NaviBike: Comparing Unimodal Navigation Cues for Child Cyclists

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ABSTRACT

Navigation systems for cyclists are commonly screen-based devices mounted on the handlebar which show map information. Typically, adult cyclists have to explicitly look down for directions. This can be distracting and challenging for children, given their developmental differences in motor and perceptual-motor abilities compared with adults. To address this issue, we designed different unimodal cues and explored their suitability for child cyclists through two experiments. In the first experiment, we developed an indoor bicycle simulator and compared auditory, light, and vibrotactile navigation cues. In the second experiment, we investigated these navigation cues in-situ in an outdoor practice test track using a mid-size tricycle. To simulate road distractions, children were given an additional auditory task in both experiments. We found that auditory navigational cues were the most understandable and the least prone to navigation errors. However, light and vibrotactile cues might be useful for educating younger child cyclists.

KEYWORDS

Navigation for child cyclists, bicycle simulator, unimodal navigation cues

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Figure 1: A mid-size tricycle and helmets equipped with auditory, light and vibrotactile navigational cues for investigation in an outdoor practice test track.

1 INTRODUCTION

Existing navigation systems for cyclists are typically small screen-based devices mounted in the center of a bicycle's handlebar[1]. These devices use a "stop-to-interact" paradigm, which requires the user's visual attention [20]. While adults may not experience problems using devices standing or on-the-go, child cyclists might find them distracting or difficult to use. This might be in part due to the children's development of motor and perceptual-motor skills, which transforms from early childhood to adolescence and highly influences the way children deal with situations on the road [4, 18]. Combined with undeveloped attentional skills of children

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[1] https://goo.gl/E9xjfY

aged from six to 13 [2, 10, 30], conventional navigation systems may be particularly difficult for children to use, especially in unfamiliar environments.

To assist cyclists on the road, researchers have previously augmented bicycle accessories with vibrotactile, light, and audio feedback. Some examples include an ambient helmet-based light display for route-guidance [31], a vibromotor belt for navigation [29], and projected maps on the road [9]. However, these systems were typically focused on adults and not on child cyclists. Therefore, it remains unclear how best to represent navigational cues for child cyclists in an understandable and non-distractive way.

In our work, we investigate how visual, auditory, and vibrotactile feedback integrated into a helmet and a bike can be used as navigational aids for children. We particularly focus on these different single modalities, because of their success with adult cyclists', particularly in increasing awareness and conveying instructions unobtrusively [21, 24, 25, 29]. We conducted two experiments to compare these three navigation modalities in a bicycle simulator and in an outdoor practice test track (Figure 1). To simulate cognitive load, we employed an auditory distraction task [33] in both experiments. We found that auditory navigation was the most preferred method in the presence of the distraction task in both lab and controlled test-track experiments. It was also the least prone for navigation mistakes. In this paper, we contribute an empirical evaluation of different unimodal navigation instructions for child cyclists.

2 RELATED WORK

Previous research has investigated the representation of navigational cues using visual, auditory and tactile displays and showed advantages and disadvantages for each of these feedback types. For example, in the automotive domain visual displays provide detailed information, but often distract drivers from the main task of driving and monitoring the road situation [16]. To supplement visual displays, auditory feedback is often used, but can be difficult to hear in noisy environments. Finally, tactile displays have a limited design space to represent detailed navigation information, even though they do not overwhelm visual or auditory channels. In this section, we focus on prior work that has examined different navigation methods for cyclists.

Vibrotactile navigation. Tactile feedback on a bicycle has been primarily used to convey navigational cues. For example, Tacticycle [24, 25] explored vibrotactile navigational cues on the handlebar for exploratory bicycle trips. Further empirical investigation by Bial et al. [3] has shown that the tactile signals on the hands can be recognized 87.4% of the time under the driving condition. Commercial products, such as SmartGrips[2], have leveraged this finding to represent turn-by-turn navigation for cyclists through vibrotactile grips. These handlebar grips vibrate on the side a cyclist is supposed to turn.

In addition to vibrotactile feedback on a bicycle, researchers have also explored on-body vibrotactile cues for navigation. Similarly to handlebar vibration, Steltenpohl and Bouwer [29], Tsukada et al. [32] and Ferscha et al. [12] have utilized a vibrotactile belt around a waist to convey eight directional cues. In particular, Steltenpohl and Bouwer [29] showed that their Vibrobelt was successful in guiding the cyclists though unfamiliar routes. However, cyclists were better at navigating using the visual system. They were also better at recalling the route and showed a higher contextual understanding. Since vibrotactile feedback was shown to be an effective method for conveying spatial information for adult cyclists, we aim to investigate its suitability for child cyclists.

Light-based navigation. Various commercial systems have explored on-bicycle visual navigation systems. For example, Smarthalo[3] utilized LEDs in a circular configuration on a bicycle's handlebar to encode direction and distance. Another product called Hammerhead[4] used directional LEDs in the middle of a handlebar to indicate turn-by-turn navigational signals. However, since both these systems are commercial products, they lack an empirical evaluation of their effectiveness.

Helmets are one of the most commonly used [15] cycling accessories and are also mandatory in many countries [19]. Researchers have used helmets to show visual information to riders. Tseng et al. [31] investigated a peripheral LED-based navigation system through an LED-strip on the front side of a helmet above the eyes. They showed that riders could use the system for navigation without introducing additional distractions. Since visual feedback above the cyclists' eye is independent of head movement and utilizes peripheral vision [31], we aim to investigate the suitability of such a visual navigation aid for child cyclists.

Auditory navigation. Auditory navigation has been widely used in car navigation systems, such as Garmin, TomTom and StreetMate. One of the main advantages of auditory navigation is the ability of a driver to focus on the road and receive navigation instructions via the auditory channel in addition to a visual display. For cyclists, auditory feedback has been typically used for pedalling training systems where cyclists have to maintain a constant speed for sport performance [23]. There are not many empirically tested systems exploring navigational cues via auditory feedback for child

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[2] http://smrtgrips.com/

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

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

cyclists. In our work, we explore how auditory cues integrated in a helmet can be used to facilitate navigation for child cyclists.

