling in the natural traffic environment . The first is related to the control of the cycling process, which includes pedaling, keeping balance, and steering [2]. The second factor is related to road distraction and situational awareness. To simulate real-world cycling conditions in the bicycle simulator, we introduced a secondary task alongside the primary one. We chose a visual search distraction task applicable for children aged from six to thirteen [12]. The children had to spot an animal, which randomly appeared during cycling on the left or right side of the road, and to press a button attached to the handlebar as soon as they saw it. We specifically chose an animal (and not a car) as a traffic-unrelated stimuli to estimate the visual load of children's attention. Therefore, the goal was to estimate the level of distraction by measuring children's reaction time to this visual distraction.

4.1 Participants

We recruited 25 children (14 female) aged between six and 13 (M = 9.56, SD =2) years. They had between 0.5 to 10 years of cycling experience (M = 4.64, SD = 2) and the majority cycled two-four times per month. Eleven (out of 25) participants had previously completed a bicycle training course at their schools, where they learnt how to keep balance, show hand signals, and avoid obstacles. None of the participants had any hearing impairments, and had normal or corrected vision without color blindness.

4.2 Apparatus

To create a realistic cycling experience in safe and replicable conditions, we developed and conducted the experiment in a bicycle simulator (Figure 4). This consisted of an off-the-shelf child bicycle (24-inch wheels) mounted on a fixed Tacx platform (Antares T1000). Cycling actions, such as pedalling, steering and braking, were reflected in the simulation environment displayed on three screens in front of the bicycle to increase the angle of view and facilitate

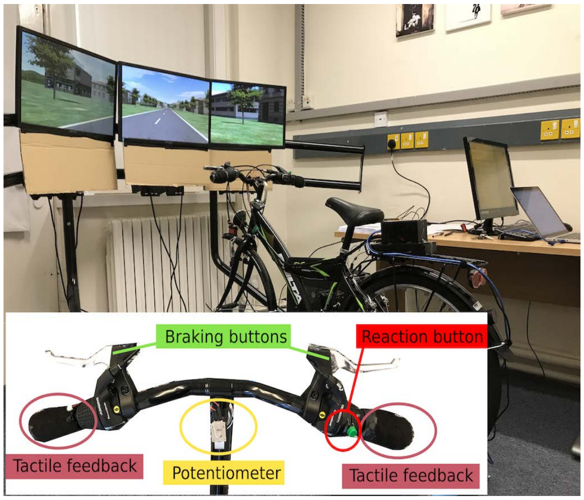

Figure 4: Bicycle simulator: handlebar with tactile feedback and a bicycle mounted on the platform with Hall effect sensor, magnets for measuring speed, servo with laser in the front and microcontrollers.

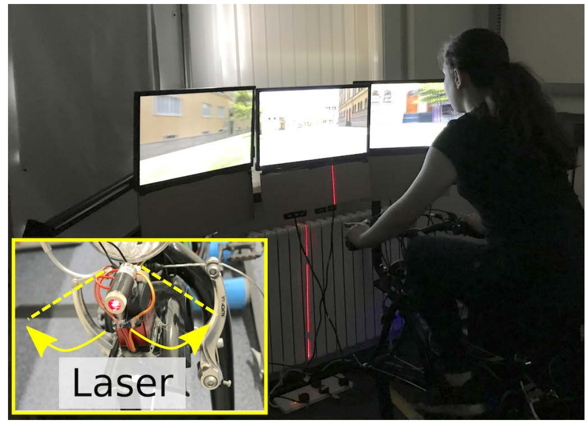

Figure 5: Laser projection: we mounted a laser on a servo in front of the bicycle to indicate lane keeping cues by turning it left or right and projected a line under the screens.

peripheral perception of the simulation. To obtain cycling speed, we used a Hall effect sensor positioned on the bicycle's frame and a set of magnets fixed on the rear wheel. Speed was calculated based on how frequently the hall effect sensor was activated by the magnets. We fixed the front fork of the bicycle to the platform, loosened the steer bolt and inserted a potentiometer into the bolt's head. This enabled free rotation of the handlebar and allowed us to measure the rotation angles. Buttons placed under the brake levers detected braking activities. A full stop was detected when the brake lever was pulled and activated the button. Releasing the brake lever, deactivated the button and resumed cycling. If pedalling was stopped, the bicycle continued its movement for the next couple of seconds, and then braked to a full stop.

