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Designing Multimodal Assistance Systems for Child Cyclists

Dissertation zur Erlangung des Grades eines
Doktors der Ingenieurswissenschaften

vorgelegt von

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Tag der Disputation: 12.12.2019

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Oldenburg, den 29. August 2019

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Zusammenfassung

Das Erlernen des Fahrradfahrens ist in vielen westlichen Ländern ein wesentlicher Bestandteil der Entwicklung von Kindern. Dies ist ein zeitaufwändiger Prozess, der regelmäßiges Training erfordert, um die erforderlichen motorischen und Wahrnehmungsfähigkeiten zu erlangen. Da sich Kinder körperlich und geistig noch entwickeln, sind ihre Fähigkeiten zur Bewältigung von alltäglichen Verkehrssituationen begrenzt, was häufig zu einem geringen Situationsbewusstsein und zu Verkehrsunfällen führt. Zum Beispiel könnte es für ein 9-jähriges Kind eine Herausforderung sein, auf einer stark befahrenen Straße in der Innenstadt zu fahren, die Kontrolle über ein Fahrrad zu haben und auf Gefahren zu achten. Unser Ansatz zur Unterstützung von fahradfahrenden Kinder besteht in einer Erweiterung von Fahrrad und Helm mit multimodalen Hinweisen, um die Sicherheit zu erhöhen, ohne eine zusätzliche kognitive Belastung und Ablenkung zu erzeugen.

Basierend auf der Multiple-Resource-Theorie untersuchen wir die Verwendung von visuellen, vibro-taktilen und auditiven Modalitäten zur Gestaltung von Assistenzsystemen. Wir untersuchen eine Kombination dieser Modalitäten an verschiedenen Positionen am Fahrrad sowie am Helm. Diese Hinweise repräsentieren Warnungen, Navigationshinweise, Spurhalteassistenz und Empfehlungen zum Verkehrsverhalten. Für die visuelle Modalität haben wir die Verwendung von ambientem Licht, Augmented Reality-Indikatoren und symbolbasierter Projektion in einem Helm, ambientes Licht am Fahrrad und Laserprojektion untersucht. Wir explorierten vibro-taktiles Feedback an den Griffen des Lenkrads sowie dem Sattel. Schließlich untersuchten wir akustische Signale am Fahrrad und Helm als Sprach- und Ton-basierte Anweisungen. Wir haben die Experimente unter zwei Bedingungen durchgeführt: Laborexperiment in einem Indoor-Fahrradsimulator und kontrollierte Teststrecken-Experimente auf dem Verkehrsübungsplatz. Wir haben einen Human-centered Design Prozess verwendet, um Nutzer in die iterative Bewertungen einzubeziehen. Zusätzlich untersuchten wir die Fahrradleistung von Kindern und die Wahrnehmung von unterstützenden Hinweisen bei visuellen und auditiven Ablenkungsaufgaben.

Die Ergebnisse dieser Arbeit zeigen, dass multimodale Assistenzsysteme geeignet sind, fahrradfahrende Kinder ohne mentale Überlastung und Ablenkung zu unterstützen. Wir stellten fest, dass Kinder mehr Zeit benötigen visuelle als akustische oder vibro-taktile Signale wahrzunehmen. Bei Priming-Stop-Aktionen war die Reaktionszeit kürzer, wenn alle drei Modalitäten gleichzeitig verwendet wurden. Darüber hinaus stellten wir fest, dass akustische Navigationshinweise am verständlichsten und am wenigsten anfällig für Navigationsfehler sind. Visuelle und vibro-taktile Hinweise können jedoch hilfreich sein, um jüngere Kinder zu trainieren. Insbesondere die Kombination aus dem ambientem Licht im Helm und Vibration am Lenker hat sich als die am besten geeignete Lösung erwiesen, um Spurhalteassistenten auf Straßen mit fehlender Infrastruktur darzustellen.

Darüber hinaus haben wir gezeigt, dass ikonische Hinweise in der Head-Up Display Kinder am effektivsten an die Sicherheitsgesten erinnern. Basierend auf den Ergebnissen dieser Arbeit stellen wir uns die Kombination von vier Signaltypen, d. h. Warnungen, Navigation, Spurhalteassistenten und Sicherheitsgestenerinnerungen, im allgemeinen Assistenzsystem für Kinder vor.

Abstract

Learning to ride a bicycle is an essential element of children's development in many western countries. This is a time-consuming process, which often requires regular training to obtain necessary motor and perceptual-motor skills. Since children are physically and mentally developing, their abilities to sufficiently cope with traffic situations are limited, which often leads to low situational awareness and road accidents. For example, it might be challenging and mentally demanding for a 9-year old child to cycle on a busy road in a city center, have a control over a bicycle and pay attention to road hazards.

Our approach for supporting child cyclists lies on a multimodal augmentation of bicycle and helmets with multimodal cues to increase safety without adding additional cognitive load and distraction. Based on the Multiple Resource theory, we investigate the usage of visual, vibrotactile, and auditory modalities to design assisting systems. We explore a combination of these modalities on various locations on a bicycle and helmets. These cues represent warnings, navigation, lane keeping assistance, and traffic behavior recommendations. For the visual modality, we studied the use of ambient light, augmented reality indicators, and icon-based projection in a helmet, ambient light on a bicycle, and on-road laser projection. We explored vibrotactile feedback on a handlebar's grips and a saddle. Finally, we investigated the auditory feedback on a bicycle and in helmets as speech- and beep-based instructions. We conducted the experiments in two conditions: lab experiments in an indoor bicycle simulator and controlled test-track experiments on an outdoor practice test track. We also used Human-centered Design as the method to involve users in the iterative evaluations. Additionally, we examined children's cycling performance and perception of assisting cues in the presence of visual and auditory distraction tasks.

The results of this work show that multimodal assistance systems are suitable to support child cyclists without mental overload and distraction. We found that children spent significantly more time perceiving visual than auditory or vibrotactile cues. When priming stop actions, reaction time was shorter when all three modalities were used simultaneously. Additionally, 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. In particular, we found the combination of ambient light in the helmet and vibration on the handlebar can be the most suitable solution for represent lane keeping cues on the roads with missing infrastructure. Additionally, we have shown that a icon-based cues in HUD were the most effective to remind children about the safety gestures. Based on the results of this work, we envision the combination of four signal types, i.e., warnings, navigation, lane keeping cues and safety gesture reminders, in the general assistance system for child cyclists.

Acknowledgements

Over the last five years, I had a pleasure to work together with a team of great researchers in Oldenburg, who inspired me and gave me a passion for my research in Human-Computer Interaction. This period of my life in Oldenburg has given me an opportunity to grow tremendously as both a researcher and a person. First and foremost, I would like to express my gratitude to my supervisor **Susanne Boll**, who was my guiding light in the research labyrinth over the last five years. Her creativity, ideas, discussions, encouragement and support helped me with my work included in this thesis.

Many thanks go to my committee members **Stephen Brewster**, **Andreas Hein**, and **Sebastian Feuerstack** for the great discussions and the provided feedback. I also would like to express special words of thank you to Stephen Brewster for the great three months of working together in Glasgow and our weekly discussions about my "cycling" research. It was a very inspiring and life changing time for me.

Special words of thank you go to my best colleagues in the world: **Wilko Heuten** for being the best group leader, boss and the travelling buddy, **Swamy Ananthanarayan** for being my friend, spiritual and academic mentor, reader, listener and for all the great discussions we had over the last couple of years, **Torben Wallbaum** for being my friend, for all the support, making music and beer, and all the fun times together, **Shadan Sadeghian Borojeni** for being my friend, for always being there for me, and all the music exchange, **Abdallah El Ali** for being my friend, for helping me grow as a researcher, teaching me how to write and reflect. I would like to thank Swamy Ananthanarayan, Torben Wallbaum, Shadan Sadeghian Borojeni, Abdallah El Ali, and Marion Koelle for wonderful and very important coffee times we had every morning before work. Those coffee discussions were very special for me and all of us. I would like to thank other colleagues who were with me during these years: Vanessa Cobus, Christoph Trappe, Heiko Müller, Janko Timmermann, Jutta Fortmann, Christoph Korinke, Fei Yan, Andreas Löcken, Maria Rauschenberger, Yannick Feld, Erika Root, Sebastian Weiß, Uwe Grünefeld, Tim Stratmann, and Larbi Abdenebaoui.