We are encouraged by recent work [21] that has shown the applicability of multimodal feedback to present warnings to avoid car-to-cyclists collisions, specifically for child cyclists. They found that multimodal feedback drastically reduced the number of accidents in the simulated environment. In our paper however, the overarching goal is to support child cyclists with a simple, non-distracting and understandable navigation system, using different unimodal signals.

3 LAB EXPERIMENT

We began our investigation in an indoor bicycle simulator. Based on previous works that explored navigation for motocycles [26] and cars [22], we used two turn phases: *prepare to turn* and *turn now*. For auditory navigation aid, we used speech-based messages commonly used by Garmin bicycle GPSs[5] and Google Maps. Specifically, we used the phrase *"Be ready to turn left/right next"* for the preparation signal and *"Turn left/right now"* for the turning signal. For visual navigation, we used a white flashing light on the left and right side of the helmet to indicate a preparation signal, and a green flashing light for a turn now signal. We used the location above the eyes to take advantage of the peripheral vision of cyclists [31]. We used white and green blinking patterns based on previous work [22], which has shown their distinguishability in the peripheral vision. Each light pattern (both preparation and turn now) consisted of three light flashes with a duration and delay of 500 ms. For the tactile navigation aid, we used slow vibration for preparation and fast vibration for turning. The vibration delays and durations for preparation and turning were a 1000 ms and 500 ms respectively. This was based on previous work in vibrotactile navigation for adult cyclists [24], which utilized similar patterns for vibration patterns. The preparation and turning signals were shown 50 meters and 10 meters before the turn respectively (Figure 2), based on the work of Steltenpohl and Bouwer [29].

Different external factors compete for a cyclist's attention while cycling in a natural traffic environment . One of the factors is related to the control of the cycling process, which includes pedaling, keeping the balance, and steering [1]. The second factor is related to road distraction and situational awareness. Therefore, in order to simulate real-world cycling conditions in the bicycle simulator, we introduced a secondary cognitive distraction task together with the primary task. We chose an auditory distraction task, applicable for children aged from six to thirteen [33]. The children had to react to a buzzing sound by pressing a button attached to the handlebar while cycling. The auditory distraction was presented at random intervals from 10 to 20 seconds and sometimes overlapped with navigation instructions. Although this could have conflicted with the auditory navigation instructions, it is reflective of real world circumstances where distractions (particularly auditory) can appear at any point in time. The goal was to estimate the level of distraction by measuring children's reaction time to the auditory load.

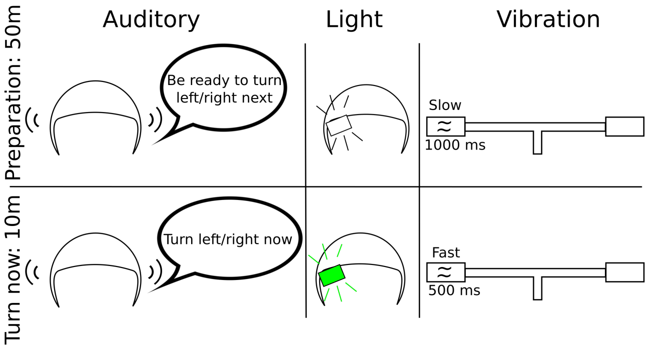

Figure 2: Overview of feedback encodings for navigation cues used in both lab and controlled test-track experiments. Children experienced speech and blinking light in the helmet, and vibration on the handlebar with "preparation" and "turn now" phases, presented at 50m and 10m before turning respectively.

Participants

We recruited 24 children (11 female) aged between six and thirteen (M = 9.5, SD = 1.74) years. They had between two to nine years of cycling experience (M = 5.71, SD = 1.94). None of the participants had any hearing impairments, and had normal or corrected vision without color blindness.

Apparatus

To create a realistic cycling experience in a safe environment with replicable conditions, we conducted the experiment in a bicycle simulator. We developed our own simulator, consisting of an off-the-shelf bicycle (24-inch) mounted on a fixed Tacx platform (Antares T1000). Cycling actions, such as pedalling, steering and braking, were reflected in the simulation environment projected on the wall in front of the bicycle. 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 a free rotation of the handlebar and allowed us to measure the rotation angle of turns. Buttons placed under the brake levers detected braking activities. A full stop was

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[5] https://goo.gl/E9xjfY

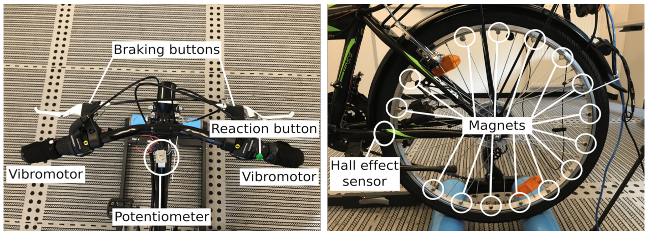


Figure 3: Bicycle simulator: handlebar with a vibrotactile feedback (left) and rear wheel with hall effect sensor and magnets for measuring speed (right).

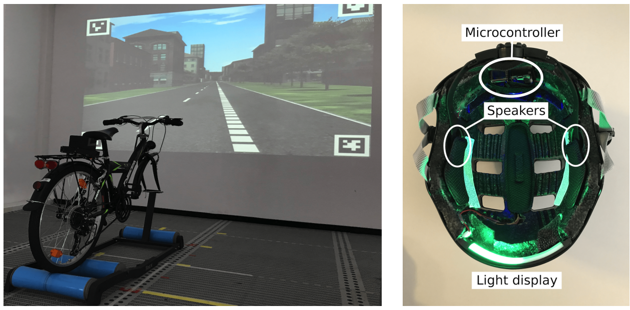
detected when the brake lever was pulled and released the button. Releasing the brake lever, pressed the button and resumed cycling (Figure 3). If pedalling is stopped, a bicycle continues its movement for the next couple of seconds, and brakes allow an immediate full stop.