We used the SILAB driving simulation software to create the simulation environment[13]. Although SILAB is normally used for car simulations, we were able to customize it for our needs. The simulation consists of a straight street with eight sets of cars parked on the left side of the road (UK). Based on the "Guide for the planning, design, and operation of bicycle facilities" [1], the virtual bicycle lane in the simulation corresponded to 1.5m (5 feet) width.

To represent the lane keeping cues, we fitted the bicycle with vibration motors on the left and right grips of the handlebar and a laser (5mW, 650nm) mounted on a servomotor in front of the bicycle to project a light beam under the screens (Figure 5). The vibromotors, hall effect sensor, potentiometer, buttons and servo were directly connected to an Arduino Primo microcontroller, which communicated with the simulation software via WiFi.

We also augmented a child's cycling helmet with LEDs on the left and right sides of the visor close to the eyes (LED helmet, Figure 1) and another one with a head-up display in the front (HUD helmet, Figure 6). LED strips in the LED helmet were directly connected to a NodeMCU 8266 board with an integrated Wi-Fi module and powered by a lithium ion (LiPo) battery. The microcontroller and the battery were integrated in the back of the helmet. For the HUD helmet, we added an Android smartphone (Nexus 5) placed in a holder made of transparent plexiglass in the front, and a battery power bank at the back of the helmet to balance the weight and charge the smartphone on-the-go. Visual cues displayed on the smartphone display were directly projected onto the plexiglass surface in the front. Communication between the simulation and both helmets, i.e., microcontroller and the smartphone, was accomplished via a WiFi connection.

For the visual search task, we added a button on the right side of the handlebar to measure the reaction time. This was connected to an Arduino Uno programmable board, which communicated with the simulation software via a USB-connection.

4.3 Study Design

We used a within-subject study design with type of lane keeping aid as the independent variable. The experiment consisted of five experimental conditions: *vibration*, *ambient light*, *head-up display*, *laser projection*, and *no lane keeping assistance* (baseline). The order of the conditions was randomized and unique for every participant. The total duration of the simulation portion of the experiment was approximately twenty minutes with setup and calibration. The entire study was approved by the ethical review board at our university. Each child received £6 for participation.

4.4 Measures

To compare lane keeping cues, we measured the following dependent variables:

Accumulated trajectory error left and right (in units of the bicycle simulator): we summed up the areas between the left and right side of the virtual bicycle lane and the cycled trajectories (Figure 7 left).

Percentage of time within the lane: we calculated the fraction of time a cyclist spent within the virtual bicycle lane.

[13] https://wivw.de/en/silab

Figure 6: HUD helmet: visual cues displayed on the smartphone were reflected in the plexiglas surface of a holder in the front. A battery power bank at the back was used to balance the weight and charge the smartphone.

Standard deviation of a trajectory: we calculated standard deviation of cycled trajectories.

Reaction time (in ms): we measured the time between presentation of the distraction (e.g., animal) and a button press, inline with previous work by Wierda and Brookhuis [37].

Response omissions: we counted the number of times children missed the distraction presented in the simulation.

Understandability (5-point Likert scale, 5 – most understandable): for each condition, every participant subjectively estimated the understandability of each lane keeping cue.

Distraction (5-point Likert scale, 5 – most distracting): for each condition, every participant estimated the level of distraction while cycling with a given lane keeping cue.

4.5 Procedure

After obtaining informed consent from participants' parents, we collected children's demographic data. We then explained the lane keeping cues to participants and provided a brief overview of the procedures. Afterwards, children familiarized themselves with the bicycle simulator and all types of lane keeping assistance with a test ride. The experiment started when children felt comfortable.