Last but not least, I would like to thank my family for their unconditional support: my parents Tetiana Matviienko and Volodymyr Matviienko for giving me everything they could, especially the freedom to become the person I am today, and for supporting me in getting the education I wanted. Further, I would like to thank my sister Anastasiia Matviienko for being there for me and supporting me on this journey. I sincerely apologize for being far away for such a long period of time.

Contents

1 Introduction

Cycling is an essential element of children's development in many western countries. At the age of six to seven years old children start cycling to school, visit their friends, or attend sport and art courses after school on their own. However, child cyclists often need a long time to master cycling and gain experience. Sometimes they even have to attend additional cycling courses to develop the necessary set of skills. From the developmental point of view, this time-consuming process of mastering cycling is often restricted by children's motor and cognitive abilities [HPSR14, SKHC$^+$16, BRSB04]. Motor skills are necessary for pedalling, steering, balancing, and braking, and cognitive abilities facilitate the perception of the surrounding environment, paying attention and making judgements and decisions about traffic situations. Most of these skills mature at the age of 12-15 [HPSR14, SSE$^+$06, LVG08], therefore child cyclists need an additional assistance before they reach a sufficient cycling level.

Necessity of sufficient motor and perceptual-motor skills shows that cycling safety and ergonomics are inseparable. Cycling is a meeting point of physics and human factors. Bicycle's stability is influenced by the distribution of a cyclist's weight, bicycle's geometry, and forward speed of the bicycle. A combined bicycle's center of mass and rider's leaning forward facilitate successful navigation. The lean is performed by the rider using the handlebars directly with the hands or indirectly by leaning the bicycle [Faj00]. The rider normally steers the bicycle, but under certain conditions the steering may be provided by the bicycle itself [MPRS07]. Besides physical elements of cycling, human factors also play an important role in an ergonomic cycling experience. Many muscles are involved in the cycling process to ensure a balanced and safe ride. The back muscles absorb road surface shocks and keep the upper body and head in the required position, the shoulders play an important role in reducing pressure on the hands and back, and the buttocks support almost a half of the whole body load [1].

Navigation, obedience of traffic rules, obstacle and collision avoidance are some aspects of the cycling experience, which every cyclist faces all the time. Since child cyclists are still acquiring the necessary skills to master these elements of cycling, different technical cycling improvements were introduced to assist them on the road. For example, Car2X technology [Nar13] enables an exchange of messages between traffic members, which contain their speed and location, to avoid collisions. Such systems for cycling support provide important information, however perceiving and processing this information need an efficient and child-oriented presentation to avoid mental overload. In particular, the presentation of information using visual and auditory senses needs a careful design, given that these senses play an important role in dealing with traffic situations and road hazards to ensure high awareness of the surrounding environment.

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[1] https://www.ergotec.de/files/service/downloads/Humpert_The_Ergonomics_Guide.pdf

Figure 1.1: Existing cycling assistance systems: TactiCycle [PPB09] (upper right), Gesture-Bike [DVÜ+15] (upper left), SmartHalo[1] *(lower right), and HammerHead*[2] *(lower left). The images were taken from the corresponding research papers and official web-sites.*
[1] `https://www.smarthalo.bike` [2] `http://tiny.cc/x2x4kz`

Children's sensory perception is limited. For example, children are not always capable of perceiving and processing vast amount of information simultaneously. Imagine a 9-year old child cycling on a busy street paying attention to other cyclists, cars and traffic lights. It demands many visual resources to process the surrounding environment, due to the high complexity of the road situation. A child might oversee an upcoming car from the left or right side and end up in a collision. Imagine another child navigating alone for the first time from home to a new primary school using a smartphone mounted on the handlebar. While adults might not experience any problems in such a situation, it might be difficult for a child to use screen-based navigation to navigate in an unfamiliar environment, due to high demand on visual resources and constant switching of attention. Cycling on a street without bicycle lanes is also demanding and potentially dangerous. Given that most perceptual-cognitive abilities are still developing, a child might have difficulties estimating a safe distance to the side and the center of the road, due to an overload of sensory information needed for road-related activities. Difficulties in estimating safe distances might lead a child to the opposite lane or in the worst case to an accident. Finally, a shoulder check and hand signals play an important role for conveying cyclists' intends to other road users [DDBL+13]. Children often tend to forget to do these safety gestures. This might be due to a lack of cycling experience or training courses, forgetfulness or a high load of information through the visual channel. This missing indication of child's intentions might lead to an accident.

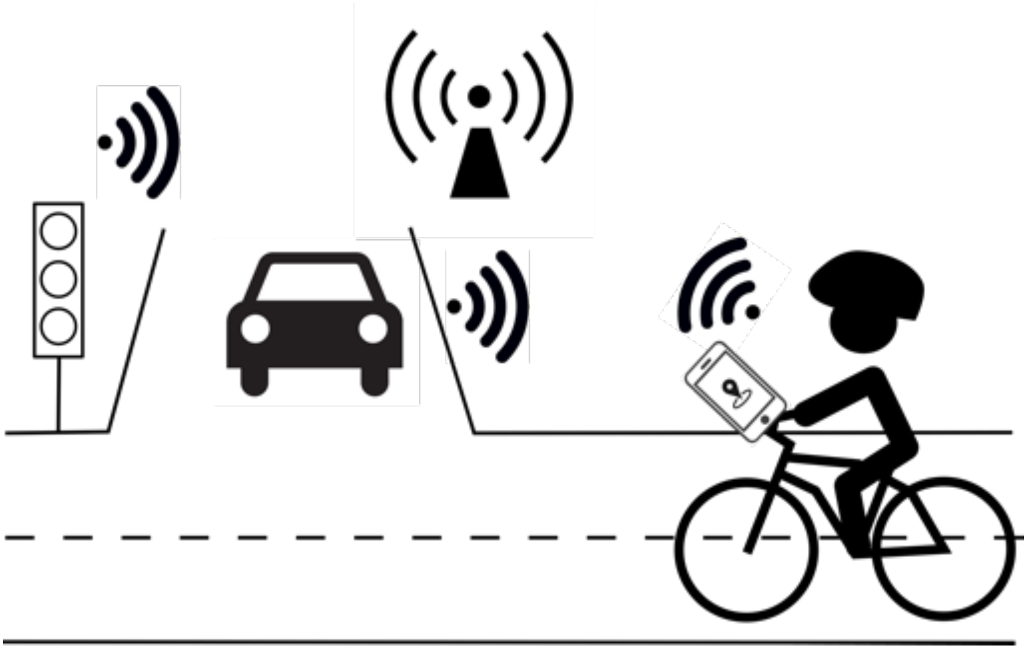

Figure 1.2: A vision of future infrastructure to support cyclists on the road.

In these four scenarios based on recent statistical reports about cycling accidents [EURa, EURb, PB12, Ell14], children's senses are insufficient to cope with surrounding information, e.g., handle collisions, navigate in unfamiliar places, or cycle on the roads without cycling infrastructure. They show that children aged between six to 13 are the most vulnerable group among cyclists, which is partly due to developing motor and cognitive skills. To sum up, we outline four main reasons to focus on technical assistance for child cyclists in this work: (1) high accident rates, (2) increase of cycling mobility, (3) lack of cycling infrastructure and training courses, and (4) children's developing motor and cognitive skills.

Previously, both academics and engineers attempted to assist cyclists by developing different technological assistance systems. They primarily focused on cyclist navigation and the ways to increase awareness of other road users by increasing cyclists' visibility. However, a limited number of these systems work was empirically evaluated with cyclists. One of the first systems was a bicycle with integrated vibration motors in the handlebar, called TactiCycle, which was introduced in 2009 [PPB09]. It was empirically shown that augmentation of a bicycle with a tactile feedback can provide information to a cyclist without introducing additional mental overload. Similar to this idea, a belt with vibromotors, called Vibrobelt, was used to explore on-body vibration cues for navigation in unfamiliar routes [SB13]. A couple of commercial solutions were introduced to navigate cyclists using visual assistance on the handlebar. An LED-based navigation product, called Smarthalo [2], indicates distance and direction via different light patterns. Hammerhead [3] is a bike accessory that also can be fixed to the handlebar and indicates turn-by-turn navigation cues through directional LEDs. In 2015, a motorcycle helmet was fitted with an LED-strip above eyes for peripheral guidance [TLCC15]. In the same year, Dancu et. al used a map projection in a front of the bicycle to show navigational cues for the cyclist and a projection in the back to show the turn intentions to other road users [DVÜ+15]. Some solutions are shown in Figure 1.1.

