Augmenting Bicycles and Helmets with Multimodal Warnings for Children

Andrii Matviienko[1], Swamy Ananthanarayan[2], Shadan Sadeghian Borojeni[1], Yannick Feld[2]
Wilko Heuten[1], Susanne Boll[2]

[1] OFFIS - Institute for
Information Technology
Oldenburg, Germany
{firstname.lastname}@offis.de

[2] University of Oldenburg
Oldenburg, Germany
{firstname.lastname}@uni-oldenburg.de

ABSTRACT

Child cyclists are often at greater risk for traffic accidents. This is in part due to the development of children's motor and perceptual-motor abilities. To facilitate road safety for children, we explore the use of multimodal warning signals to increase their awareness and prime action in critical situations. We developed a bicycle simulator instrumented with these signals and conducted two controlled experiments. We found that participants spent significantly more time perceiving visual than auditory or vibrotactile cues. Unimodal signals were the easiest to recognize and suitable for encoding directional cues. However, when priming stop actions, reaction time was shorter when all three modalities were used simultaneously. We discuss the implications of these outcomes with regard to design of safety systems for children and their perceptual-motor learning.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords

Child Cyclists; Bicycle Safety; Multimodal Warnings; Collision Avoidance; Bicycle Simulator.

INTRODUCTION

The number of cyclists worldwide has increased considerably over the last couple of years [36]. Most notably, cyclists comprise 26% of the population in the Netherlands, 18% in Denmark and 10% in Germany [35]. Even though the number of accidents with cyclists has decreased over the last two decades [1, 40], bicyclists still remain a highly underrepresented group and belong to the category of vulnerable road users.

Recent accident reports show that child cyclists aged between six and thirteen years suffer the most road related injuries of any age group [8, 12]. One of the reasons for the high accident rate in this group lies with the cognitive developmental differences that affect the performance of cycling activities. The development of motor, cognitive, and sensory information processing skills changes from childhood to adolescence, which greatly influences how children are able to navigate complex traffic situations [6, 23].

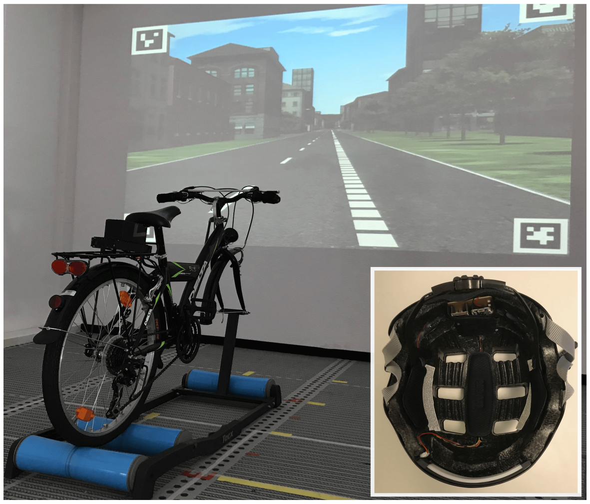

Figure 1: An indoor bicycle simulator consisting of a projected street view connected to a stationary bike. It was used to investigate on-bicycle and helmet locations for warning signals.

In recent years, researchers have augmented helmets, bicycles, and clothing accessories with ambient, vibrotactile, and audio cues to improve rider safety. Notable examples include a vibrotactile belt to aid navigation [43], a display projected on the road surface to show cyclist intention [10], a GPS-based collision detector [47], and a peripheral light display integrated in a helmet for distraction-free route guiding [45]. These systems however have been developed for cyclists in general and not particularly for younger children (aged 6-13). It is unclear what feedback modalities work with this age group and how best to convey alerts and warnings understandably and intuitively.

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Our work aims to fill this gap and increase safety for child cyclists. We investigate how visual, vibrotactile, and auditory feedback situated in the helmet and bike can be used to convey warning signals (Figure 1). We explore a multimodal approach motivated in part by its success in the automotive domain, particularly in increasing driver awareness [24], and conveying navigation information [26] and warning cues [33]. Although these systems have been developed for adults in a different domain, they are safety critical systems and serve as a good starting point for our work with children, especially since they aim to present information without additional mental load. We also adopt simulator based evaluations and showcase a bicycle simulator (Figure 1) we developed to explore children's cycling behavior in a safe and controlled environment.

In our first exploratory experiment, we investigated how well children recognized and understood unimodal and multimodal signals at different positions on the bicycle. We discovered that unimodal signals were better for encoding directional cues and multimodal signals for urgent immediate actions. In the subsequent study, we explored the efficacy of these encodings in the two most common car-to-cyclist collisions, namely, when cars are entering the street at junctions and from parked locations [8, 14, 22].

Our main research contributions include:

1. A set of on-bicycle and helmet locations for auditory, vibrotactile, and visual feedback suitable for child cyclists.
2. An initial set of multimodal warning encodings based on a simulator evaluation for children's bicycle safety.

BACKGROUND & RELATED WORK

Although there has not been much work on bicycle safety systems focused particularly on children, researchers have designed a number of support systems for cyclists in general. In this section, we examine existing work in this area, followed by a discussion of the challenges associated with developing technology for a user group whose motor and cognitive processing skills are still maturing.

Cyclist Support Systems

In recent years, cyclist support systems have seen considerable growth in both academia and industry in line with the increasing number of cyclists. These systems have focused on supporting cyclist navigation, preventing collisions, or increasing visibility on the road. Typically, these technological interventions have focused on augmenting either the bicycle, the cyclist (via on-body feedback), safety equipment (e.g., helmet), or the environment around the cyclist.

Bicycle Based Systems

Systems that augment bicycles have focused on tactile or visual feedback. Tactile feedback has primarily been used for navigation, while visual feedback has been used to increase visibility in addition to supporting navigation.