We used SILAB simulation software[6] to create a virtual traffic environment. Although SILAB is normally used for car simulations, we customized it for our particular use case. The simulation consists of a set of city blocks with a dedicated bicycle lane, where the cyclist could turn left, right or continue going straight at every junction (Figure 4a).

Vibration motors on the left and right grips of the handlebar were used to represent the navigational cues. We also augmented a child's helmet with two speakers on the left and right sides close to the ears for auditory feedback. The helmet also contained visual feedback in the form of an LED strip above the eyes. The vibromotors, hall effect sensor, potentiometer and buttons were directly connected to an Arduino Primo microcontroller, which communicated with the simulation software via WiFi. Two speakers and a light display in the 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, battery and MP3-player were integrated in the back on the helmet. Communication between the simulation and the helmet was accomplished via a WiFi connection (Figure 4b).

For the auditory distraction task, we added a button on the right side of the handlebar (Figure 3) and a speaker mounted on a tripod behind the bicycle (Figure 5). Both the button and the speaker were connected to an Arduino Uno programmable board, which communicated with the simulation software via a USB-connection.

To determine the children's eye gaze during the experiment, we used Tobii Pro Glasses 2[7], which are light-weight and easy to calibrate, especially while working with children. Each calibration took on average 10 seconds. The 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 to 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 condition.



(a) (b)

Figure 4: (a) A SILAB-based bicycle simulator and (b) helmet with auditory and visual navigation cues. Green light on the left side of the helmet indicates a turn left.

Study Design

The study was designed to be within-subject with type of *navigation aid* as the independent variable. The experiment consisted of three experimental conditions, based on three modalities: *auditory*, *visual* and *tactile*. The order of the three conditions was randomized. We ensured to have a comparable ratio of participants per sequence of conditions, i.e., 7 participants started with speech, 10 – with light, and 7 – with vibration. Every participant cycled once with each navigation aid and experienced six trials per condition: three turns left and three turns right. The navigation cues appeared in random order for different conditions. Every experimental condition took on average five minutes per 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 of our university. Each child received €10 for participation.

Measures

To compare navigational aids for child cyclists, we measured the following dependent variables:

Reaction time: we measured the time between presentation of the auditory distraction and the button press, inline with previous work by Wierda and Brookhuis [33].

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

Error rate: we counted the number of mistakes a child made while following a navigational aid.

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

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

Response omissions: we counted the number of times children missed the auditory distraction.

Understandability (5-point Likert scale, 5 - most understandable): for each condition, every participant estimated the understandability of each navigation aid.

Demand (5-point Likert scale, 5 - most demanding): for each condition, every participant estimated the required mental load while cycling with a given navigational aid.

Procedure

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

Children's primary task was to cycle within the bicycle lane in the simulated virtual world and follow the navigational cues. The secondary task was to press the button on the right side of the handlebar as soon as possible upon hearing the auditory distraction from the rear speaker positioned behind them (Figure 5). After each condition, children were asked to estimate the understandability and the demand of navigational cues using a 5-point Likert scale. At the end of the study, we conducted a brief semi-structured interview about any issues they faced and their preferences for the different navigation aids. The entire study lasted approximately half an hour.

Results

Reaction time. We discovered that reaction times for the auditory distraction task remained consistent across different navigation cues. We did not observe a significant difference for *reaction time* among auditory navigation (M = 1178ms, SD 454 = 270), vibration (M = 1282ms, SD = 303) and light (M = 1283ms, SD = 357) in presence of the auditory distraction task (χ^2 = 1.65, p = 0.44) (Table 1).

Duration and frequency of glances. The eyegaze tracker did not provide any new information regarding children's focus. Based on eyetracker data, we found that children's eyes were always on the road and they were not distracted by the navigation signals.

Error rate. We found that participants were making less mistakes following the navigation cues using speech (4.9%) than vibration (11.8%) or light (20.8%). We also observed a significant difference for the error rate using a Friedman test (χ^2 = 6.39, p = 0.041). However, we found a statistical difference in error rate only between auditory and light-based navigation methods (Z = -2.77, p < 0.01).

	RT, ms	**Error rate, %**	**Response omissions, %**	**Understandability**		**Demand**	
				M	*SD*	*M*	*SD*
Speech	1178	4.9	19.2	4.79	0.41	1.67	1.01
Light	1283	20.8	19.2	3.3	1.06	2.52	1.27
Vibration	1282	11.8	21.7	3.87	1.1	2.08	1.02

Table 1: Summary of results for the lab study. RT = reaction time.

Response omissions. The percentage of missed signals from the auditory distraction task was similar among all navigation methods: auditory (19.2%), light (19.2%), and vibration (21.72%). Child cyclists tended to miss one out of five auditory distraction signals while following the navigation aid independent of modality. This is in-line with prior work by Wierda and Brookhuis [33], who also showed a 20% error rate for auditory distraction task.

Understandability and Demand. Children found auditory navigation the most understandable (Md = 5, IQR = 0), followed by vibration (Md = 4, IQR = 2) and light (Md = 3, IQR = 1.5), based on the Likert scale results. We also observed a significant effect for *understandability* using a Friedman test (χ^2 = 19.32, p < 0.01). Auditory navigation was perceived significantly more understandable than vibration (Z = -2.96, p < 0.01) and light (Z = -3.7, p < 0.01). However, we did not observe a significant effect between vibration and light navigation (Z = -1.17, p = 0.24). All post-hoc analyses were conducted with a Bonferroni correction to avoid type I errors.

As for *demand*, we did not find a significant difference among auditory (Md = 1, IQR = 1), vibration (Md = 2, IQR = 2) and light (Md = 3, IQR = 2) navigation using a Friedman test (χ^2 = 3.76, p = 0.15).