Most of these systems are targeted towards adult cyclists. Therefore, we lack empirical evidence about their effectiveness for children. In this work, we build on previous works about assisting systems for adult cyclists, which employ the idea of using visual, tactile, and auditory feedback to represent assisting cues unobtrusively and without additional mental load. Our work aims to better understand the nuances of these types of feedback modalities and how children can effectively use them while biking.

In general, we envision an assistance for cyclists as a set of components communicating with each other (Figure 1.2). For example, an on-board computer of a bicycle exchanges information about its location and speed with other road users and infrastructure using a wireless Car2X technology [Nar13]. This infrastructure ensures sending notifications about dangerous situations and facilitates a safe behavior of cyclists and car drivers. However, in this work, we focus on the signals received by cyclists and explore the design space with regard to how and where these signals can be conveyed to a child cyclist.

Since the design space is very large, we split it between on-bicycle and on-cyclist parts to find suitable locations to place visual, tactile, and auditory feedback (Figure 1.3). We outline the design space based on the applicability of modalities and their positions. For example, visual feedback on a bicycle can be placed on the handlebar, bicycle frame and wheels. Tactile feedback can be positioned on the five points of a body's contact to a bicycle: two handlebar grips, a saddle, and two pedals. Finally, haptic feedback can be added to a bicycle's crankset and a rotary part of a front frame. On-cyclist locations also offer different locations for visual, auditory, and a combination of visual and tactile feedback. Visual feedback can be placed close to a cyclist's eyes and auditory feedback can be positioned close to the ears. Both visual and tactile feedback can added on the hands, arms, head, body, legs, and feet.

Besides on-bicycle and on-body locations, the surrounding environment offers additional design space possibilities to represent assisting cues for cyclists. Within the scope of this work we primarily focus on the on-bicycle and on-body locations to place assisting cues, because supporting a cyclist is the goal of this work and not all combinations of location-modality presented in Figure 1.3 is applicable. This

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

[3] https://www.idgconnect.com/idgconnect/news/1004684/hammerhead-bike-navigation-light

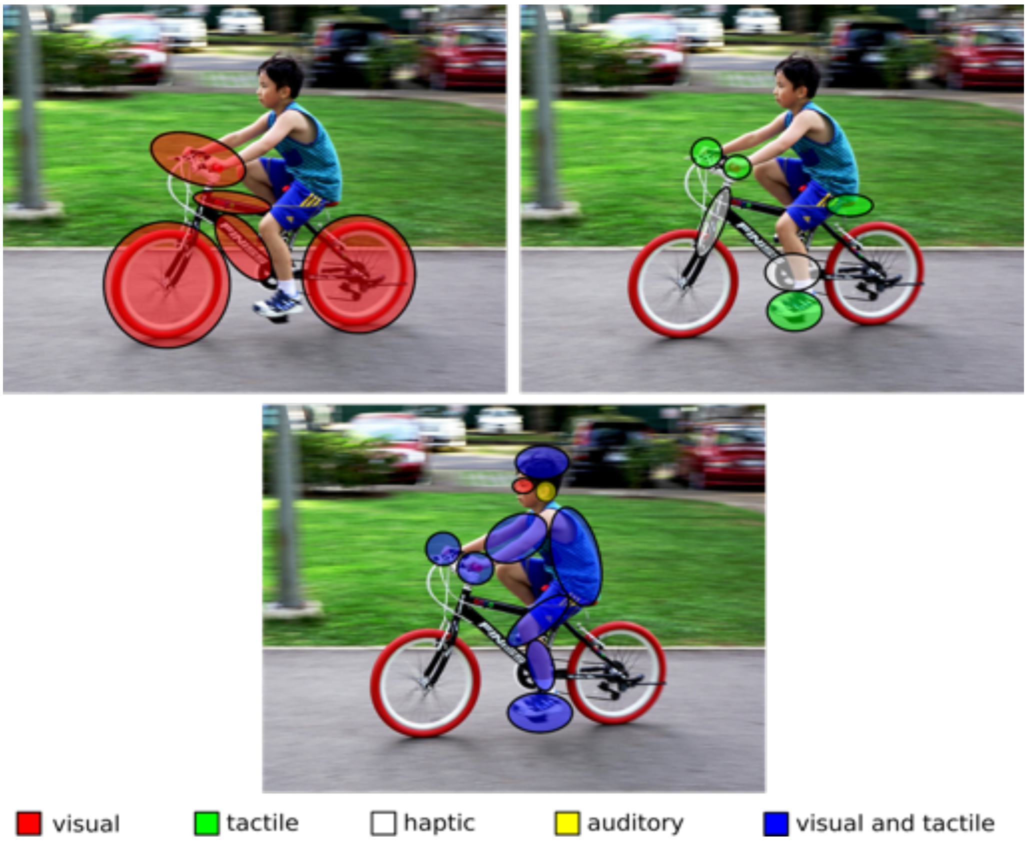

Figure 1.3: Overview of the design space. We split the design space on the on-bicycle (top) and on-cyclist (down) feedback. Positions on a bicycle cover visual, tactile and haptic feedback and positions on a cyclist – visual, auditory and a combination of visual and tactile. Image by Jason Goh from Pixabay.

automatically restricts the design space we explore in this work. Moreover, we start our investigations with locations on essential cycling elements, i.e., bicycles and helmets, which restricts the design space even further. However, in one experiment with lane keeping cues we also explore the environment around a cyclist and investigate the use of projection in the front. This is the starting point of exploring the design space, which explores the locations and feedback.

1.1 Challenges: Distraction, Perception, Developing Skills

To outline the challenges of information perception and processing, we refer to the model of information processing introduced by van Erp [Erp07], which includes three phases: sensing/perceiving a stimulus, comprehending this stimulus and executing a corresponding action. This means that information has to be first perceived by a child, i.e., it has to make its way from a device to the brain. Afterwards, the brain has to process this information in the area with corresponding and available resources. Finally, the perceived information might take too much attention and cause an additional distraction, thus delaying the execution of an action. This delay might be caused by developing motor and cognitive skills, responsible for controlling a bicycle and perceiving the surrounding environment.

1.1.1 Distraction

By distraction we refer to the lack of attention to something important. Distraction is one of the consequences of children's undeveloped motor and cognitive skills. If a cyclist is distracted, this might lead to loss of bicycle control or an accident. Existing systems for cyclists are typically represented graphically on small screen-based devices mounted in the center of a bicycle's handlebar. A straightforward example using a smartphone for navigating from A to B would be entering a destination in the Google Maps app on a smartphone and placing it on the handlebar 1.4. These devices use a "stop-to-interact" paradigm, which requires the user's full visual attention [MT13]. It becomes even more dangerous when GUI-based devices are used during cycling, which requires constant attention shift between the environment and instructions on a smartphone. While adults may not experience problems using devices standing or "on-the-go", child cyclists might find them distracting or difficult to use.

Auditory or tactile interfaces are an alternative to visual interfaces. However, the challenge is to present information in an understandable and non-distracting way. If navigation is too loud, it might distract other road users, it can feel embarrassing when others can hear the instructions, or instructions might be missed in a noisy environment. Head phones can help with these problems, however there is a risk of missing environmental cues, which may lead to the loss of situational awareness. Tactile signals might as well be missed while cycling on a bumpy road or in gloves during winter time. Alternative methods to GUI-based interfaces have their advantages and disadvantages, but they require a thorough exploration of the design space of these modalities with child cyclists.

1.1.2 Perception

By perception we refer to the ability of processing and interpreting signals received by human senses. Unclear or non-suitable presentation of signals has no use if they cannot be perceived and interpreted by a human brain.

Environmental factors play an important role in the perception of interfaces. It might be difficult to cycle during a night-time using a smartphone due to a high contrast between the screen and the environment, or on a sunny day due to light reflections, which would require few seconds for the eyes to adjust.

Figure 1.4: Bicycle navigation using a Google Maps on a smartphone.

Raindrops on the screen or a large distance from the eyes might also decrease the visibility of a GUI interface. Similarly, processing auditory signals might collide with environmental noise or bumpy roads might reduce the perception of tactile interfaces.

Generally speaking, the selection of the modalities for presenting information to cyclists might account for environmental and developmental factors to ensure perception of the signals in time. Moreover, one has to account for possible mental overloads in processing additional information [Wic02, Wic08]. For example, driving a car and talking to a friend on a passenger seat might not be a problem, but following navigation instructions on the display and looking at the road while driving might increase mental load.