A good example of the use of vibrotacile feedback is TactiCycle, which employs vibration motors on the handlebar to provide navigation cues for cyclists on exploratory bicycle rides [34, 30]. Empirically speaking, different encodings of vibrotactile feedback can be felt on the hands 87.4% of the time while riding [4]. Commercial projects such as SmrtGrips[1] have leveraged this finding to present turn-by-turn navigation cues to cyclists via vibrotactile grips. These grips work intuitively by vibrating on the side the user is expected to turn.

A variety of commercial products have explored the use of on-bicycle visual systems. Garmin Varia Rearview radar[2] is a bike accessory that warns of vehicles approaching from behind using a visual notification on the screen fixed to the handlebar. Smarthalo[3] employs a round LED-based navigation device on the handlebar to encode distance and direction. Another such example is Hammerhead[4], which is a bike accessory that can be fixed to the handlebar to provide turn-by-turn navigation through directional LEDs. These commercial devices however require a paired smartphone for displaying information and route planning. Perhaps the most obvious use of visual feedback is for cyclist visibility. The use of headlights and rear lights on bicycles are already required by law in some European countries. RevoLights[5], takes this idea a step further and provides a 360° lighting system on the wheels along with handlebar activated turn signals.

Since these vibrotactile and visual systems have been designed for cyclists in general, they could potentially be used by children as well. However, it is unclear how these modalities would be interpreted by children. Moreover, some of these systems require an additional smartphone which young children often lack. Since many of the on-bicycle visual systems are commercial products, there is also little empirical evidence on their effectiveness. Our work aims to better understand the nuances of these fundamental feedback modalities and what children can effectively use while biking.

On-body and Helmet Based Systems

Apart from augmenting the bicycle, researchers have also explored on-body systems for navigation and collision detection. Similar to grip based navigation discussed in the previous section, Vibrobelt explores on-body vibration cues for navigation [43]. Although Vibrobelt was successful in guiding cyclists through unfamiliar routes, users were faster when using a visual navigation system. Additionally, they were better at recalling the route and showed higher contextual route understanding with the visual system. Vibrotactile feedback was also previously investigated for collision prevention between cyclists and pedestrians. Yoshida et al.'s [47] proposed system warns both pedestrians and cyclists through their smartphones about an impending collision at a blind corner. They showed that collisions could be prevented by using their GPS-based algorithm and vibrotactile feedback.

The use of low-resolution visual displays has also been investigated for conveying the current state of the cyclist [15]. These wearable displays which can be attached to the arm, the head,

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[1] http://smrtgrips.com/

[2] https://buy.garmin.com/en-GB/GB/p/518151

[3] https://www.smarthalo.bike

[4] https://www.dragoninnovation.com/customer-projects/hammerhead

[5] https://revolights.com/

and the back automatically serve as turn and stop signals by inferring their placement on the body, body movements, and bicycle acceleration. Kräuter et al. [21] extended this set of on-body signals and investigated different light patterns for stopping, slowing down, and indicating turns on a cyclist's back.

Perhaps the most common bicycle safety accessory is the helmet. Researchers have used helmets to convey both visual and auditory feedback to the riders as well as other traffic participants. For example, Schopp et al. [39] augmented a cyclist's helmet with a bone conduction speaker to warn cyclists of approaching vehicles outside their field of view. They reported that participants perceived increase in situational awareness and could easier identify hazardous situations. Jones et al. [20] enhanced a cyclist's helmet for both input and output. They used lights placed on the back of a helmet to indicate turn signals through head-tilting, and a microphone to communicate location to other drivers. Similarly, Blink Helmet, utilized manual buttons on the sides of the helmet to indicate stop and turn signals[6]. From a navigation perspective, Tseng et al. [45] investigated peripheral light movement in a helmet to guide riders without introducing additional distraction.

On-body systems are certainly promising considering their seamless integration with the rider. However, their use with children might prove to be less successful, considering that they require a conscious effort to wear and position. Children are often less patient than adults and might not wait to check if on-body systems are properly working [16]. Moreover, from a child interaction perspective, they are simply less practical as they need to be transported and remembered [19]. Admittedly, these issues also exist with bicycle helmets, however, in many countries they are mandated safety equipment for children. Therefore, they might serve as a more compelling platform for safety technology especially in the form of peripheral visual feedback [27] and audio cues.

Environment Based Systems

Another interesting approach involves the use of projection systems for navigation and safety. Dancu et al. utilized map projections in front of the bicycle for route guidance and turn signal projections in the rear to alert other traffic participants of rider intention [10]. Other systems such as Lumigrids[7] and Xfire[8], used projected grids to detect obstacles such as potholes, and project a virtual bike lane on the road. Although these systems are encouraging, it is unclear how effective they are. For example, researchers discovered that projected map surfaces were less efficient, harder to use, and perceived less safer than heads-up displays [10]. Moreover, from a children's design perspective, it would be valuable to have a system that is useful during both daytime and nighttime.

Development of Children's Cycling Skills

Technological assistance systems have to contend with a number of challenges when dealing with child cyclists. These include poor turn maneuvers, lack of bicycle control, inadequate awareness, and distraction due to playing [42]. Undoubtedly, some of these issues are related to the development of children's motor and perceptual-motor abilities [6, 11, 9]. For example, cycling subskills, such as balancing, pedalling, steering, or braking, develop at different rates [2]. Learning one of these skills, such as braking, is relatively easy but becomes more difficult when combined with other actions.

Furthermore, cycling requires additional contextual skills such as obstacle negotiation, speed adjustments after an over-the-shoulder look [11], observing traffic signals [6], estimation of car speed [7], understanding of road crossing behavior and gap acceptance [31]. The issue here lies in the difficulties children face in synchronizing perceptual information with motor movements [7, 32]. Children ideally acquire all necessary skills before they start cycling on the road. However, this is often not the case, as can be seen from the statistical reports about cyclists' accidents [8, 12]. Moreover, learning these skills requires real-life practice.