Problems and Preferences. During the post-study interview, all children mentioned that they found the navigation instructions useful and helpful, and would need them when cycling in unfamiliar places. With respect to the children's preferences for navigation methods, we found that children preferred auditory navigation the most (n=14), followed by vibration (n=7) and light (n=3). For example, children often referred to car navigation devices used by their parents. "*With speech I could easily cycle as with a navigation in my parents' car*" [P15]. Moreover, with the auditory navigation two (out of 24) children used hand signals while cycling to indicate their traffic intentions, even though it was not their task during the experiment. These two children mentioned that the auditory navigation freed their hands for hand signals, unlike vibration. Sometimes children found it difficult to explain, why they preferred one navigation method over another, since both auditory and vibration navigation were easy to use. For example, P2 mentioned: “*Speech was good, but I find vibration more precise.*” The only problem twelve (out of 24) children experienced was the recognition of direction with the light-based implementation. They could always see the light peripherally (e.g., color and blinking), but had difficulties determining whether it was left or right. As P20 remarked, “*Light was clear and understandable. I couldn’t just see it always well, whether it was left or right*”. None of participants reported any problems understanding or memorizing the navigation signals.

Discussion

Although there was no significant effect in reaction time between the three modalities, children made the fewest mistakes with auditory navigation and perceived it as the most understandable and the least demanding. As P15 mentioned, this may be in part due to children’s experience with GPS navigation systems in their parents’ car. Moreover, they may be used to direct speech commands from their parents while cycling together. Future auditory navigation systems for children might include parental voices due to their familiarity and increased trust [7, 8].

Vibration-based navigation cues can be seen as a supplementary navigation method to speech, due to a low number of navigation errors (<12%) and its high understandability. Although this is in line with findings for adult cyclists [24], the placement of the vibrotactile cues would be better served on the body, especially since children have to show hand signals while cycling [13]. However, this would mean one extra safety gear to be worn by children. While there has been previous work in detecting hand gestures while cycling [9], hand signalling reminder systems need further exploration. We can also use the preparation navigation signal from our implementation to serve as a reminder for children to show hand signals.

Children had the most problems with light-based navigation as evidenced by a higher number of navigational errors. This may be due to increased mental and cognitive load. They reported that the light cues were visible and understandable, but the location of the light was difficult to distinguish. Therefore, we might need to reconsider the location of visual signals to ensure unambiguous direction recognition, e.g., use LEDs further away from the center or integrate them into the sides of a helmet’s visor. Light can be also used as a supplementary navigation aid to speech in noisy environments.

As the eyegaze tracking analysis showed, the navigation instructions did not distract children from cycling, even in the presence of these different feedback modalities. It seems like children could fully dedicate their time to the dual task of motor and perceptual activities [27, 33]. This could be because children perceived the simulated environment as a game, and it was a lab environment with not many environmental distractions. However, this finding should be further investigated in the real-world conditions.

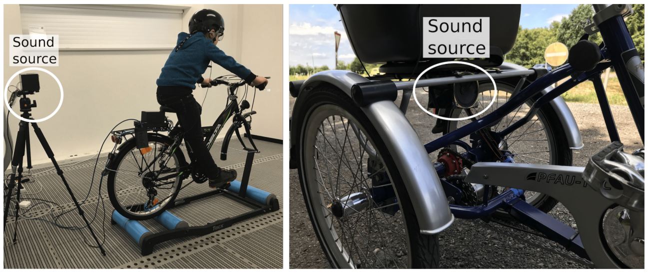

Figure 5: Setup for the auditory distraction task used in the lab (left) and controlled test-track (right) experiments. The sound source in the lab study was mounted on a tripod behind the bicycle. In the test-track study the sound source was mounted on the frame of the bike behind the seat.

We confirmed the applicability of the auditory distraction task [33] for child cyclists with ~20% omissions for all navigation methods. Unlike a working memory task, which did not provide a direct influence on situational awareness for child cyclists [17], the auditory distraction task led to a considerable number of signal omissions. However, given the differences of temperament, motor and perceptual-motor development of children in the tested age group, we observed that overly active children tended to miss external signals more often due to the lack of attention [10, 30]. This observation underlines the challenge of designing a “one-size-fits-all” assistance system for child cyclists, given the wide age range.

4 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 would not have been 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. Moreover, we had to use a tricycle instead of a regular bicycle to address any safety concerns due to balance and coordination issues based on recommendations from the IRB. Although not ideal, children still had to ride on a regular paved road, steer and maneuver the bicycle at intersections, and experience multisensory perception of the environment.

Participants

We recruited 20 children (8 female) aged between six and twelve (M = 8.95, SD = 1.67) years. Nine of them had also

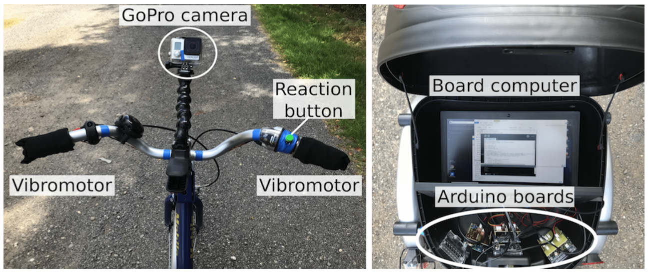

Figure 6: A tricycle equipped with a laptop in the rear cargo box, vibrtotacile feedback on the handlebar, a GoPro camera for in-field observations and a reaction button for the auditory distraction task.

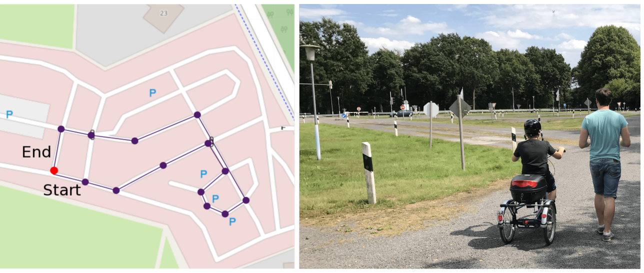

Figure 7: An outdoor practice test track: a schematic example of one route participants cycled on the test track (left) and a real-world overview of the test track with a participant and an experimenter (right).

participated in the previous lab experiment (which happened six months prior). Children had between three to nine years of cycling experience (M = 4.85, SD = 1.79). None of the participants had any hearing impairments, and had normal or corrected vision without color blindness.