The children's primary task was to cycle straight on the left side of the road without bicycle lanes in the simulation, avoid the parked cars similarly to the ones presented during the interview, and follow the lane keeping cues. The secondary task was to press the button on the right side of the handlebar as soon as an animal was seen in the simulation. The animal was presented six times per trial. After each condition, children were asked to estimate the understandability (5 – very understandable) and the distraction (5 – very distracting) of the lane keeping cues using a 5-point Likert scale. At the end of the study, we interviewed children about their preferences for the different lane keeping cues, choosing one the most preferred modality. The entire study lasted approximately half an hour.

4.6 Results

Trajectory and time within the lane. The trajectory error was comparable among all five conditions and we did not observe a

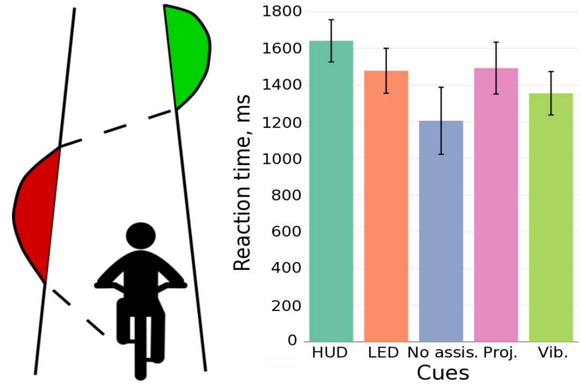

Figure 7: Accumulated trajectory error left and right: red area indicates trajectory error to the left and green – to the right. We summed these areas along the cycling trajectory, estimating an accumulated trajectory error for each side (left). Reaction times to the visual search task for the lane keeping cues (right).

significant difference using a Friedman test neither for trajectory error right (χ^2 = 6.5, p = 0.17), nor left (χ^2 = 4.86, p = 0.3). However, we observed that a trajectory error right was significantly larger than left for each lane keeping cue using Wilcoxon signed-rank test (see Table 1). We found a standard deviation of trajectories comparable among all five conditions and we did not observe a significant difference using a Friedman test (χ^2 = 4.84, p = 0.3).

We found that the percentage of children staying within the lane with vibration (46%) and LED helmet (46%) was higher than with projection (41%) and HUD helmet (40%), and comparable with no assistance (46%). We observed a significant difference for the percentage of staying within the lane using a repeated-measures ANOVA (F(4, 21) = 3.99, p = 0.015) and present all pairwise comparison using t-test in Table 2.

Reaction time. We found that cycling without assistance for the lane keeping had the shortest reaction time (M = 1206ms, SD = 555) in the visual search task, followed by vibration (M = 1356ms, SD = 551), LED helmet (M = 1478ms, SD = 588), projection (M = 1493ms, SD = 664), and HUD helmet (M = 1642ms, SD = 858) (Figure 7 right). There was a statistically significant difference between the conditions as determined by a Friedman test (χ^2 = 10, p = 0.04). We found that children's reaction time with non-visual lane keeping cues was significantly shorter than with visual ones. We present all pairwise comparison using Wilcoxon signed-rank test in Table 2.

Response omissions. The percentage for response omissions in the visual search task was comparable among all conditions: vibration (19.3%), LED helmet (23.9%), HUD helmet (23%), projection (21.1%), and no assistance (23.7%). We did not find a statistical difference among the conditions using a Friedman test (χ^2 = 1.79, p = 0.78).

Understandability and Distraction. The understandability of the lane keeping cues was comparable among all methods: vibration (Md = 5, IQR = 1), LED helmet (Md = 5, IQR = 0), HUD helmet (Md = 5, IQR = 1), and projection (Md = 4, IQR = 1). We did not observe

	Trajectory error			RT	In lane	SD	RO	Understand.		Distract.		Pref.
	Right	*Left*	*Pairwise*	ms	%		%	*M*	*SD*	*M*	*SD*	
Vibration	577	158	Z = -3.80, p < 0.01	1356	46	1.64	19.3	4.56	0.58	1.72	0.94	6
LED helmet	615	301	Z = -3.16, p < 0.01	1478	46	1.87	23.9	4.8	0.41	1.92	1.12	10
HUD helmet	652	248	Z = -3.65, p < 0.01	1642	40	1.76	23	4.24	0.97	2.24	1.23	5
Projection	711	325	Z = -3.05, p < 0.01	1493	41	1.97	21.1	4.24	0.78	2.28	0.89	4
No assis.	590	178	Z = -3.62, p < 0.01	1206	46	1.62	23.7	–	–	–	–	–

Table 1: Summary of descriptive statistics per condition. RT = reaction time, SD = standard deviation of a trajectory, RO = response omissions, Understad. = understandability, Distract. = distraction., Pref. = preference.

a significant difference among the methods using a Friedman test (χ^2 = 7.3, p = 0.063).