Apart from age-related development of motor and perceptual-motor abilities, experience is an another influencing aspect among adults and child cyclists. As shown by Shepers [38] and Wierda and Brookhuis [46], adults have better control of their bicycles and are less likely to end up in an accident. Early training is important for improving children's cycling abilities, but technology can also play a crucial role particularly in scaffolding maturing psychomotor skills and warning children of potential accidents. Much like parents who guide their kids with instructions while cycling, our aim is to assist children "on-the-go" with technological feedback. Towards this end, we explore how existing modalities and feedback mechanisms can be used to help children while they master cycling skills.

EXPLORATORY STUDY

Since there is not much prior work investigating how children perceive different feedback modalities on a bicycle, we conducted an exploratory study to better understand what signal(s) children recognized, and how they interpreted the various cue(s). We focused on visual, auditory, and vibrotactile cues integrated in different areas of the bike (e.g., seat, handlebar, grips). Ultimately, our objective was to use the results from this study to inform the design of a bicycle warning system for children.

Participants

We recruited 15 children (7 female) aged between six and thirteen (M = 9.2, SD = 1.9) years, who had between two to nine years of cycling experience (M = 4.67, SD = 2.02). All of the participants had normal or corrected vision without color blindness and had no hearing problems. The children in the study typically cycled from 2 to 20 times per week for school, fun, or shopping.

Apparatus

We conducted the exploratory study in a bicycle simulator we developed, which consists of an off-the-shelf children's bicycle (24-inch) mounted on a stationery platform (Tacx) (Figure 2). Actions on the bike such as braking and pedalling are reflected

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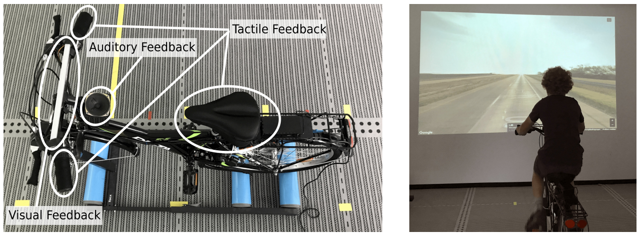
[6] `https://www.wired.com/2011/04/blink-touch-sensitive-bike-lights-built-into-helmet`

[7] `https://newatlas.com/lumigrids-led-projector/27691`

[8] `https://thexfire.com/products-page/lighting-system/bike-lane-safety-light`



(a) (b)

Figure 2: Bicycle simulator: (a) bicycle on a stationary platform fitted with unimodal and multimodal feedback (b) a child cycling through a street view simulation projected on the wall.

in a simulated environment projected on the wall in front of the bike. The environment was implemented using the Google Maps Street View API[9]. The simulation was limited to straight roads for the sake of simplicity. The bicycle was fitted with an LED display and small audio speakers on the handlebar and vibration motors in the saddle and the grips. We excluded pedals as potential feedback points since prior research has shown that riders have limited perception of vibration on their feet [3]. We conducted the study in a simulator in order to provide a safe and controlled environment for children.

The LED light display on the handlebar consisted of RGB LED strips (21 LEDs per side) enclosed in an aluminum case with an acrylic light diffuser. The diffuser was used to ensure even light distribution and to avoid dazzling the cyclist. The handlebar also contained a 3-inch speaker enclosed in an open black plexiglass box to ensure unidirectional sound. The grips of the handlebar contained four vibration motors each encased in shock tape to prevent vibrations on each side from travelling down the bar. Four vibration motors were also employed in the saddle.

To obtain cycle speed and update the simulation landscape, we used a hall effect sensor positioned on the bicycle's frame in combination with a magnet fixed to the rear wheel. Thus, we could calculate speed depending on how many times the magnet passed the sensor. A Genuino 101 microcontroller and a dedicated Android application was used to activate the actuators on the bicycle via Bluetooth.

Study Design

Our exploratory study was designed to be within-subject with the *type of signal* as the independent variable. We tested 14 different types of signals, which included both unimodal and multimodal cues (Table 1). About half the cues were unimodal and consisted of visual (e.g., LED indicator on the left, right, and entire handlebar), auditory (e.g., speech from speaker in front), and vibrotactile (e.g., left grip, right grip, saddle) feedback. Since children between the ages of six and thirteen years are already familiar with the semantics of traffic lights, we accordingly used red and green blinking lights for stop and go signals. Each light and vibration pattern consisted of three activations with the same intensity and a delay and duration of 500 ms based on the previous works for alerting drivers using visual [28], vibrotactile [18], and auditory cues [17]. We used speech-based auditory feedback with the message *"Please stop!"* due to its clarity.

The multimodal signals consisted of semantically possible combinations of visual and vibrotactile cues. For example, vibration on both grips of the handlebar in combination with the LED display illuminated fully in red could be interpreted as a cue to stop. Ambiguous combinations such as vibration on the left grip and a light indicator on the right side of the handlebar were excluded. Since we used speech for our auditory signal, we excluded it from the multimodal combinations since it had clear semantic meaning and would confuse or override the other modalities. Each of the 14 signals was presented twice in random order for 30 seconds (28 signals/child). A detailed list of all conditions is shown in Table 1.

#	Modality	Position	Pattern	Recognition
1	Vibration	Left	3 pulses	100%
2	Vibration	Right	3 pulses	100%
3	Vibration	Saddle	3 pulses	100%
4	Light	Front	3 🟥 flashes	100%
5	Light	Right	3 🟩 flashes	100%
6	Light	Left	3 🟩 flashes	100%
7	Audio	Front	Speech: *"Please stop!"*	100%
8	Vibration	Left	3 pulses	82%
		Right	3 pulses	
9	Light	Left	3 🟩 flashes	96%
	Vibration	Left	3 pulses	
10	Light	Right	3 🟩 flashes	100%
	Vibration	Right	3 pulses	
11	Light	Front	3 🟥 flashes	93%
	Vibration	Saddle	3 pulses	
12	Vibration	Left	3 pulses	63%
		Right	3 pulses	
		Saddle	3 pulses	
13	Light	Front	3 🟥 flashes	96%
	Vibration	Left	3 pulses	
		Right	3 pulses	
14	Light	Front	3 🟥 flashes	45%
	Vibration	Left	3 pulses	
		Right	3 pulses	
		Saddle	3 pulses	

Table 1: Exploratory Study: Summary of conditions and results. The cues for conditions #8-14 were activated simultaneously.