Apparatus

For this evaluation, we used a mid-size tricycle to prevent falls. To represent the navigational 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 helmet from the lab experiment to represent speech-based instructions (Figure 6). In the previous experiment, children had problems with the light-based navigation due to the location of the LEDs above their eyes. Therefore in this experiment, we used a helmet with a visor and integrated the LED strips on the sides of the visor (Figure 8). The LED strips were directly connected to a NodeMCU 8266 and powered by a lithium ion (LiPo) battery.

We used a laptop placed into the rear cargo box of the tricycle as a WiFi hotspot, a data logger and a power supply. The vibromotors were directly connected to an Arduino Uno microcontroller, which were activated via an Android application on a tablet via WiFi communication. The navigation instructions for the helmet were activated by the experimenter using an Android application.

For the auditory distraction task, we connected a button placed on the right side of the handlebar and a speaker under the rear cargo box of the tricycle (Figure 5). We used a Processing script running on the laptop to log reaction times. All Arduino boards in the rear cargo box of the tricycle were connected to the laptop via USB cables. To observe the behavior and focus of the participants, we placed a GoPro camera in the middle of the handlebar facing a cyclist (Figure 6).

Study Design

We used the same study design as in the lab experiment with every child cycling with the same three types of navigation assistance. The only change was concerning the auditory distraction task, where we added a second level with more frequent beeps. Thus, participants had to cycle two times with each navigation aid: once with a frequent (at random intervals between 5 to 10 seconds) and once with an infrequent (at random intervals between 10 to 15 seconds) occurrence of a beeping sound. We added a frequent auditory distraction level, because we found children capable of reacting to the distraction task without being overwhelmed in the lab experiment. The frequent auditory distaction level corresponds to the original intervals used in the experiment by Wierda and Brookhuis [33] and the infrequent – to the time intervals used in the lab experiment. Thus, with this study design we could observe the performance of child cyclists under two levels of mental load: high (frequent beeping) and low (infrequent beeping). Similarly to the lab experiment, the auditory distraction was overlapping with navigation instructions to increase ecological validity.

We conducted the field experiment in an outdoor practice test track, normally used as a training facility by novice car drivers. The test track consists of a network of gravel roads with intersections, old stationary parked cars, traffic signs and lights (Figure 7). For safety reasons, no other traffic (except for parked cars) were presented during the experiment.

The order of all six conditions was randomized. For every participant, we ensured a unique order of all six conditions. To activate the navigation signals, the experimenter was walking behind a participant. For preparation signal, the experimenter activated the navigation cue at ten meters, and for the turn now signal – at two meters. Every participant cycled six random routes and experienced from six to eight turns per trial (Figure 7). The experiment was conducted over the course of thirteen days: four of the days were cloudy and other nine were sunny. Every experimental condition took on

Figure 8: LED helmet with LED strips integrated into the visor for the light navigation in the test-track study.

average five minutes per participant and it took on average 40 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.

Measures

To compare navigational aids for child cyclists in the training area, we measured the following dependent variables:

Reaction time (in ms): for each condition, we measured the time between presentation of the auditory distraction and a button press.

Error rate: for each modality, we counted the number of errors a child made while following a navigation aid, i.e., when they made a turn at the wrong place.

Understandability (5-point Likert scale, 5 – most understandable): for each modality, every participant estimated the understandability of each navigation aid.

Demand (5-point Likert scale, 5 – most demanding): for each modality, every participant estimated the required mental load while cycling with a given navigation aid.

Procedure

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

Children's primary task was to cycle and follow the navigational cues. The secondary task was to press the button on the right side of the handlebar as soon as possible, when they heard the auditory distraction from the speaker. At the end of the study, we asked children to estimate the understandability and the demand of navigation cues using a 5-point Likert scale, and interviewed them about their preferences for navigation aids. The entire study lasted approximately one hour.

	RT, ms		**ER**	**Understand.**		**Demand**	
	Infreq.	Freq.	%	*M*	*SD*	*M*	*SD*
Speech	1235	1513	2.5	4.5	0.61	1.85	0.88
Light	1286	1291	5.83	3.85	0.93	2.25	1.07
Vibration	1440	1256	3.33	3.8	0.95	2.75	1.29

Table 2: Summary of results for the test-track study. Infreq. = infrequent beeping, Freq. = frequent beeping, RT = reaction time, ER = error rate.

Results

Reaction time. We discovered that reaction times for both *infrequent* (auditory (M = 1235ms, SD = 438), light (M = 1286ms, SD = 498) and vibration (M = 1440ms, SD = 902)) and *frequent* (auditory (M = 1513ms, SD = 986), light (M = 1291ms, SD = 529) and vibration (M = 1256ms, SD = 577)) distraction task remained consistent across different navigation cues. There was no statistically significant interaction between the effects of distraction level and navigation methods on reaction time (F (2, 14) = 0.15, p = 0.86). We did not observe a statistically significant main effects of the *distraction level* (F(1,7) = 0.18, p = 0.69) and *navigation methods* (F(2,14) = 1.09, p = 0.36) on the reaction time using a two-way repeated-measures ANOVA. In relation to the results from the lab experiment, the reaction times for infrequent distraction in the test-track study were greater by 57 ms for auditory, 3 ms for light and 158 ms for vibration (Figure 9).

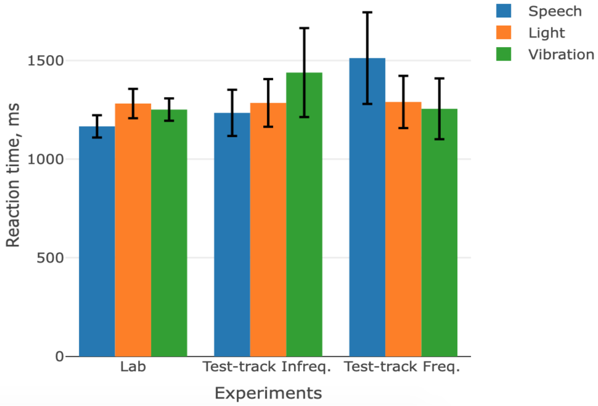

Figure 9: Summary of reaction times in lab and controlled test-track experiments.