As for distraction, it was also comparable among all lane keeping cues: vibration (Md = 1, IQR = 1), LED helmet (Md = 2, IQR = 1), HUD helmet (Md = 2, IQR = 2), and projection (Md = 2, IQR = 1). We did not observe a significant difference for it using a Friedman test (χ^2 = 4.7, p = 0.2).

Problems and Preferences. We found that the majority of children (n=10) preferred LED helmet the most, because it was easy to use without obstructing the road. As our participants remarked: *"Ambient light was good, it keeps flashing until you do the right thing, it's easier to see than the rest."* [P9, 7 years old]. *"Ambient light was at the sides, so I could see the road better and it helped me to keep the distance."* [P8, 6 years old]. However, one (out of 25) participant mentioned that the light in the LED helmet was too flashy and it was distracting him from cycling.

Other six children preferred vibration, because it did not require visual attention and participants could freely focus on the road. *"Vibration was good and easy to understand and I could focus on the road."* [P4, 9 years old]. *"With vibration you don't have to see things and you are not afraid of the road and you can feel it with your nerves."* [P19, 11 years old]. However, due to the vibration of a bicycle on the platform, five children reported that sometimes they had problems distinguishing the side of the vibration. Two of them mentioned that vibration felt "strange" and "unusual", and one participant remarked that the vibration in the hands was unpleasant.

Due to the peripheral representation of HUD arrows, five participants preferred them, because they could freely focus on the road and see the blinking arrows in front. *"HUD arrows were not distracting and you can see them at the edge of your eyes. You can still see what in front of you while seeing the arrows."* [P18, 11 years old]. Also, the fact that HUD arrows were integrated in the helmet made children feel safer. *"I will feel safer with a helmet and I would wear it all the time to help me with overtaking the cars."* [P18, 11 years old]. The biggest issue with the HUD helmet, however, was the visibility of the arrows, when they were overlapping with the screen in the front. *"I couldn't really see the arrows at some point, because it was overlapping with the screen."* [P17, 10 years old].

The remaining four children preferred the laser-based projection, because they did not like signals close to the eyes. *"Projection was not too close to your face, and you don't have flashes of green on each side. It tells you, you are doing okay and it was easy to follow."* [P23, 13 years old]. However, one child mentioned feeing distracted by looking down at the projection. *"Projection was distracting me from the road, because I had to look down."* [P4, 9 years old].

None of the participants reported problems regarding the understandability of the signals. Two children (out of 25) mentioned that they prefer cycling without any technology, because it was too distracting and they were already good cyclists. *"I wouldn't prefer to have any assistance, because it was much easier for me without it and it distracts me."* [P5, 8 years old]. *"No assistance is better, so I could focus more on the steering and pedalling."* [P9, 7 years old].

Despite the absence of statistical differences for some quantitative measures, we found that children preferred vibration and LED helmet for lane keeping cues based on the qualitative data. We observed that with vibration and LED helmet children stayed within the lane longer than with HUD helmet or laser projection, but it was on the same level as without any cues. Reaction times to the secondary task indicated that child cyclists tended to oversee one out of five external visual stimulus independent of the type of lane keeping assistance, which is inline with the previous work with child cyclists in the bicycle simulator [24]. The reaction time to the external visual stimulus was shorter for the vibration method and no assistance in comparison to the visual lane keeping cues. Similar to previous work [24], we observed comparable reaction times to the external stimuli. We found that a trajectory error to the left and right with lane keeping assistance was comparable to a condition without assistance. This was most likely caused by the high sensitivity of the potentiometer used for steering in the bicycle simulator and children's unfamiliarity with it. Despite a test ride before the experiment, children needed time to adjust to a new cycling experience in the bicycle simulator. Moreover, children positively reacted to the use of lane keeping assistance during the post-study interview. Therefore, to avoid the limitations from the lab experiment, we decided to evaluate the lane keeping assistance in a follow-up controlled test-track experiment on a mid-size tricycle.