The study scenario involved cycling straight without the possibility of a left or right turn, because we wanted to engage children in riding and focus their attention on the road. At this stage, we decided to exclude regular traffic and pedestrians from the simulation to investigate on-bike multimodal feedback without additional mental load and distraction. The study was conducted with approval from the ethical review board at our university. Each child also received €10 for participation.

Procedure

After obtaining informed consent, we conducted a brief interview with each child to better understand issues they faced while cycling. Topics included: traffic problems they encountered, current knowledge of traffic signs and rules, cycling

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[9] https://developers.google.com/maps/documentation/javascript/streetview

safety measures, and general cycling routines. Specific to cycling, we asked children how well they understood the traffic light colors and the four traffic signs most common in accident scenarios: stop, give way, priority road, crossroads with right-of-way from the right [22, 14].

After a brief overview of the procedures, children familiarized themselves with the different feedback modalities while taking a test ride in the simulator. They started the study when they felt comfortable. During the experiment, we asked participants to stop cycling when they recognized a signal. When they stopped, we asked the following two questions:

1. *Which part(s) of the bicycle was (were) communicating?*

2. *What do you think the bicycle was trying to "say"?*

If at least one of the signals was missing in their answers, we marked it as unrecognized. At the end of the study, we briefly interviewed each child about their personal preferences for on-bicycle feedback, what they liked or disliked about the current implementation, any changes they would make, what they could imagine on their own bicycles, and the context and value of such signals. The entire study lasted approximately 40 minutes.

Results

The exploratory study helped us to discover suitable positions for visual, vibrotactile and auditory cues on the bicycle. We also obtained the recognition rate of various unimodal and multimodal signals. Lastly, we collected the subjective preferences and interpretations of children.

Existing Problems

Despite the small sample size, we confirmed the previous work of Sandels [37] and found that children faced problems noticing and interpreting traffic signs on the road. Although all participants knew the meaning of stop signs and traffic lights, only a few understood some of nuances of various traffic laws. One participant (12 years old) reported that she often has problems understanding right-of-way at crossings. Six (out of 15) children knew the meaning of the priority road sign, and one child knew the purpose of the "give way" sign. None of the children knew the meaning of the sign for "crossroads with right-of-way from the right" (as per European road law).

Recognition rate

We found that unimodal signals (Table 1, #1-7) were recognized 100% by all children and in all conditions. The combination of vibration and light was recognized (>81%, #8-11) better for signals with clear semantics. For example, green light on the right handlebar and vibration in the right grip (#10) was perceived as a navigation instruction. A vibration on both grips was interpreted as a stop signal (#8). However, when vibration was presented in more than two locations, interpretations became ambiguous. For example, the lowest recognition rate occurred for signals with vibration at three locations with (#12, #14). This could be because of confusing semantics or a potential increase in mental load due to multiple signals of the same nature. However, the recognition rate remained high for situations when two positions were used for vibration and one for light (#13). Children clearly identified this condition as a stop signal, similar to conditions #8-11.

Preferences and Interpretations

Generally, children did not face any issues understanding most signals, however the interpretations for vibration signals were sometimes ambiguous. The majority of children (n=10) interpreted individual vibrations on the left or right grip as a turn signal. Similarly, simultaneous vibrations on the left and right grips were perceived as a stop instruction (n=8). Vibration on the saddle was interpreted as a stop or slow down (n=9). Thus, there was no consistent agreement on how vibration was interpreted at different locations. On the other hand, the interpretation of light was unambiguous among all children, due to their familiarity with the traffic light metaphor. They perceived red blinking light as a signal to stop or danger, and green light as an allowance to go.

Given the ambiguity of interpretations for vibration signals, we asked children in the post-study interview additional questions regarding the combinations of vibration and light. Interestingly, when red light was combined with vibration, all of the children interpreted the color as danger or stop, and the vibration as an indicator of direction. So for example, if red light was combined with vibration at the saddle, then it signalled caution from behind. Similarly, red light combined with vibration at the left grip, meant an approaching danger from the left. However, when green light was combined with vibration, children perceived it as a navigation instruction, such as turn left (vibration in left grip), right (vibration in right grip), or go straight (vibration on both sides). Essentially, the semantics of color enhanced the interpretation of vibrational cues and vice versa. However, vibration can also be used by itself for encoding directional cues [30].

Children did not have problems recognizing and understanding the auditory feedback, since it was clear and explicit. However, in the post-study interview they reported the audio cue as: (1) too spontaneous and frightening due to the computerized voice, (2) a possible distraction to other cyclists, (3) invasive and less private, (4) potentially subtle in a noisy environment.

BICYCLE WARNING SIGNAL DESIGN

Although most of the unimodal and multimodal encodings showed a high recognition rate and were easy to understand for children, it was unclear how effective these signals were in car-to-cyclist collisions. Based on related work and the set of locations and encodings derived from the exploratory study, we designed warning signals for different traffic situations.

For less urgent situations, directional cues [13] with unimodal encodings consisting of either auditory [17] or vibrotactile [18] feedback have typically been used in the past for guiding drivers' attention. We also found a high recognition rate for unimodal cues among child cyclists in our exploratory study. Thus, unimodal encodings are a natural solution for representing directional cues.