1.1.3 Developing Cycling Skills

Child and adult cyclists differ in their motor and cognitive development. Motor skills, responsible for pedalling, balancing, braking and steering, are developing until the age of twelve. In particular, obstacle avoidance matures at the age of eleven [PRP97] and visual motor coordination at the age of ten to twelve [GO05].

Cognitive abilities are usually divided into perceptual-cognitive and visual developmental groups and are responsible for the perception of the surrounding environment, paying attention and making decisions in regard to traffic situations. Perceptual-cognitive development skills, selective and switching attention mature at the age of twelve and are vital in cycling. Moreover, different perceptual systems mature at different times. For example, static and dynamic visual acuity fully develops at the age of 10-12 [GO05], while the saccade system matures at the age of 15 [HPSR14].

Children aged between 6 and 13 experience the highest rate of accidents within the cycling group [EURa, EURb], which is in part caused by the developing motor and perceptual-motor skills. Therefore, this age range lies in the focus of this thesis. We elaborate more on children's development with regard to cycling skills in Chapter 3.

1.2 Approach: Multimodal Information Presentation

In general, we have identified three challenges to design assisting systems for child cyclists. These are distraction, perception, and developing skills. We base our research on four aspects relevant for the assistance of child cyclists:

- Statistical reports show that children under age of 15 have the highest accident rate within the cycling group [EURa, EURb]. Moreover, the majority of accidents with child cyclists happen when crossing a road or at the junctions [PB12, Ell14, $\mathrm{GSS}^{+}16\mathrm{b}$] (see Figure 1.5 for examples). Therefore, the first type of assistance for child cyclists that we explore in this work is *warning signals* – signals that notify a cyclist about upcoming danger or/and require a braking activity.

- Existing navigation systems for cyclists are commonly screen-based or LED-based devices mounted on the handlebar. These devices display map information or give directions using LED's position, which typically requires cyclists to look down for directions. Child cyclists might face a higher level of distraction using such navigation aids due to their developmental differences in motor and perceptual-motor skills compared to adults. Thus, we focus on alternative and non-distracting *navigation cues* for child cyclists as a second type of assistance for child cyclists.

- Missing cycling infrastructure is often a reason to avoid cycling due to the safety concerns. We aim to assist child cyclists on the roads with missing infrastructure, e.g., bicycle lanes, and we explore techniques to support children in keeping a virtual bicycle lane. Therefore, a third type of assistance for child cyclists – *lane keeping cues* – is meant to help cyclists to maintain a safe position on the road in the absence of cycling infrastructure.

- Cycling *safety gestures*, such as hand signals and a shoulder check, are an essential part of safe manoeuvring while navigating on the road. Child cy-

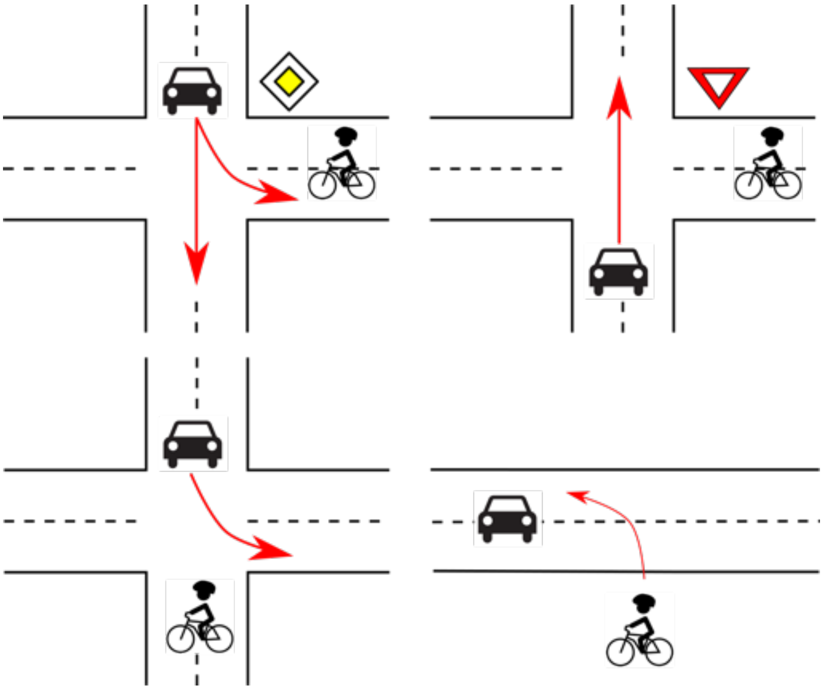

Figure 1.5: Examples of the most dangerous situations for car-to-cyclist collisions based on the statistical reports [GSS+16b]: a car is approaching from the right on the secondary road (upper left), a car is approaching from the left on the main road (upper right), a car is making a left turn in front of a cyclist (lower left), and a cyclist is entering the street making a turn left (lower right).

clists, in particular, might have difficulties performing safety gestures or even forget about them, given their lack of cycling experience, road distractions and differences in motor and perceptual-motor abilities compared to adults. Therefore, the last type of assistance for child cyclists that we explore in this work is safety gestures, which are designed to remind child cyclists about safety gestures "on-the-go".

To overcome these challenges and represent these assisting cues in an understandable and non-distracting way, we employ a multimodal approach. A multimodal approach implies a presentation of information through visual, auditory, and tactile channels sequentially or simultaneously. The advantage of this approach lies in the avoidance of mental overload and possible interference with visual and auditory perception of the surrounding environment, essential for a safe cycling.

We explored children's abilities to perceive visual signals in the periphery of their visual field of view, auditory cues positioned close to their ears, and implicit vibrotactile feedback integrated in the handlebar during the experiments with a stationary bicycle simulator and on a test track. We based this approach on the Multiple resource theory (MRT) [Wic08] and the Prenav model [Erp07]. MRT shows that different types of mental resources do not compete with each other, and therefore do not increase mental load, and the Prenav model suggests avoiding cognitive effort by carefully considering information presentation. In the following, we outline both models in more details.

Single resource theory was discarded after the introduction of a multiple resource theory, which showed that an additional task neither doubles the number of mental resources nor decreases the performance by two. The findings indicate that different types of tasks might require different types of mental resources, i.e., tasks which demand the same mental resource will increase mental load more than tasks of different nature. Multiple resource theory introduced by Wickens [Wic08] presents four dichotomous dimensions, which include perceptual modalities (visual and auditory), processing stages (cognition and responding), visual channels (focal and ambient), and processing codes (spatial and verbal) that account for time-sharing performance. This model shows that performance decreases depending on tasks that compete for the same mental resources. Wickens' Multimodal resource theory is supported by physiological evidence that speech and motor activity tend to be controlled by the frontal lobe in the brain and perceptual and language comprehension activity is controlled by the temporal lobe. Tactile modality is not included in the presented model. However, the sense of touch is controlled by the parietal lobe of the brain and has a different nature compared to visual and auditory perception. Thus, we include it as an additional perceptual modality in our work. Visual, tactile and auditory signals are processed by different regions of the brain, which allows us to explore simultaneous and consequent combinations of these signals. In this thesis, we refer to the signals processed by the same type of one mental resource as *unimodal* and by different types of mental resources as *multimodal*.

Another model, introduced by Van Erp [Erp07], describes pre-attentive tasks, i.e., tasks that do not demand any mental resources and do not cause interference among multiple tasks. This model is called Prenav Model and is based on the Multiple Resource Theory [Wic08], Veltman and Jansen's workload framework [VJ04], Rasmussen's model [Ras83], and Vicente and Rasmussen's model [VR88, VR90]. It introduces four stages for usage of mental resource: (1) sensation, (2) perception, (3) decision, and (4) action loop. The main idea behind this theory is to avoid generation of cognitive effort (decision making) using two shortcuts: sensation -> actionloop and perception -> actionloop. The first shortcut implies intuitive information presentation, which does not require an additional thinking process, e.g., a cyclist keeping a balance, braking, or any the other kind of reflexive and trained tasks. The second shortcut employs bypassing the decision process by using automated "if...then" rules. For instance, a cyclist decelerates when approaching a crossing.