5 CONTROLLED TEST-TRACK EXPERIMENT

The goal of the controlled test-track experiment was to confirm the results from the lab experiment on an outdoor track. From an experimental perspective, running the study in real-world traffic conditions would have been ideal. However, due to safety concerns this was not possible (or approved) by our institutional review board (IRB). Therefore, we aimed for an approximation with an outdoor test track. This marks a gradual shift towards ecological validity. We used a tricycle instead of a regular bicycle to avoid safety concerns due to balance and coordination issues based on recommendations from the IRB. Although not ideal, children still had to ride on a paved road, steer and maneuver a real bicycle, and

	Vibration LED	Vibration HUD	Vibration Projection	Vibration No Assis.	LED HUD	LED Projection	LED No Assis.	HUD Projection	HUD No assis.	Projection No assis.
% within the lane	t = 0.2	t = 3.46	t = 2.43	t = 0.17	t = 2.23	t = 2.21	t = -0.03	t = -0.32	t = -2.13	t = -1.76
	p = 0.84	**p < 0.01****	**p = 0.02***	p = 0.87	**p = 0.035***	**p = 0.037***	p = 0.98	p = 0.75	**p = 0.043***	p = 0.09
Effect size	0.04	0.69	0.49	0.03	0.45	0.44	-0.01	-0.06	-0.43	-0.35
Reaction time	Z = -1.03	Z = -2.61	Z = -0.57	Z = -1.55	Z = -1.1	Z = -1.06	Z = -2.35	Z = -1.9	Z = -2.65	Z = -1.77
	p = 0.31	**p < 0.01****	p = 0.57	p = 0.122	p = 0.27	p = 0.29	**p = 0.019***	p = 0.057	**p < 0.01****	p = 0.077
Effect size	-0.15	-0.37	-0.08	-0.22	-0.16	-0.15	-0.33	-0.27	-0.37	-0.25

Table 2: Lab study results: Summary of pairwise comparisons for the time within the lane and reaction times. All post hoc analyzes were conducted with a Bonferroni correction to avoid type I errors. *<.05 **<.01

experience multisensory perception of the environment. The tricycle also allowed us to focus on the steering aspect of lane keeping, without the potential influence of stability or cycling technique.

5.1 Participants

We recruited 15 children (4 female) aged between six and twelve (M = 9, SD = 1.77) years. They had between three to eight years of cycling experience (M = 5, SD = 1.65). All of the participants had no hearing problems and had normal or corrected vision without color blindness. None of them had participated in the previous lab experiment.

5.2 Apparatus

For this evaluation, we used a mid-size tricycle to prevent falls (Figure 8). To represent the lane keeping cues, we fitted a tricycle with the same vibration motors on the left and right grips of the handlebar as in the simulator, and used the same LED and HUD helmets. To increase the visibility of the arrows in the HUD helmet, we added black tennis grip bands in front of the helmet (Figure 9). This change did not occlude much of the field-of-view, but would require looking upwards. The LED helmet remained unmodified from the lab experiment. We changed the laser to one ten times more powerful (50 mW) than the lab bicycle. However, despite increasing the brightness, the laser projection was still not fully visible during the day time. Therefore, we excluded this condition from the field experiment.

We used a laptop placed into the rear cargo box of the tricycle as a WiFi hotspot and a power supply. The vibromotors were directly connected to an Arduino Uno microcontroller. All lane keeping cues were activated by the experimenter using an Android application via WiFi communication two meters before an obstacle. The Arduino board in the rear cargo box of the tricycle was directly connected to the laptop via a USB cable. To observe the behavior and focus of the participants, a GoPro camera was placed in the middle of the handlebar facing the rider (Figure 8). To simulate parked cars on the side of the road as in the interview and bicycle simulation, we used eight cardboard boxes. However, this time the boxes were placed on the right side on the road, because the experiment was conducted in Germany. Due to the low precision of the GPS systems, we could not track the trajectories of cyclists. Instead, we focused on the qualitative responses to the cues in the real world, as we could not do the detailed recording that we did in the lab experiment.