From statistical reports, we found that car-to-cyclist collisions happen most frequently when cars enter the street from junctions or from parked locations (left or right) [8, 14, 22]. To

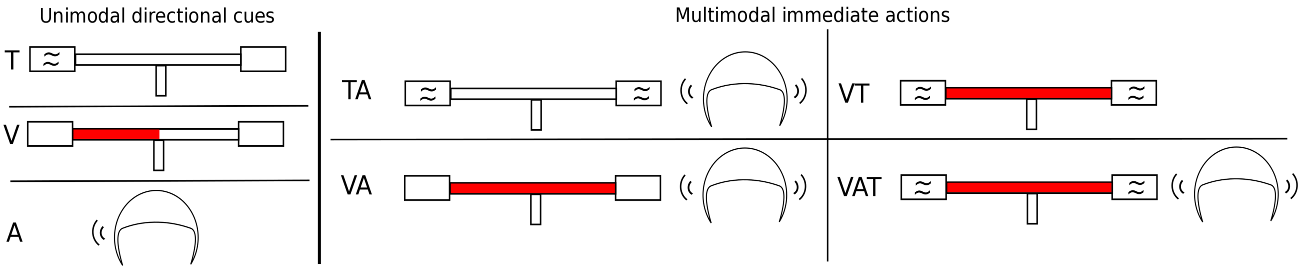


Figure 3: Overview of encodings for directional cues and immediate actions. Tactile and visual feedback were presented on the handlebar and auditory was integrated in the helmet. For example, the unimodal directional cue on the left a car approaching from that direction. V = visual, T = tactile, A = audio, TA = tactile + audio, VA = visual + audio, VT = visual + tactile, VAT = visual + audio + tactile.

depict these situations in the simulation, we utilize three unimodal encodings (visual, tactile, and auditory) for left and right directional cues.

However, in the situations with higher urgency [25] riders do not always have time to react to a directional cue. Instead, they have to react immediately, such as braking after perceiving an alert. We refer to such high urgency situations as requiring *immediate action*. In our exploratory study, we found that some multimodal feedback had a high recognition rate among child cyclists. To fully explore their effect on immediate action situations, we employ four multimodal encodings: three bimodal and one trimodal. We pair tactile (T), visual (V), and auditory (A) feedback for the bimodal signals and combine all three for trimodal. Previous work in the automotive domain have also shown that immediate action cues encoded multimodally have a hig recognition rate [33]. The summary of encodings for both directional cues and immediate actions are shown in Figure 3.

We created twelve experimental conditions that include all possible combinations for directional cues and immediate actions by combining all encodings. Additionally, we added a 13th condition without any warning signals as a baseline. The summary of all conditions is shown in Table 2.

#	Condition	Directional cue	Immediate action
1	T+VT	Tactile	Visual+Tactile
2	T+TA	Tactile	Tactile+Auditory
3	T+VA	Tactile	Visual+Auditory
4	T+VAT	Tactile	Visual+Auditory+Tactile
5	V+VT	Visual	Visual+Tactile
6	V+TA	Visual	Tactile+Auditory
7	V+VA	Visual	Visual+Auditory
8	V+VAT	Visual	Visual+Auditory+Tactile
9	A+VT	Auditory	Visual+Tactile
10	A+TA	Auditory	Tactile+Auditory
11	A+VA	Auditory	Visual+Auditory
12	A+VAT	Auditory	Visual+Auditory+Tactile
13	No signals	–	–

Table 2: Experimental conditions: For example, in the first condition a cyclist experiences a tactile feedback as a directional cue and visual+tactile feedback as an immediate action.

EXPERIMENT

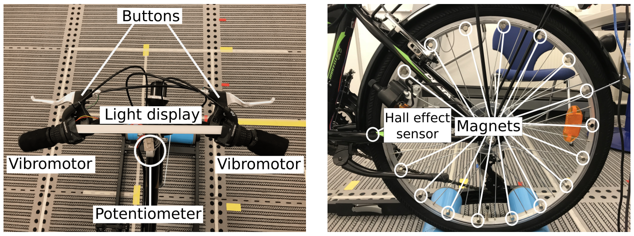
To investigate the efficacy of these unimodal and multimodal signals in the two most common car-to-cyclists collisions, we conducted a second experiment in the bicycle simulator.

Participants

We recruited 24 children (10 female) aged between six and thirteen years (M = 9.38, SD = 1.91) using social networks and personal contacts. Children typically had two to nine years of cycling experience (M = 5.75, SD = 1.82). All of them had no hearing problems and had normal or corrected vision without color blindness.

Apparatus

To create a more realistic cycling experience in comparison to the exploratory study, we extended the functionality of the bicycle simulator. We added a potentiometer on the handlebar to measure rotation angle, buttons to detect braking activities (Figure 4a), and multiple magnets on the rear wheel for a better estimation of speed (Figure 4b). Children could now turn left and right, which made their cycling experience more realistic.



(a)

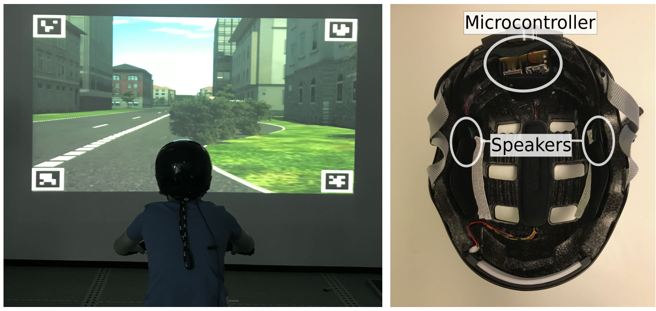
(b)

Figure 4: Bicycle simulator: (a) handlebar with visual and tactile feedback (b) rear wheel with hall effect sensor for measuring speed.

The light display on the handlebar and the vibration motors on left and right grips remained the same (Figure 4a). However, the saddle vibration was removed, since we did not explore any conditions where a car was approaching from behind. Similar to the exploratory study, each light, vibration, and auditory pattern consisted of three activations with the same intensity with a delay and duration of 500 ms. The vibromotors, light display, buttons, and potentiometer were directly connected to an Arduino Primo microcontroller, which communicated with virtual simulation via WiFi.