Both theories suggest that the challenges of distraction, perception, and undeveloped motor and perceptual-motor skills can be addressed by presenting assist-

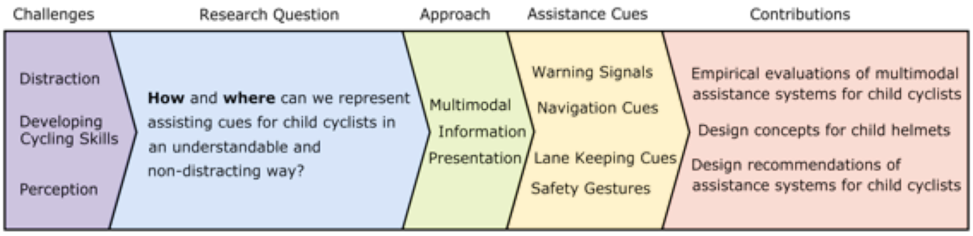

Figure 1.6: Overview of connections between challenges, approach, research question and contributions.

ing information in an understandable and non-distracting way, suitable for child cyclists. This implies representation of information for processing by available mental resources. The visual and auditory perception systems play a crucial role in conveying information to assist cyclists. In particular, focal vision is the main channel to provide information regarding possible hazards during cycling on the road. The sense of hearing helps to identify approaching cars from behind or occluded by other objects on the road. Findings from previous research based on the Multiple Resource Theory showed that peripheral vision and the sense of touch allow to increase the amount of processed information without causing an additional mental load.

In this thesis, we follow an interactive human-centered design approach and focus on the improvement of the prototypes after each iteration. This design approach is widely applied in both industry and academia [PRS$^+$94]. We explore the design space addressing sensory stimulations on a bicycle and helmets through laboratory and test-track experiments. This thesis investigates how to represent different types of assistance for child cyclists via vibrtotactile, visual and auditory feedback.

1.3 Research Questions and Contributions

This section outlines four research questions addresses in this thesis and its contributions. The main contribution of this work is the empirical evaluation of multimodal assistance systems with child cyclists. We conclude that augmentation of bicycles and helmets with visual, vibrotactile and auditory cues can assist children in navigation, correct their cycling behavior and has the potential to increase children's safety on the road. The overview of connections between challenges, approach, the overarching research question and contributions is shown in Figure 1.6.

RQ1 (Warning Signals): How can we represent *warning signals* for child cyclists in an understandable and non-distracting way? In Chapter 4, we explore the design space of warning signals. In Section 4.1, we provide statistical information about accident rates, existing augmentation technologies for bicycles, helmets, and clothes, and outline the lack of empirical evaluation for multimodal warning signals with child cyclists. In Section 4.2, we present an indoor bicycle simulator built for the evaluation of multimodal interfaces with children. We explore which positions on a bicycle are suitable for placing particular type of feedback and which combination of signals has the highest recognition rate. In Section 4.3, we introduce two types of warning signals: directional cues and immediate actions. We present the design space of unimodal directional cues and multimodal immediate actions. In Section 4.4, we report a study in a bicycle simulator, which explored the efficacy of uni- and multimodal warnings in two scenarios: (1) a car is approaching from the left or right on a crossing and (2) a hidden car starts driving out of a parking lot. We show that unimodal acoustic and vibrotactile encodings are applicable for directional cues and trimodal warnings are better for understandability and lead to shorter reaction times.

RQ2 (Navigation Cues): How can we represent *navigation signals* for child cyclists in an understandable and non-distracting way? In Chapter 5, we explored the design space of encodings for navigation cues. In Section 5.1, we presented possible distraction problems of screen-based interfaces placed on the handlebar and existing uni- and multimodal methods to overcome these problems. In Section 5.2, we start exploring the design space of unimodal navigation cues in a bicycle simulator in the presence of auditory distractors. Based on the results from the laboratory experiment, in Section 5.3 we outline the results from the follow-up test-track evaluation on the tricycle in the presence of the auditory distraction task with two levels.

RQ3 (Lane Keeping Cues): How can we represent *lane keeping cues* for child cyclists in an understandable and non-distracting way? In Chapter 6, we explore the design space of encodings for lane keeping cues. In Section 6.1, we provide an overview of statistical accident's data, lack of cycling infrastructure, recent enhancements in cycling assistance systems, and outline the lack of empirical evaluation of assistance for child cyclists in the absence of cycling infrastructure. In Section 6.2, we explored safety-related issues child cyclists faced and their behavioral patterns when encountering particular traffic situations using semi-structured interview, following a user-centered design approach. In Section 6.3, we explore the design space of unimodal lane keeping cues in a bicycle simulator in the presence of visual distractors. In Section 6.4, we outline the results from the follow-up test-track evaluation on the tricycle.

RQ4 (Safety Gestures): How can we represent *safety gesture reminders* for child cyclists in an understandable and non-distracting way? In Chapter 7, we explore the design space of reminders about safety gestures. In Section 7.1, we outline the importance of hand signals and shoulder checks for safe cycling and lack of mandatory regulations in many countries. In section 7.2, we presented a design of reminders for safety gestures based on previous works. In Section 7.3, we describe a possible technical solution for a fully functioning system to enable recognition of cyclists' behavior in real-time. Fi-

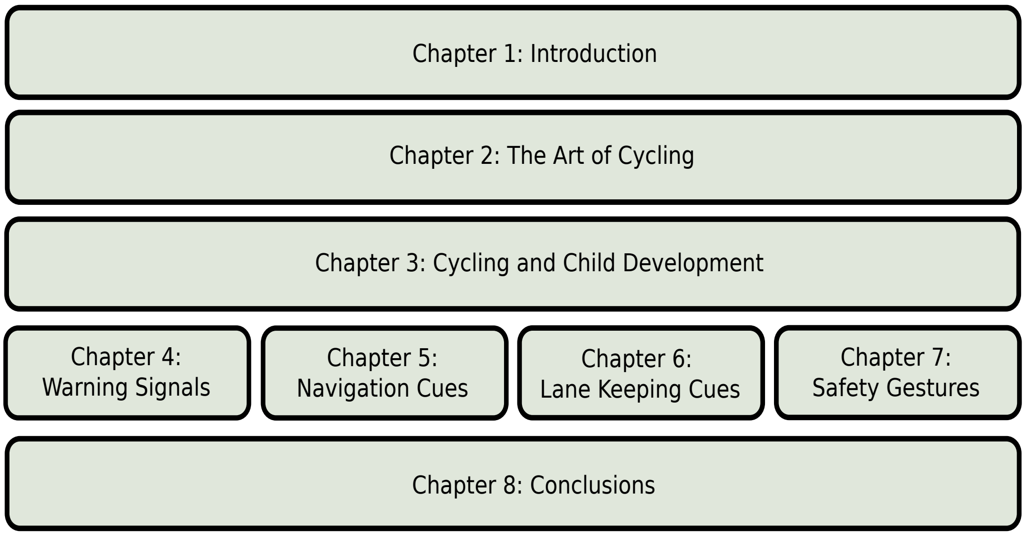

Figure 1.7: Thesis Structure.

nally, in Section 7.4, we explore the design space of safety gesture reminders in a test-track experiment.

1.4 Thesis Structure

This section outlines the structure of the thesis. Each research question listed in the previous section is addressed by one chapter. This structure is graphically illustrated in Figure 1.7.

Chapter 2 outlines the state-of-the-art in cycling. It starts with the history of cycling and its development over the last 200 years, followed by current trends and benefits of cycling. This chapter also provides an overview about cycling accidents with the focus on child cyclists and existing cyclists assistance systems.

Chapter 3 provides the fundamentals of children development with the focus on the age range between six and 13, given the highest accidence rate in this age range among cyclists. It outlines motor and perceptual-motor skills, and children's abilities for visual control and attention.

Chapter 4 presents the work from two laboratory experiments in a bicycle simulator, exploring multimodal warning signals. It starts with an exploratory study about the perception of the signals on different locations of the bicycle during cycling and continues into deeper and more granular investigation of prior warnings (directional cues) and urgent warnings, which imply immediate action.

Chapter 5 explores navigation cues in two different test environments: bicycle simulator and a test-track. Both of the experiments are focused on the encoding of navigation cues unimodally, i.e., using visual, vibrotactile, auditory encodings, under the presence of auditory distraction task. The auditory distraction task was added in order to simulate the road traffic distraction, and therefore to increase the ecological validity of the results.

Chapter 6 outlines the work with regard to encodings for lane keeping cues. In comparison to the two previous chapters, it also explores the use of projected surfaces. The first method implies a laser projection in front of a bicycle and the second exploits the projection in the front of the eyes via a helmet with a heads-up display. This chapter presents the results from one laboratory experiment in the instrumented bicycle simulator and one experiment from the controlled test-track study.