5.3 Study Design

We used the same study design as in the lab experiment, where every participant had to cycle with three types of lane keeping assistance and once without any assistance as a baseline. The order of all four conditions was randomized. For every participant, we ensured a unique order of all four conditions.

We conducted the controlled test-track experiment on an outdoor practice track in Germany, normally used as a training facility by novice car drivers. The test track consisted of a network of gravel roads with intersections, old stationary parked cars, traffic signs and lights. However, children cycled on the straight road (200m), similarly to the lab experiment. The roads on the test track did not have any cycling infrastructure. For safety reasons, no other traffic (except for parked cars) were presented during the experiment. The experiment was conducted over the course of eleven days: four of the days were cloudy and other seven were sunny.

To activate the lane keeping cues, the experimenter walked behind or next to a participant. Every experimental condition took on average five minutes per participant and it took 20 minutes to complete the cycling part of the experiment. The entire study was approved by the ethical review board of our university. Each child received €10 for participation.

5.4 Procedure

After obtaining informed consent from participants' parents, we collected children's demographic data. We then explained the lane keeping cues and provided a brief overview of the procedures. Children had a chance to familiarize themselves with the tricycle and the different types of lane keeping feedback with a test ride. The experiment started when children felt comfortable.

The children's task was to cycle on the straight road, follow the lane keeping signals and safely overtake the cardboard obstacles. After each condition, children were asked to estimate the understandability (5 – very understandable) and the distraction (5 – very distracting) of the lane keeping signals using a 5-point Likert scale. At the end of the study, we interviewed children about their preferences and the problems they experienced with different lane keeping signals. The entire study lasted approximately half an hour.

5.5 Results

None of the children experienced an accident by cycling into the cardboard obstacles on the road and each safely overtook the obstacles. Only one child did not turn back to the side of the road after

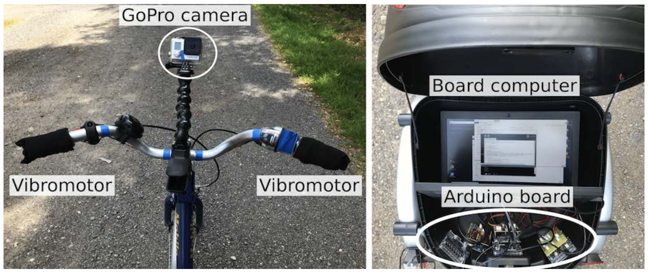

Figure 8: A tricycle equipped with a laptop in the rear cargo box, vibrtotacile feedback on the handlebar, and a GoPro camera for in-field observations.

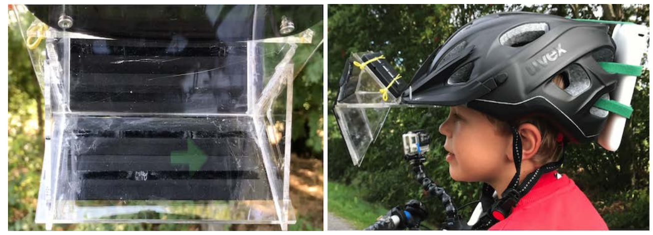

Figure 9: HUD helmet: we added black tennis grip bands in front of the helmet to increase the visibility of the reflected visual cues.

overtaking in the condition without any assistance. In comparison, five children did not turn back to the side using a Lego cyclist in the initial interview. Another child reported that he did not want the lane keeping signals, because he felt more comfortable without them. *"I don't think I need such signals. I'd rather cycle without them. I think I was confident without the signals than with them."* The other 14 participants found the signals helpful and would like to have them in particular situations with a lot of traffic or all the time. As our participants remarked: *"In the cities like New York with lots of traffic, I would definitely need an additional support for my cycling. When there is a lot going on the street, I would definitely need them, but not all the time."* [P12, 9 years old]. *"I find the signals helpful. I can also imagine myself relying on them, if the bicycle "know" that it is safe to overtake a car."* [P14, 12 years old].