Helmet

Although children did not face any issues with the auditory feedback in the exploratory study, they perceived the computerized voice as frightening and highlighted issues with privacy and noise pollution. Consequently, we decided to move the auditory feedback to the helmet. We integrated two speakers in the left and right side of the helmet (Figure 5b). The speakers were connected to a NodeMCU 8266 board[10] with an integrated WiFi module and powered by a lithium ion (LiPo) battery. The microcontroller, battery, and MP3-player were integrated in the back of the helmet. Communication between the helmet and the simulation was accomplished via a WiFi connection.



(a) (b)

Figure 5: (a) A child is approaching a car hidden behind a bush in a SILAB-based bicycle simulator and (b) helmet with auditory warning signals.

Simulation

In order to create a more realistic simulation experience, we used SILAB driving simulator software[11]. While this simulation software is normally used for car simulators, we were able to customize it for our bicycle simulator (Figure 5a). We added a custom bicycle lane to the road and virtual cars to the simulation to model dangerous situations. The simulation consisted of one long street with a set of junctions, where a car would randomly appear either from left or right direction, or enter the road from a hidden street-parking spot behind the bushes.

Study Design

The study was designed to be within-subject with *type of warning signal* as the independent variable. The experiment consisted of thirteen experimental conditions (Table 2). Within these thirteen conditions, we explored two types of dangerous situations for cyclists on the road based on prior statistical reports [8, 14, 22]. The first type of situation was at junctions, where a car was approaching either from left or right, and children were notified via directional cues. If danger of collision remained, they were presented with a follow-up immediate action signal to prime braking. The second type of situation was on the road, where a car spontaneously left a parking spot hidden behind a bush. In this situation, since there was no time to present a directional cue for cyclists, they were presented with an immediate action signal and instructed to brake as soon as possible. Thus, every participant experienced six trials for each condition: three with a directional cue followed by an immediate action and three with immediate action only. All signals were presented before a car appeared on the road. In total, each participant experienced each directional cue encoding 12 times (3 times/condition x 4 conditions) and 18 times for each immediate action encoding (6 times/condition x 3 conditions). For the baseline condition without warning signals participants were asked to cycle carefully and avoid road hazards.

Each experimental condition took on average three minutes and the simulation portion of the study lasted approximately forty minutes per participant. The entire study was approved by the ethical review board at our university. Each child received €10 for participation.

Procedure

After obtaining informed consent, we collected children's demographic data. Afterwards we provided a brief overview of the procedures, which included explanations of directional cues and immediate action signals. Children familiarized themselves with all types of feedback during a test ride in the simulator. They started cycling when they felt comfortable.

Children' task was to cycle within the bicycle lane in the simulator, and react appropriately every time they perceived a warning signal. When they perceived a directional cue, they were free to choose whether to brake, slow down or continue cycling. When they perceived an immediate action signal, their task was to safely stop. At the end of the study, we interviewed the children about their preferences for the different warning signals. The entire study lasted approximately one hour.

Measures

To compare warning signals for child cyclists, we measured the following dependent variables:

Reaction time: for each immediate action signal, we measured the time between presentation of the signal and braking.

Duration and frequency of glances: for each condition, we measured focus using an eye gaze tracker and calculated the duration and frequency of off-road glances.

Number of accidents: we counted the number of occurrences a child virtually crashed into a car.

Understandability (Likert scale): for each (out of seven) encodings (Figure 3), every participant estimated the understandability of each signal.

Distraction (Likert scale): for each condition (Table 2), every participant estimated the distraction of each signal combination.

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[10] https://en.wikipedia.org/wiki/NodeMCU

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

We used Tobii Pro Glasses 2[12] to determine the children's eye gaze during the experiment. The glasses are light-weight and easy to calibrate with children. The eye tracker was calibrated with a standard procedure that comes with the eye tracker software. Each calibration took on average 10 seconds. These head-mounted glasses were used to detect the position of the eye gaze in the visual marker coordinate system. We used four virtual markers integrated into the simulation in front of the cyclist in order keep a permanent track of the participants' eye gaze. We used the standard eye tracker software to record two videos (from field and eye camera) per each trial for subsequent video analysis.

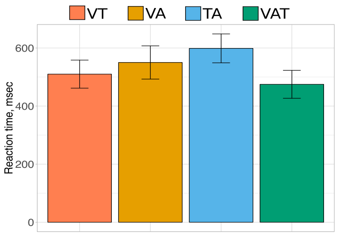
We hypothesized that the cyclist's reaction time for immediate action signals with trimodal encodings (Table 2: condition #4, #8 and #12) would be shorter than bimodal. We based this hypothesis on previous work by Politis et al. [33] that compared reaction times for various multimodal signals for car drivers. We also hypothesized that cyclists would spend more time perceiving visual warning signals. Finally, we hypothesized that children would consider non-visual encodings the least distractive for directional cues.

RESULTS

We found that children were safer cycling with warning signals than without them. With warning signals there were no accidents, whereas without them the accident rate was 13%.

Reaction Time

The encoding with three modalities had the shortest *reaction time* (M = 474.96, SD = 230.83), followed by the visual+tactile (M = 510.02, SD = 231.73), the visual+auditory (M = 550.16, SD = 274.39) and the tactile+auditory (M = 598.73, SD = 238.69) encodings (Figure 6a). However, we did not observe a significant difference among them ($\chi^2 = 4.3$, $p = 0.23$). As predicted, we found that reaction time for immediate action signals is shorter for trimodal encodings. Thus, child cyclists react faster on trimodal warning signals than on bimodal. Ideally, we would also measure the reaction time for a condition without warning signals. However, we found that most of the children were cycling unrealistically careful and braking at every junction before seeing a car.



(a)

Signals	Understandability	
	M	*SD*
V	4.19	1.14
T	4.57	0.73
A	4.57	0.8
VT	4.6	0.68
TA	4.65	0.68
VA	4.62	0.76
VAT	4.9	0.3

(b)

Figure 6: (a) Reaction times for immediate action encodings and (b) understandability for all signals (5 - very understandable).