Error rate. We found that participants made less navigation errors in the controlled test-track experiment than in the lab study; the error rate was under 6% for all modalities: auditory – 2.5%, light – 5.83%, vibration – 3.33%. However, we did not observe a significant difference for the error rate using a Friedman test (χ^2 = 1.14, p = 0.57). Only one child had problems distinguishing between left and right, and therefore made navigation errors with speech. The navigation errors with light was often caused by the brightness of the sun, which required more focus on the helmet. *"I had to concentrate a bit more on the light to see it."* [P14, 9 years old]. However, we did not face any issues with direction recognition using light navigation, as we did in the lab experiment. Six children made errors using vibrotactile cues, because they had problems distinguishing slow and fast vibration. *"The vibration patterns were a bit more difficult and demanding to distinguish than other signals."* [P14, 9 years old].

Understandability and Demand. Similar to the lab experiment, auditory navigation was the most understandable (Md = 5, IQR = 1), based on the Likert scale results, followed by vibration (Md = 4, IQR = 1.25) and light (Md = 4, IQR = 2). We also observed a significant effect for *understandability* using a Friedman test (χ^2 = 9.76, p < 0.01). Auditory navigation was perceived significantly more understandable than light (Z = -2.54, p = 0.011) and vibration (Z = -2.72, p < 0.007). However, we did not observe a significant effect between vibration and light (Z = -0.74, p = 0.46).

As for *demand*, we found that auditory (Md = 2, IQR = 1) and light (Md = 2, IQR = 1.25) navigation were the least demanding, followed by vibration (Md = 3, IQR = 1.5). A lower demand value for the light cues was most likely due to a better implementation of the LED strips in the visor helmet. We also found a significant difference among the three modalities using a Friedman test (χ^2 = 7.5, p = 0.024). Auditory navigation was perceived significantly less demanding than vibration (Z = -2.52, p = 0.012). However, we did not observe a significant effect between light and other two cues (vibration: Z = -1.47, p = 0.14, speech: Z = -1.66, p = 0.096).

Problems and Preferences. We found that children preferred auditory navigation the most (n=13), because it was clear, exact and mentally non-demanding, which is inline with our results from the lab experiment. As our participants mentioned: *"Speech gives exact instructions and tells you exactly, what you have to do."* [P1, 12 years old]. *"I can cycle better and I don't have to look away. It was always good to hear."* [P5, 7 years old]. None of the children reported any problems with hearing the speech-based instructions.

Children who preferred light-based navigation (N=4) and vibration-based instructions (N=3) were under the age of nine and mentioned that the light was easy to see and faster than other options. *"I've seen the instructions faster than with other signals."* [P15, 9 years old]. *"I could always see it very well and knew exactly, where I had to turn left or right."* [P13, 9 years old]. Another child mentioned that it was easy for her to follow the vibration cues and she did not have to wear a helmet, which is why she liked it the most. *"It was simple for me. I knew exactly where I had to go."* [P18, 7 years old]. As previously observed in the lab experiment, one child was again showing hand signals during the cycling with all three navigation systems.

However, children faced some difficulties with the different cues. Two children reported that sometimes with the auditory navigation they had to pay more attention, because the instructions were presented slower in comparison to other methods. *"One has to pay little more attention to it [speech]."* [P2, 9 years old]. *"[Speech] instructions were not as fast as with the light."* [P15, 9 years old]. One child mentioned that she confuses left and right sometimes: *" I don't distinguish left and right very well. I confuse them time after time."* [P18, 7 years old].

Other two children mentioned the problem of cycling during the bright day using a light-based navigation. *"In the sun it was sometimes hard to see [the light]."* [P8, 11 years old]. Two children found the blinking LED strips distracting. *"In the sun it was sometimes hard to see. But it was very clear to see the green light, where I had to turn."* [P8, 11 years old]. *"It was very distracting. When you cycle in the street, everything is blinking, for example, a police car, and it can be too much."* [P19, 12 years old]. Five children suggested to shift the lights to the front of the visor to increase the visibility of the lights. *"I would shift it [light] closer to the front."* [P3, 8 years old].

The biggest problem with the vibration was distinguishing slow and fast patterns. However, none of the children reported that they did not feel the vibration signal while cycling. *"I had problems sometimes to distinguish between fast and slow vibration, but I felt everything."* [P4, 11 years old].

5 DISCUSSION

In general, children could use auditory-, light- and vibration-based navigation instructions in both lab and test-track experiments. While the auditory navigation was the most preferred, light- and vibration-based navigation cues were positively perceived in both experiments and can be used as supplementary navigation aids for younger children.

Navigation systems need to grow with children. As alluded to earlier, the results from our experiments accentuate the challenge of designing a "one-size-fits-all" navigation system for child cyclists, given the wide age range and rapid development of motor and perceptual-motor skills between six and thirteen years old [5]. We focused on this age range (6-13 years), because in many cycling-friendly countries children start cycling alone at the age of 6 and experience significant difficulties. In fact, recent accident reports show that child cyclists in this age range (6-13 years) suffered the most road related injuries of any age group [6, 11].

Given the developmental differences, we suggest multimodal (i.e., multiple unimodal) navigation cues for younger children and speech for older. This would help the one seven year old, who had trouble distinguishing between left and right, which caused navigation errors with speech in our evaluation. In this case, simultaneous activation of light and auditory cues might prove to be more useful. This solution might be temporary, until a child feels confident in distinguishing between left and right. Moreover, since the reaction time increased with auditory navigation in presence of the frequent distraction task, multimodal navigation might be useful in demanding and noisy environments. The reaction times to multimodal warnings in previous work [21] were almost two times shorter, because children cycled without external distraction and reacted only to the signals. This differs from the two studies presented in this paper, where reaction time was higher, because children faced both the auditory distraction task and navigation signals simultaneously.