Understandability and Distraction. As in the lab experiment, all lane keeping methods received comparable scores for understandability: vibration (Md = 4, IQR = 1.5), LED helmet (Md = 4, IQR = 1.5), HUD helmet (Md = 3, IQR = 1.5). We did not observe a significant effect for it using a Friedman test (χ^2 = 4.98, p = 0.83).

As for distraction, HUD helmet (Md = 3, IQR = 2.5) was perceived more distracting than vibration (Md = 2, IQR = 1) and LED helmet (Md = 2, IQR = 2). We also found a significant difference among the three modalities using a Friedman test (χ^2 = 7.58, p = 0.023). The HUD helmet was perceived significantly more distracting than vibration (Z = -2.48, p = 0.013) and LED helmet (Z = -2.41, p = 0.016). However, we did not observe a significant effect between the LED helmet and vibration-based (Z = -1.01, p = 0.31) lane keeping signals.

Problems and Preferences. The majority of children (n=7) perceived the vibration as very easy to use, which is inline with our findings from the lab experiment. As one of our participants mentioned: *"It did not bother me at all and it was simply very good. I liked it."* [P13, 7 years old]. However, other five children mentioned that sometimes vibration distracted them. *"Vibration has distracted me a little bit more than light, and I didn't always felt it on the handlebar. This made me automatically look down."* [P6, 9 years old].

Regarding the LED helmet, children did not experience problems seeing the light signals placed in the LED helmet and could use the advantage of peripheral light to see the signals very well on the sunny days. *"I could always see the light. The visor has reflected the light a little bit, but it was also good to see it in the sun."* [P3, 11 years old]. Only one child (out of 15) reported the problem with seeing the light on the sunny day. *"Sometimes I couldn't see the light very well because of the sun."* [P5, 7 years old].

Five children liked the clarity of the HUD arrows, since it was less abstract than the blinking LEDs. *"I clearly see where I have to go. It is clear."* [P11, 6 years old]. The visibility of HUD indicators was sometimes an issue under the direct sun and was better seen in the shadows. As one child commented: *"I could see it very well in the shadows, but in the sun it was a bit hard to see the arrows."* [P1, 9 years old].

6 DISCUSSION

Interestingly, children's cycling performance without any lane keeping assistance was comparable to situations with vibration and LED helmet based on the quantitative measures. Our qualitative results, however, showed that children found the feedback to be helpful and expressed subjective preferences for the LED helmet and vibration on the handlebar. The question we ask ourselves is, why was lane keeping assistance still perceived positively and helpful, despite the absence of statistically significant difference for quantitative measures. If lane keeping cues would be completely unhelpful and distracting, they would not receive positive feedback during the interviews as well as high scores for understandability and low for distraction. In our opinion, the possible explanation for this outcome might be the lack of realism in the test environments. Although we tried to mimic realistic conditions by simulating a distraction in the lab experiment, we admit that both experiments did not ideally reflect the real-world traffic conditions. We agree that it is vital to examine the effectiveness of these techniques in real-world situations, however that is only possible if an initial design space is carved out that establishes the effectiveness of unimodal cues in guiding children. For safety reasons and IRB limitations, we were not able run the experiments with real traffic and pedestrians.

Despite the limitations and statistically insignificant results, we foresee the results of our research as preliminary steps towards a full-fledged cycling assistance system for children. The work presented although not fully generalizable provides insights into what may work with children. For example, the HUD indicators were perceived better in the test-track than in the lab experiment due to better visibility, in part due to the black contrast material added to the helmet. We believe that the HUD helmet was outperformed by other modalities due to its current implementation and needs further exploration. For example, EverySight[14] has recently introduced AR glasses for cyclists based on microLED technology for adult cyclists, which provides a better visibility of the signals in comparison to the current implementation of our prototype. The laser-projection has visibility limitations in bright environmental conditions, similar to previous work on projected surfaces for cyclists [8, 9], but can be potentially used when it is dark and might be useful for other road users, given that they are getting cheaper and widely available. We envision that they can be used around bicycles to improve safety by providing assistance and increasing cyclists' visibility during the night-time. In this case, the projected interface can transform the physical environment around cyclists into a safety zone.