Condition	Duration of glances, msec		Frequency of glances		Distraction	
	M	*SD*	*M*	*SD*	*M*	*SD*
T+VT	771	1476	0.7	1.4	1.39	0.66
T+TA	0	0	0	0	1.3	0.47
T+VA	564	909	0.5	0.8	1.2	0.52
T+VAT	901	1753	0.8	1.6	1.25	0.55
V+VT	2659	2876	2.1	2	1.94	1.18
V+TA	848	1010	1	1.3	1.72	0.96
V+VA	1825	3015	1.7	2.2	1.75	1.02
V+VAT	1651	3371	1.2	2.2	1.33	0.56
A+VT	488	1277	0.4	1.1	1.33	0.58
A+TA	0	0	0	0	1.55	0.89
A+VA	428	1311	0.4	1.1	1.6	0.88
A+VAT	575	1556	0.5	1.1	1.06	0.24

Table 3: Summary of descriptive statistics per condition. Baseline without signals received zero 'off-road' glances. V = visual, A = auditory, T = tactile. Likert Scale (5 - very distractive).

Duration and Frequency of Glances

We discovered that the *duration of glances* was on average longer (between 1.6 and 2.7 seconds) for conditions where two visual cues were presented rather than one (between 0.5 and 0.9 seconds). Additionally, we found that the *frequency of glances* was on average higher for conditions with two visual cues (between 1.2 and 2.1 times) than with one (between 0.4 and 0.8). We also observed a significant effect for encodings with two, one, and zero light signals for both *duration of glances* ($\chi^2 = 76.47$, $p < 0.001$) and *frequency of glances* ($\chi^2 = 72.84$, $p < 0.001$) using a Friedman test. Thus, as predicted, we found that children spent more time perceiving visual warning signals than tactile or auditory. Due to the large size of the table (12x12x3) for all pairwise comparisons, we present one example for conditions with two (V+VA), one (A+VA) and zero (A+TA) visual cues (Table 4) instead. All post-hoc analyses were conducted with a Bonferroni correction to avoid type I errors. The statistical tests were applied for data points from all participants per each condition, or separately for directional cues and immediate actions, where applicable.

	Duration of glances	Frequency of glances
A+TA **A+VA**	Z=-2.02 **p=.043**	Z=-2.06 **p=.039**
A+TA **V+VA**	Z=-2.93 **p=.003**	Z=-2.94 **p=.003**
A+VA **V+VA**	Z=-2.2 **p=.028**	Z=-2.06 **p=.04**

Table 4: Summary of the post-hoc Wilcoxon signed-rank tests for duration and frequency of glances for three selected conditions.

Understandability and Distraction

In general, all warning signals were understandable (mean > 4) and non-distractive (mean < 2). However, some signals were more understandable and less distractive than others.

Tactile (M = 4.57, SD = 0.73) and auditory (M = 4.57, SD = 0.8) encodings for directional cues were more understandable

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[12] https://www.tobiipro.com/product-listing/tobii-pro-glasses-2

than visual (M = 4.19, SD = 1.14) encodings, based on Likert scale results (Figure 6b). However, no significant differences were observed ($\chi^2 = 5.34$, p = 0.069). The trimodal encoding of immediate action was more understandable (M = 4.9, SD = 0.3) than the bimodal encodings: tactile+auditory (M = 4.65, SD = 0.68), visual+auditory (M = 4.62, SD = 0.76) and tactile+visual (M = 4.6, SD = 0.68). We also observed a significant difference between the trimodal and bimodal encodings using a Friedman test ($\chi^2 = 10.13$, p = 0.017). The encoding with three modalities was also statistically more understandable than tactile+auditory (Z = -2.75, p = 0.006), visual+auditory (Z = -2.512, p = 0.012) and tactile+visual (Z = -3.115, p = 0.002). However, there was no significant difference for bimodal encodings. In summary, the trimodal encoding performed better for understandability and reaction time.

As for the *distractiveness* of different conditions (5 - very distractive), we observed that conditions with more visual signals (e.g., V+VT and V+VA) were more distractive than others. This is in line with our eye gaze tracking data (Table 3). We also observed a significant difference for *distractiveness* using a Friedman test ($\chi^2 = 21.36$, p = 0.03). However, as mentioned above, we do not provide the full comparison matrix due to its size.

With respect to children's preferences for different encodings of directional cues, we found that children preferred visual cues the most (n=11), followed by auditory (n=8), and tactile (n=5). Children ranked the trimodal signal (VAT) as the most preferred for immediate action (n=16), followed by VT (n=4), TA (n=3), and VA (n=1). They argued that it was harder to miss an immediate stop action if all signals were presented simultaneously. Children cited that excessive brightness, noisy environments, or bumpy roads could prevent one from recognizing one of the modalities.

Problems and Preferences

During the post-study interview, 23 children mentioned that they found the warning signals helpful and could imagine having them on their own bicycle or helmet. None of participants reported any difficulties understanding or memorizing the warning signals. One child voiced that she had problems recognizing the direction of the car from the audio encodings: *"With beeping it was hard for me to say sometimes whether a car comes from left or right."* [P7] The rest of the particpants had no problems recognizing unimodal encodings for direction.

Most of participants (18 out of 24) reported that just using visual signals alone for directional cues was too distractive, because they had to explicitly look down at the handlebar; this is in line with our eye gaze tracking data. The other six children disclosed that although they could see the light from the handlebar in the periphery of their vision, they still looked down out of curiosity. As P22 remarked, *"Sometimes I was looking down at light, even though I could always see it and understand what it means."* Six children requested a stronger vibration signal to enhance perception. *"Sometimes I couldn't perceive the vibration as good as the other two signals"* [P19]. However, none of the children reported any problems recognizing directional cues from vibration. Most of participants (23, except for P7 – see above) mentioned no problems with audio signals. For example, P21 commented: *"With beeping one knows immediately – aha, something is going to happen soon."*

DISCUSSION

In general, children did not have any accidents when warning signals were present. Unimodal signals were the simplest and most easily recognized. Consequently, they have the most potential for encoding directional cues. This finding is in line with prior work in on-bicycle [30] and on-body [4] feedback tested with adults. Tactile feedback was a particularly useful modality for conveying spatial cues to child cyclists, which is also in line with previous work in the automotive domain [18]. Vibration on both sides of the handlebar and saddle allows us to unambiguously encode four different directions. Multimodal signals, especially trimodal encodings, were the most effective for immediate action representation. However, this depends on the combination of modalities and their locations.