LED helmet design. The helmet, used in the lab study, had a design flaw in the placement of the LEDs. We were able to clearly distinguish between left and right when developing the prototype, but, unfortunately, children were not. This was due to the positioning of the LEDs, which required children to shift their gaze, instead of using their peripheral vision. The helmet's design flaw was fixed in the subsequent test-track trial with the aid of a visor, which allowed the LEDs to be recognized peripherally without directional ambiguity. While the visor-based helmet may have made a difference in the lab study, we found that in the test-track trial, when both light and audio were working, children still preferred audio-based feedback. We suspect that a similar outcome would have resulted from the lab study.

Educating child cyclists. Looking over the shoulder and perfoming hand signals are an essential part of safe manoeuvring while navigating on the road [13]. Even though these safety manoeuvres were not a part of the experiments, some of our participants (N=3) naturally showed hand signals before making a turn. However, most of the children still need to be educated and reminded about the right sequence of actions before performing a turn, namely looking over the shoulder, showing hand signals, turning. In this case, multimodal feedback might play a helpful role. For example, vibration on the handlebar can be coupled with the auditory navigation in the helmet to remind children about showing a hand signal with a hand from the corresponding vibrating grip. This solution can be used to educate children on the correct road traffic behaviors, when cycling. Coupled with previous work, which can detect cyclists' head movement [14] and hand gesture [9], we can remind children to perform the safety manoeuvres with vibration on the handlebar or on the wrist.

Employing off-the-shelf navigation systems. Existing solutions for cyclists, such as Garmin bicycle GPSs and Google maps, already provide speech-based navigation cues. Typically, cyclists place such devices in the middle of the handlebar [24, 25], keep a smartphone in a pocket, or use ear buds to listen to navigation instructions. Placing navigation devices on the handlebar or in a pocket might reduce the chance of hearing the navigation instructions, especially in noisy environments. However, wearing earbuds might prevent hearing other environmental sounds important for safe cycling [28]. Moreover, it is also restricted or prohibited in some US states. Thus, placing speakers in a helmet coupled with these technologies may be a viable option. As a result, off-the-shelf solutions can be leveraged without creating too much custom hardware and software systems.

6 LIMITATIONS

Given the sample size and cultural background of the participants, it is hard to generalize our results to a wider group of children. However, with these findings we provide the first empirical evaluation of unimodal navigation cues for child cyclists in the presence of an external distraction. Additionally, we conducted the test-track study during the summer, which might have influenced how quickly children finished the experiment. Also, since we conducted the test-track experiment on a mid-size tricycle, we were not able to fully explore coordination and balance issues children may have faced. However, this was unavoidable, since we wanted to create safe conditions for cycling.

7 CONCLUSION

In this paper, we investigated different unimodal signals for child cyclists and their effectiveness for navigation. From our lab and test-track experiments, we found that the auditory navigation performs the best in the presence of the auditory distraction task. Additionally, we propose that combination of light and auditory signals might be useful for children of younger age to distinguish between left and right. We also found that the vibration feedback coupled with the speech navigation instructions might be used as a reminder to show hand signals before performing a turn. Lastly, off-the-shelf solutions, such as Garmin bicycle GPSs and Google Maps, might be potentially used by children, if the speakers are placed in the helmet and keep the ears open.

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REFERENCES

[1] PW Arnberg, E Ohlsson, A Westerberg, and CA Ostrom. *The ability of preschool and school children to manoeuvre their bicycles. Linkoping: National Road and Traffic Research Institute, 1978.* Technical Report. Report.

[2] Benjamin K Barton and Barbara A Morrongiello. 2011. Examining the impact of traffic environment and executive functioning on children's pedestrian behaviors. *Developmental psychology* 47, 1 (2011), 182. https://doi.org/doi:10.1037/a0021308

[3] Dominik Bial, Dagmar Kern, Florian Alt, and Albrecht Schmidt. 2011. Enhancing outdoor navigation systems through vibrotactile feedback. In *CHI'11 Extended Abstracts on Human Factors in Computing Systems*. ACM, 1273–1278. https://doi.org/10.1145/1979742.1979760

[4] Valdimar Briem, Karl Radeborg, Ilkka Salo, and Hans Bengtsson. 2004. Developmental aspects of children's behavior and safety while cycling. *Journal of pediatric psychology* 29, 5 (2004), 369–377. https://doi.org/10.1093/jpepsy/jsh040

[5] Karin C Brocki and Gunilla Bohlin. 2004. Executive functions in children aged 6 to 13: A dimensional and developmental study. *Developmental neuropsychology* 26, 2 (2004), 571–593.

[6] European Commission. 2016. Proactive Safety for Pedestrians and Cyclists: Accident Analysis, Naturalistic Observations and Project Implications. (2016). http://www.prospect-project.eu/

[7] Benjamin R. Cowan, Derek Gannon, Jenny Walsh, Justin Kinneen, Eanna O'Keefe, and Linxin Xie. 2016. Towards Understanding How Speech Output Affects Navigation System Credibility. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, New York, NY, USA, 2805–2812. https://doi.org/10.1145/2851581.2892469

[8] Nils Dahlbäck, QianYing Wang, Clifford Nass, and Jenny Alwin. 2007. Similarity is More Important Than Expertise: Accent Effects in Speech Interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '07)*. ACM, New York, NY, USA, 1553–1556. https://doi.org/10.1145/1240624.1240859

[9] Alexandru Dancu, Velko Vechev, Adviye Ayça Ünlüer, Simon Nilson, Oscar Nygren, Simon Eliasson, Jean-Elie Barjonet, Joe Marshall, and Morten Fjeld. 2015. Gesture bike: examining projection surfaces and turn signal systems for urban cycling. In *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces*. ACM, 151–159. https://doi.org/10.1145/2817721.2817748

[10] Matthew WG Dye and Daphne Bavelier. 2010. Differential development of visual attention skills in school-age children. *Vision research* 50, 4 (2010), 452–459. https://doi.org/10.1016/j.visres.2009.10.010

[11] Jenny Ellis. 2014. *Bicycle safety education for children from a developmental and learning perspective.* Technical Report. https://doi.org/10.13140/2.1.5050.8801

[12] Alois Ferscha, Bernadette Emsenhuber, Andreas Riener, Clemens Holzmann, Manfred Hechinger, and Dominik Hochreiter. 2008. Vibrotactile space-awareness. (2008).