Vibration feedback on the handlebar was positively perceived by the participants, because it did not require visual attention. This finding is inline with prior work in on-bicycle feedback to represent directional cues [23] and turn-by-turn navigation [24, 27, 29]. Ambient light in the helmet was also positively perceived due to its peripheral and non-demanding information representation, which fits with previous work about ambient light in helmets [35]. However, the brightness of the light signals needs to be adjusted depending on the outside brightness. Based on the previous work [23, 24], we think that by further combining vibration and LED helmet cues we might avoid limitations of both modalities and increase children's performance for lane keeping, which is inline with previous work for car drivers [28].

6.1 Distraction and reaction time

We observed that the reaction time to the visual distraction task from the lab experiment was between 1,3 and 1,7 seconds, which is comparable to the reaction times to the auditory distraction task presented to child cyclists during navigation [24]. However, the reaction times to both auditory and visual distraction tasks were shown to be 2-3 times longer than to the multimodal warning signals, which were between 500 and 600 ms [23]. We assume that this difference in the reaction times might be caused by the following two reasons: (1) method of reaction and (2) priority of the task. As for the method of reaction, children pressed an additional button placed on the handlebar for the distraction tasks, and braked for the warning signals, which was most likely a more natural way of reacting to an external danger. As for the priority of the task, children's primary task with the warning signals was to react to them, and not to an external distraction. For example, in our lab experiment, children's primary task to follow a lane keeping cue and to react to a distraction had a lower priority, much like similar prior work in navigation [24].

6.2 Towards trust in cyclist assistance systems

It was clear from our interviews with kids that confidence was a key issue when riding on unknown streets or neighborhoods. Children naturally avoided traffic situations where they felt uncomfortable with some children even going so far as walking the bicycle on the sidewalk when encountering an obstacle. Therefore, if children are to use lane assistance systems, trust is critical to adoption. Even for adults, in the field of autonomous vehicles, it has been shown that trust is necessary for a driver to give up control [5]. Developing trust in the system with children, therefore, may take time and require a graded and transparent approach that requires further study. However, as more children trust the system, the more they will tend to use it [26], thereby increasing the number of children riding on the roads. This can potentially contribute to "safety in numbers" [17] and expand the range of mobility for child cyclists. Thus, in this respect, we see our work as playing a role in improving the confidence for child cyclists to become increasingly mobile.

6.3 Lane assistance as an intermediary technology

In many cycling-friendly countries, children start cycling alone at the age of 6 and experience significant difficulties during this initial learning period. Although we could have focused on just younger children, we expanded our age range (up to 13 years) based on accident statistics. We found that children (even of young age) are capable of reacting to the external visual distraction task, follow lane keeping instructions, and cycle at the same time. Narrowing the age range of the children would provide more granular design recommendations for older/younger children, however we think of our work as a first step towards using these technologies. We plan to conduct further studies that can narrow down specific designs for different age groups. Moreover, we did not observe particular differences between younger and older children in our studies.

Ultimately, the construction of cycling infrastructure with dedicated bicycle lanes is the ideal solution to increase cyclists' safety [10, 15]. More countries around the world aim to support the use of bicycles for the safety, health and ecological reasons. However, this is a time consuming process, which is not always in the list of priorities in some countries around the world. In this sense, we hopefully see our unimodal lane keeping assistance work with children as an intermediary technology. Coupled with recent low-cost bicycle enhancements [3], such as laser scanners and ultrasonic sensors, we can support safe maneuvers "on-the-go" and promote "safety in numbers" [17], making cycling attractive for children.

7 CONCLUSION

In this paper, we investigated the effectiveness of unimodal lane keeping cues for child cyclists. From the semi-structured interview we found that children have problems on the roads with parked cars and no cycling infrastructure. To support them we conducted the lab experiment, where children expressed their subjectively preferences for vibration on the handlebar and ambient light in the helmet over other lane keeping cues. However, in the follow-up controlled test-track experiment, we discovered that ambient light has visibility limitations on the sunny days, and the multimodal combination of ambient light with vibration might be a better solution, which it needs further explorations.

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[14]https://everysight.com

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