"The more, the better"

When it comes to alerting children of immediate danger, multimodal encodings were the most effective. Not only did children prefer these encodings, but they also performed better in terms of reaction time. As one child stated, *"The more, the better. It decreases the chance of me missing the signal."* Although we did not find a statistically significant decrease in reaction time between bimodal and trimodal signals, the simultaneous activation of tactile, visual, and auditory feedback is an effective combination. It alerts the rider on all sensory fronts that a potential accident is about to occur. Moreover, even if a child misses one modality due to environmental conditions, such as excessive brightness, bumpy roads surfaces, or street noise, the other modalities are still present. This recommendation is in line with findings from the automotive domain by Politis et al. [33]. They found that visual combined with audio and tactile signals was promising in conveying urgency both quickly and accurately. Visual signals however played a crucial role in conveying urgency. Similarly, we found that children also reacted faster to encodings with visual cues (Figure 6a). This highlights the dominance of vision in perception studies. Vision is indeed special both psychologically and epistemically and dominates other senses such as audition and touch [44].

Visual Location Design

Therefore, the placement of visual feedback in a bicycle warning system needs to be carefully considered. In our implementation, conditions with more visual signals were typically more distractive (Table 3), suggesting that we should reconsider its design and location. Although children could see the light display on the handlebar peripherally, the eye gaze tracking data shows that they spent considerable time looking at the display explicitly. This was in part due to curiosity, but it could also be that they were attracted to the light itself. To prevent this distraction, it might be valuable to consider shifting the display to the helmet to facilitate peripheral processing. Prior work by Tseng et al. with scooter helmets highlights how such a system might work [45]. In their system, a lightweight LED strip is attached to the front edge of a scooter helmet to provide 1D cues for turn-by-turn navigation. They found that the helmet effectively guided scooter drivers without introducing visual distractions. A similar approach has also been investigated in ski helmets for preventing collisions from behind [27]. However, further research is required on how best to adapt these techniques for bike helmets since they typically tend to sit higher on the forehead, thereby limiting any peripheral vision advantages.

Additionally, future designers have to consider the duration of warnings patterns very carefully, given the reaction time of 500-600 ms. A delay and duration of a signal might be reduced to 100-200 ms to avoid lengthy signals of 2.5 seconds, which might distract children even more in the real world Since in reality a collision prevention will include the time to detect an event, present and process it, and lastly react to it. This might be especially challenging when combining warnings with other signals, for example, navigation.

Supporting Perceptual-Motor Learning

Our goal in this work was to design a bicycle warning system for child cyclists. This led to the development of a simulator with an augmented bike and helmet to test children in different accident scenarios. While running our studies however, we observed how children were naturally cautious while biking and anticipated potential issues. The simulator had become a learning environment in addition to an evaluation tool. Since children's motor and cognitive processing skills are still maturing, the simulator can serve as a multimodal feedback tool for perceptual-motor learning. There is some evidence to advocate that concurrent multimodal feedback can be useful for learning complex motor tasks [41]. As Sigrist et al. suggest, "in the early, attention-demanding learning phase, concurrent augmented feedback may help the novice to understand the new structure of the movement faster and prevent cognitive overload, which may accelerate the learning process" [41]. The bicycle simulator in this case, can support coordination, teach children to recognize traffic scenarios, and raise situational awareness.

Study Limitations

Undoubtedly, an obvious limitation for both studies is that children were cycling in a bicycle simulator. As a result, children did not encounter real-world traffic situations with the associated background noise, pedestrians, cyclists, weather conditions, and road infrastructure. More so, the bicycle simulator was sometimes perceived in a playful, game-like way. However, our aim was to conduct both experiments in a controlled, replicable, and safe manner.

The participants were instructed to use brakes when presented with immediate action signals to enable measuring the reaction time, but in reality accident avoidance involves a combination of steering and braking. When a car pulls out from a parking slot, braking and steering away from it places the cyclist further away from harm than braking in a straight path towards it. However, in the presence of the upcoming traffic the cyclist might face another car after changing a cycling trajectory. It would be interesting to explore these cycling strategies in real world conditions.

To mitigate some of these issues, we could introduce background noise in the simulator and more complex virtual traffic scenarios. Moreover, to simulate distraction and mental load we could add secondary tasks such as n-back [29] or external stimuli [5]. However, our aim is to uncover how efficient these signals are in real world traffic and environmental conditions, and how children's performance and perception would change with more external factors affecting their attention. Perhaps another approach would be to conduct future experiments in a restricted outside training area.

Given our sample size in both experiments and the cultural background of our participants, it would be hard to generalize our results to a larger population of children. However, our studies provided initial warning signals applicable for child cyclists. It would be interesting to evaluate our system and compare our results among children of different backgrounds.

CONCLUSION

In this paper we investigated unimodal and multimodal warning signals for child cyclists and their effectiveness in collision avoidance. From two simulator evaluations, we derived a set of on-bicycle and helmet locations for multimodal feedback applicable for warning representation. We showed that with the support of warnings child cyclists faced no accidents in the bicycle simulator. Additionally, we discovered that children spend more time perceiving visual than auditory or vibrotactile cues. We also found that unimodal encodings were applicable for directional cues and multimodal for immediate actions. Lastly, trimodal warnings performed better for understandability and lead to shorter reaction times.

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