[13] United Nations Economic Commission for Europe (UNECE). 1968. Vienna convention on road traffic (with amendment 1), article 14, paragraph 3. (1968).

[14] Eric M Jones, Ted Selker, and Hyemin Chung. 2007. What you said about where you shook your head: a hands-free implementation of a location-based notification system. In *CHI'07 Extended Abstracts on Human Factors in Computing Systems*. ACM, 2477–2482.

[15] Subramaniam Kulanthayan, RS Radin Umar, H Ahmad Hariza, MT Mohd Nasir, S Harwant, et al. 2000. Compliance of proper safety helmet usage in motorcyclists. *Medical Journal of Malaysia* 55, 1 (2000), 40–44.

[16] Andrew L. Kun, Tim Paek, Željko Medenica, Nemanja Memarović, and Oskar Palinko. 2009. Glancing at Personal Navigation Devices Can Affect Driving: Experimental Results and Design Implications. In *Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '09)*. ACM, New York, NY, USA, 129–136. https://doi.org/10.1145/1620509.1620534

[17] Esko Lehtonen, Jasmiina Airaksinen, Kaisa Kanerva, Anna Rissanen, Riikka Ränninranta, and Veera Åberg. 2017. Game-based situation awareness training for child and adult cyclists. *Royal Society open science* 4, 3 (2017), 160823. https://doi.org/10.1098/rsos.160823

[18] Zeuwts Linus, Ducheyne Fabian, Vansteenkiste Pieter, D'Hondt Eva, Cardon Greet, and Lenoir Matthieu. 2015. Associations between cycling skill, general motor competence and body mass index in 9-year-old children. *Ergonomics* 58, 1 (2015), 160–171. https://doi.org/10.1080/00140139.2014.961971

[19] Alison K Macpherson, Patricia C Parkin, and TM To. 2001. Mandatory helmet legislation and children's exposure to cycling. *Injury Prevention* 7, 3 (2001), 228–230.

[20] Joe Marshall and Paul Tennent. 2013. Mobile interaction does not exist. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*. ACM, 2069–2078.

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

[22] Andrii Matviienko, Andreas Löcken, Abdallah El Ali, Wilko Heuten, and Susanne Boll. 2016. NaviLight: investigating ambient light displays for turn-by-turn navigation in cars. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*. ACM, 283–294. https://doi.org/10.1145/2935334.2935359

[23] Ryo Okugawa, Kazuya Murao, Tsutomu Terada, and Masahiko Tsukamoto. 2015. Training system of bicycle pedaling using auditory feedback. In *Proceedings of the 12th International Conference on Advances in Computer Entertainment Technology*. ACM, 17. https://doi.org/10.1145/2832932.2832972

[24] Martin Pielot, Benjamin Poppinga, Wilko Heuten, and Susanne Boll. 2012. Tacticycle: supporting exploratory bicycle trips. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*. ACM, 369–378. https://doi.org/10.1145/2371574.2371631

[25] Benjamin Poppinga, Martin Pielot, and Susanne Boll. 2009. Tacticycle: a tactile display for supporting tourists on a bicycle trip. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services*. ACM, 41. https://doi.org/10.1145/1613858.1613911

[26] Manoj Prasad, Paul Taele, Daniel Goldberg, and Tracy A Hammond. 2014. Haptimoto: Turn-by-turn haptic route guidance interface for motorcyclists. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 3597–3606.

[27] Sabine Schaefer, Ralf Th Krampe, Ulman Lindenberger, and Paul B Baltes. 2008. Age differences between children and young adults in the dynamics of dual-task prioritization: Body (balance) versus mind (memory). *Developmental Psychology* 44, 3 (2008), 747. https://doi.org/10.1037/0012-1649.44.3.747

[28] Agnieszka Stelling-Kończak, Marjan Hagenzieker, and Bert Van Wee. 2015. Traffic sounds and cycling safety: The use of electronic devices by cyclists and the quietness of hybrid and electric cars. *Transport Reviews* 35, 4 (2015), 422–444.

[29] Haska Steltenpohl and Anders Bouwer. 2013. Vibrobelt: tactile navigation support for cyclists. In *Proceedings of the 2013 international*

conference on Intelligent user interfaces. ACM, 417–426. https://doi.org/10.1145/2449396.2449450

[30] Lana M Trick, Fern Jaspers-Fayer, and Naina Sethi. 2005. Multiple-object tracking in children: The "Catch the Spies" task. *Cognitive Development* 20, 3 (2005), 373–387. https://doi.org/10.1016/j.cogdev.2005.05.009

[31] Hung-Yu Tseng, Rong-Hao Liang, Liwei Chan, and Bing-Yu Chen. 2015. LEaD: Utilizing light movement as peripheral visual guidance for scooter navigation. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services*. ACM, 323–326. https://doi.org/10.1145/2785830.2785831

[32] Koji Tsukada and Michiaki Yasumura. 2004. Activebelt: Belt-type wearable tactile display for directional navigation. In *International Conference on Ubiquitous Computing*. Springer, 384–399. https://doi.org/10.1007/978-3-540-30119-6_23

[33] M Wierda and Karel A Brookhuis. 1991. Analysis of cycling skill: A cognitive approach. *Applied Cognitive Psychology* 5, 2 (1991), 113–122. https://doi.org/10.1002/acp.2350050205