Chapter 7 presents the results from one controlled test-track experiment, where we compared multimodal and projected safety gesture reminders. We also provide one possible technical implementation of the fully working bicycle system, which combines both the recognition of the environment and the cyclists' behavior, coupled with the signals explored and presented in Chapters 4-7.

Chapter 8 outlines the general contributions of this work, design recommendations for a cycling assistance system and a possible stand-alone system. Finally, it presents limitations and future directions of this research.

2 The Art of Cycling

This chapter reviews different aspects of the cycling. It starts with cycling history, current trends and cycling benefits, followed by the overview of bicycle accidents and their causes, and existing methods to improve cycling from the perspective of education, infrastructure and technological advances.

2.1 Cycling History, Trends and Benefits

2.1.1 Cycling History

The invention of the two-wheeled vehicle, which requires balancing by a rider, is over 200 years old from now and dates back to 1817. A civil servant Baron Karl von Drais (Grand Duke of Baden in Germany) has constructed his "running machine", a so-called "draisine", as an alternative to horses, which experienced mass deaths from starvation due to the crop failure in 1816. To move this horse-like vehicle forward riders had to push themselves off the ground using their feet. Although riders only used their feet, they could reach a speed of up to 13 km/h. However, due to the high number of accidents, its popularity has decreased and was prohibited in some countries. To solve the problem of a high accident rate engineers and researchers have focused on technical improvements of a draisine. They created iron-banded wheels, increased their size and added pedals and cranks. This improved version of a running machine got a name "bone-shaker" in England due to its metal wheels and rigid frame. In 1860s, to increase the cycling comfort engineers have further added iron frames for stability and robustness of a bicycle, solid rubber tires and ball bearings for a smoother movement [Her04].

Later in 1870s, Frenchman Eugène Meyer designed a high bicycle with an enlarged front wheel to enable higher speeds. However, this modification in a bicycle's design has drastically reduced cycling safety, since a rider was positioned high in the air and the speed has considerably increased. One decade later engineers and inventors have focused on making cycling safer, which is considered to be a time of a safety bicycle invention. John Kemp Starley, an English inventor and industrialist who is widely considered the inventor of the modern bicycle, added a steerable front wheel, a chain drive to the rear wheel and changed the design to equally sized wheels. John Dunlop, a Scottish inventor who re-invented pneumatic tyres for his child's tricycle and developed them for use in cycle racing, improved the cycling comfort by adding a pneumatic bicycle tire, which made cycling even more popular in Europe and North America. The rough design of the bicycle from 1880s remained primarily unchanged until nowadays. Cycling industry focused on adding gears to overcome different types of landscapes and surfaces. For example, almost one hundred years later, in 1980, the first mass-produced mountain bike appeared to enable cycling off-pavement over a variety

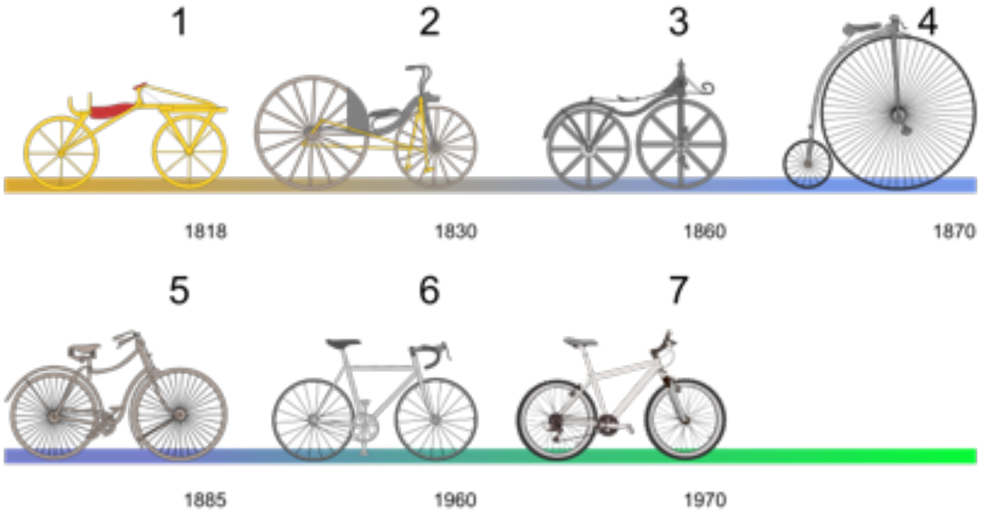

Figure 2.1: Evolution of bicycle development. Source: `http://tiny.cc/ary4kz`

of surfaces [Her04]. The overview of bicycle development over the last 200 years is shown in Figure 2.1[1].

Despite the long history of cycling and its numerous technical improvements and benefits, it took unique turns in the worlds, which led to diverse trends and challenges around the globe.

2.1.2 Cycling Trends

Cycling has become free, enjoyable and ecologically friendly mean of transportation, with a high accessibility level almost among all age groups. Children can experience tricycles, cycling enthusiasts can enjoy the speed of tracking and trekking bicycle, and elderlies – electric bicycles. However, bicycle usage remains inconsistent around the world. For example, only about 1-2% of cycling trips are made by cycling in the North America, Canada, United Kingdom and Ireland, in comparison to more than 10% in most of North Western Europe: the Netherlands (26%), Denmark (18%) and Germany, Sweden, Finland and Belgium (10%) [PB12]. The similar tendency is observed for the distance cycled per capita, which ranges from 0.1 km in the United States and 0.2 km in the United Kingdom to 1 km in Germany, 1.6 km in Denmark, and 2.5 km in the Netherlands [PB12]. The most cycling cities in the United States, the United Kingdom, Australia and Canada

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[1] Image source: `https://commons.wikimedia.org/wiki/File:Bicycle_evolution-numbers.svg` attributed by Al2 [CC BY 3.0 (https://creativecommons.org/licenses/by/3.0)]

still have the lowest cycling rates than the least cycling cities in the Netherlands, Germany and Denmark. The purpose of cycling also varies depending on the country. For example, majority (60%) of bicycle trips in the United States have recreational purposes in comparison to 38% in Germany, 35% in the United Kingdom, 27% in the Netherlands, and 10% in Denmark. In Northern Europe cycling has primarily utilitarian purposes, including travelling to work or school and shopping [PB12]. Particularly for children, cycling is often a preferred, since it is a fast and easy way of going to school. When growing older children increase their cycling distances and expand their range of mobility. They start to attend sport and music courses, visit their friends or go shopping. Typically, the daily distance increases from 3.6 km per day for 6-12 years old to 8.4 km for 13-17 years old children [Zeu16]. Increase of the mobility range often implies more sophisticated navigation and requires child-oriented navigation cues. We explore the design space for navigation cues in details in Chapter 5.

Despite differences in cycling trends around the world, cycling offers a wide and universal range of benefits for all age groups.

2.1.3 Cycling Benefits

Cycling combines an endless number of benefits, including the improvement of physical and mental well-being, decrease of air and noise pollution, and increase of social connectedness when cycling in groups or commuting to work.

The rapid increase of mechanisation in the last half of the twentieth century replaced daily walking and cycling activities with motor vehicles in many developed and developing countries. However, given deterioration of today's ecological situation and consequent health problems, cycling popularity is increasing again. Primarily, it provides excellent opportunities to remain physically active on the daily basis and remains a convenient way of riding to work, shops, visit friends in the close proximity, and do recreational rides [PB12]. On the other hand, cycling is also a fun and inclusive form of exercise for all ages and a great way to actively explore new landscapes.

Regular cycling leads to numerous health benefits. For example, cross-sectional studies have shown correlations between active commuting and body mass index, lipid levels, and blood pressure [HPH+02, WR08]. The studies conducted in both Europe [HSBJJ07] and Asia [HPH+02, OMMI07] have shown a better general health profile for people who cycle on regular basis. In particular, one study reported an association between general health and chronic diseases among regular cyclists aged between 50 and 70 [HBG+08]. Cycling is also beneficial for the physical state of children [LOR08]. For instance, it was shown that active commuting to school was associated with an increase of physical activity in a study with 6805 English schoolchildren [VS10], and was further supported by study with children in Denmark [OTB+11]. In general, children who cycle to school have significantly higher cardiovascular fitness state [CWJ+08, ALC+09].

Except for the health benefits, cycling is ecologically friendly and is often an alternative to motor vehicles, which belong to a major of source of air and noise pollution in urban areas [pol]. For example, road transportation contributes 22% of total greenhouse gas emissions in the UK [dep]. In Australia, transportation emission rose between 1990 and 2005 and reached the 30% level, which is expected to rise to 67% by 2020 [aus08]. Switching from motor vehicles to bicycles can improve the situation with traffic congestions and the air quality by reducing the amount of greenhouse gas emissions. Traffic also vastly contributes to noise pollution, which often leads to insomnia, stress and hearing damages [DPP00, Bui00]. Alternatively, cycling can facilitate relaxation, reduce stress reduction, and improve social interaction and emotional well-being. For example, cyclists find their trip to work more pleasant than going by car [GU07] and is appreciated by commuters as an opportunity for social interaction [PB12].

In general, cycling has a great potential to improve public health and reduce the emission of greenhouse gases, however, road safety remains one of the biggest challenges in today's cycling situation, given the high number of bicycle accidents.

2.2 Cycling Accidents and Their Causes

Despite the numerous health and ecological cycling benefits, cycling safety is one of the biggest challenges related to cycling in many developed and developing countries. In this section, we will provide an overview of the current cycling situation with respect to bicycle safety and accidents, based on the recent statistical data from EU and the US.

Although road travel has generally become safer over the last decade, the same cannot be said about cyclists, who remain in the majority of killed and injured road users, particularly in urban areas. Cyclist' death level in the EU is at 8% (2016) and it is slowly rising (6% in 2007). Transferring this percentage into a number of fatalities gives us about 2000 killed cyclists in road accidents in the EU countries in 2016 [EURa, EURb]. Cyclists' fatality level is low in comparison to motorcycles (14%) and cars/taxis (47%), but it still requires attention and improvement. For example, Germany has a positive tendency for children's accident rate over last 40 years, however the accident's rate still remains high (Figure 2.2).

Zooming into the latest accidents statistics shows that the age groups with the highest percentage of fatalities in European Union are children aged under 14, namely between 5 and 14, and older adults aged above 65. Germany is again inline with this tendency with around 10.000 child cyclists under 15 years old, who were either killed, or weakly/strongly injured in traffic accidents in 2017 (Figure 2.3). The percentages for these age groups are almost twice as high as the average for all age groups, including place two (age group between 50 and 55)

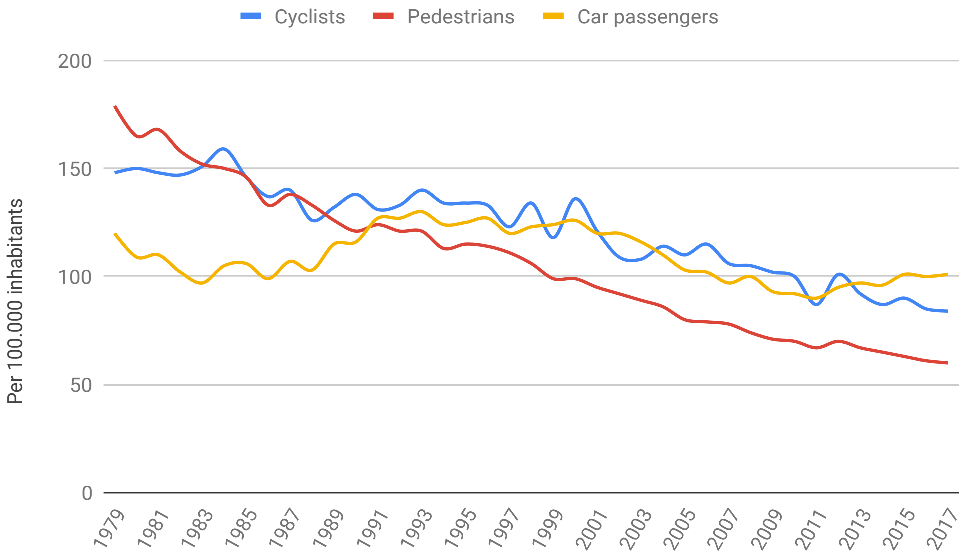

Figure 2.2: Children in accidents over last forty years in Germany. Source: DESTATIS 2017.

and place three (age group above 75). After zooming into more detailed overview (Figure 2.4), we see that the accident rate for child cyclists increases, starting with the age of six until 14-15. Statistical data from the Netherlands [PB12] and the United States [Ell14] show the same accident's picture with child cyclists aged between six to 13 being the most vulnerable road users. Therefore, in this thesis we focus on designing assistance systems for child cyclists in this age range.

Most frequently cycling accidents occur at road intersections, cycle tracks and cycle lanes, which might require an additional and a more careful design of these facilities in the future. Almost half of cycling accidents involves a collision with motorized vehicles. Over a quarter (28%) of the cyclists' fatalities in EU occur at the junctions and is considered one of the most dangerous areas. Entering the street is considered to be the second most dangerous situation in most of the European countries [Pos06, KHL15, IH12, RS98, bas]. In Chapter 4, we investigate the design of warnings signals for these two types of situations. For both bicycle riders and others involved in accidents "premature action" is often the cause. Premature action describes a critical event with an action started too early, before a signal was given or required conditions established [EURb]. Going in the incorrect direction (for example turning left instead of right or leaving the road without following the intended direction of the road) is among the first top three causes for the cycling accidents. Moreover, movements taken too far and manoeuvres that last for too long, such as not returning to a correct lane, often lead to accidents between bicycle riders and other road users when sharing road

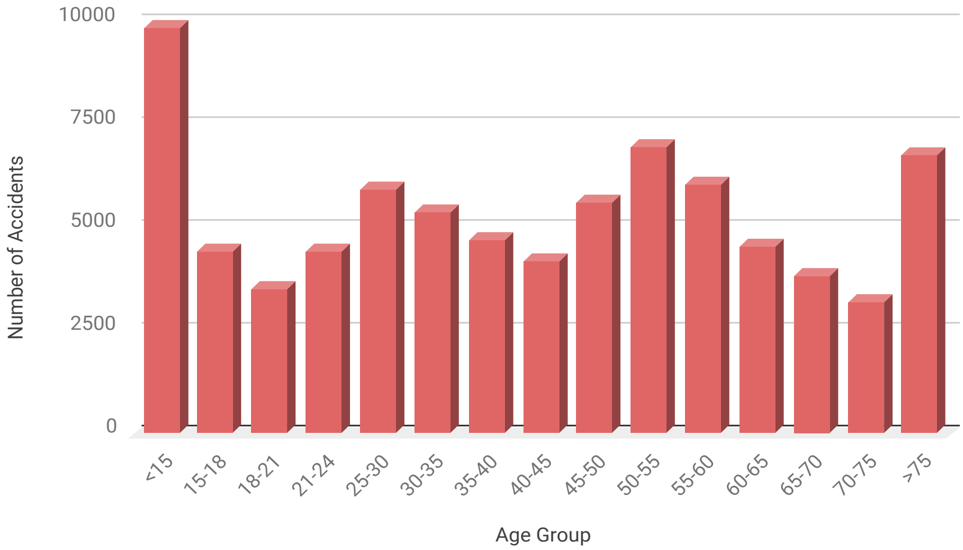

Figure 2.3: Number of cyclists' accidents per age groups in Germany in 2017. Source: DESTATIS 2017.

space [EURb]. This fact, in particular, motivates this work to explore assistance signals focused on the lane keeping and safety gestures.

To provide a full picture of cycling accidents we derived a list of the causes, based on the statistical data and types of accidents defined in previous work [Pos06, KHL15, IH12, RS98, bas].

1. Cyclist violated road traffic regulations or behaved unexpectedly (violation of priority or stopping rule, overtaking rules, changing lanes, going ahead and turning, inappropriate speed).
2. Cyclist underestimated required time to cross a street.
3. Cyclist was riding on the wrong side/direction of a street.
4. Cyclist did not see an upcoming vehicle due to obstruction on the road.
5. Cyclist had problems navigating in the crowded city.
6. Cyclist lost control, balance, fell of the bicycle, or braked too violently.
7. Cyclist did not look right/left properly.
8. Cyclist was not visible.
9. Car driver "fail to look" into a cyclist direction.

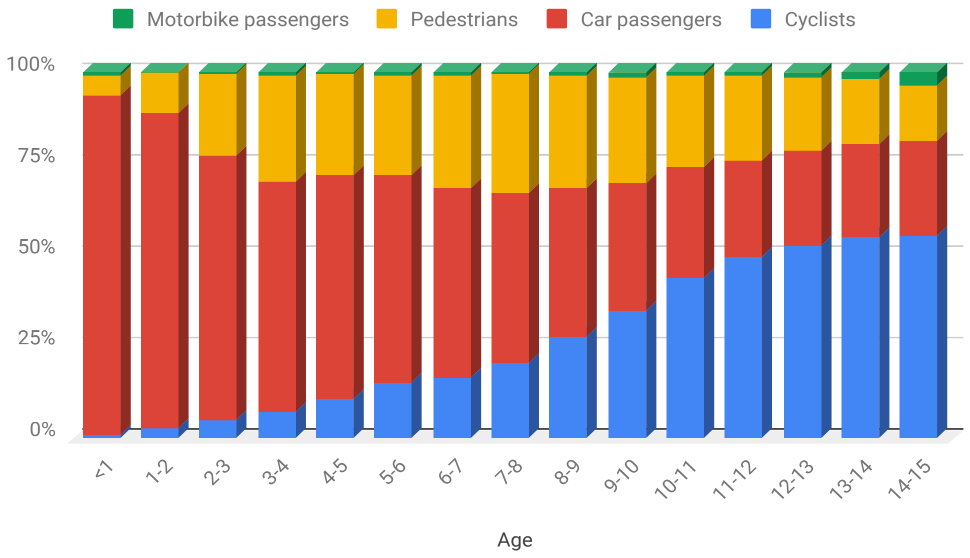

Figure 2.4: Road accidents for children under 15 per transportation type in Germany in 2017. Source: DESTATIS 2017.

10. Car driver “look but fail to see”: car driver did not see the cyclist coming and opened the door at the parking.

There are different methods to address existing cycling problems, which include improvements for (1) cycling education, (2) cycling infrastructure and (3) technological assistance. We outline these methods in details in the following section.

2.3 Existing Methods to Improve Cycling

The accident rate for child cyclists aged from six to 13 is the highest together with adults older than 65 within the cyclists group. Since the former age group is in the focus on this work, in this section we will outline the existing approaches towards increasing safety for child cyclists, which include (1) safety education and regulations and (2) design and improvements of cycling infrastructure.

2.3.1 Safety Education and Helmet Regulations

In many countries, cycling safety is focused on educational programs and additional safety regulations (e.g., helmet use). Usually the training programs emphasize mastering of the basic cycling skills, such as steering, pedalling, braking and balancing, traffic rules and signs, and safety gestures, such as hand signals and shoulder look [cyc]. However, we lack evaluation of effectiveness for cycling programs to identify the most effective educational strategies. A key step for bicycle communities would be a better understanding of effective educational programs for child cyclists.

Helmet regulations is an ongoing debate in many countries. Helmets decrease the risk of head injuries during bicycle accidents [MR13], which led many governments to adopt mandatory usage of helmets, particularly for children. For example, the British Medical Association and twenty-one states and the District of Columbia support these mandatory helmet regulations on the legislative level. However, not every government went that far and many critics mention that additional laws outweighs the health benefits and decrease cycling popularity [Car99]. Moreover, some European countries, such as France, Germany and the Netherlands, have strict liability laws that place more responsibility in the bicycle accidents on drivers [Fed03], while the United Kingdom and United States have no such special responsibility implications on drivers. Differences in helmet regulations among many countries and lack of evidence for efficient and successful cycling programs motivated us to design and develop helmets, which can support cyclists, in particular children, “on-the-go”. We primarily focused on the technical solutions to encourage cyclists to cycle more, given additional assistance integrated in helmets.

2.3.2 Cycling Infrastructure

Improvements in cycling infrastructure is one more way of making cycling safe and accessible. Normally, bicycle-friendly environments address two aspects of infrastructure: (1) spatial distribution of points-of-interest, such as schools, shopping areas, parts, and (2) connectivity between these places. Both of these aspects depend on the city planing, investment decisions, and distances between the locations. We also know that closer is better than further away. For example, Tal and Handy showed that 60% of children cycled to the soccer field, located in a half-mile distance from their homes. This number dropped to 10% for children living 2.4-6.4 km away from the soccer field [TH08]. Depending on the age, cycling skills and physical state of children, they are capable of cycling different distances. For example, a 6-years old child who could not cycle to the soccer field 4 km away can cover this distance at the age of 9. This makes cycling infrastructure and city planing inflexible and might be exclusive for some age ranges. For us it was another motivation to explore a more flexible solution than cycling infrastructure by augmenting bicycles and helmets with assisting technology for cycling.

Differences in adult and child cycling vary and suggest various behavioral patterns. For example, less experienced adult cyclists prefer low-volume roads with a dedicated bicycle infrastructure [Dil09]. Children, however, are usually restricted to the local streets for their short trips rather than dedicated bicycle infrastructure. The Netherlands and the United Kingdom implemented so-called home zones on the narrow neighborhood streets, which require motor vehicles to reduce their speed to 15 km/h [Cen04]. Some Dutch cities invest into guarded bicycle parking to encourage children to cycle to school. It increased, for instance, the number of children cycling to school in one of The Hague's secondary schools in ten times. Another Dutch invention in the city of Delft facilitated safe routes for children by adding colorful ribbons to mark dedicated routes for children [dut]. This strategy can be applied in new communities or be easily extended in the bicycle-friendly neighbourhoods.

To decrease the number of accidents, some EU countries go beyond existing compulsory safety features, such as brakes, bells, pedal and spoke reflectors, and introduce additional safety requirements, including helmets and a minimum cycling age [EURa, EURb]. Additionally, a number of measures have been identified to reduce number of accidents and injury severity, which we outline in details in the following [cro].

- **Land use planning**: To facilitate safe cycling in the urban areas bicycle lanes/roads need to be in good conditions and the cycling network should be coherent, avoiding detours and delays.
- **Road design**: The cycling infrastructure needs to employ area-wide speed reduction, safe walking routes, cycling networks and crossing facilities.
- **Visibility increase**: Additional light-colored and reflective clothing increase visibility of the cyclists on the road.
- **Vehicle design of accident opponents**: The reduction of injuries to cyclists can be facilitated by redesigning of a front for cars and heavy vehicles [Wit01].
- **Protective devices: helmets**: In Europe bicycle helmets are compulsory in Finland for all cycle use, Spain (outside built-up areas), the Czech Republic (children < 16 years), Iceland (children < 15 years), and Sweden (children < 15 years). Wearing a helmet is also mandatory in Australia, New Zealand, in twenty states of the USA, and in a number of Canadian provinces. Since only about ten countries have legislations for wearing bicycle helmets, the usage of protective devices might need to change from a recommendation to a requirement in the countries with high level of head injuries, such as the Netherlands [ORM].
- **Education and training**: Educational programs focused on the training of cyclists at the roadside need to be implemented.
- **Legal Framework and Enforcement**: Laws and penalties are important in proving protection for vulnerable road users and influencing driver behaviour.

While a lot of existing approaches focus on the improvement of cycling infrastructure and educational programs for cyclists, especially for children, over the last ten years various technological advances for cyclists have been introduced and evaluated. We outline and categorize existing cyclists assisting systems in the following section.

2.3.3 Technological Assistance

Since the invention of a bicycle over 200 years ago, the technological development for bicycles went a long way of bringing assistance for people, starting from "draisine" to e-bicycles. A variety of technological interventions has been developed for supporting cyclists, however, the evaluations of these systems have been conducted with adults (Figure 2.5). These systems have been used to assist cyclists with navigation, warning signals, traffic behavior recommendations, and lane keeping cues, which has been previously mostly done in the automotive domain, and have been typically located on the bicycle, on the body, or in the environment around cyclists. In the following subsections, we discuss previous work through the prism of these four areas and highlight challenges in designing safety systems for children.

2.3.3.1 Warnings signals

A range of research and commercial systems have explored the use of visual feedback integrated into the bicycle and a helmet to warn cyclists about upcoming danger. For example, Garmin Varia Rearview radar [2] warns the rider about vehicles approaching from behind using an on-screen visual notification mounted on the handlebar. Other warning systems for cyclists [Har13] and motorcyclists [Gra00] employed a buzzer, beeper, or lighted bulb to warn about approaching vehicles and possible collisions. Massey [MRS17] has introduced technology for tracking location and motion of multiple vehicles, which warns drivers about possible collisions at the same time.

Schopp et al. [SSH18] integrated a bone conductive speaker into a helmet to warn cyclists about approaching, out-of-view vehicles. The cyclists showed increased situational awareness and were better able to identify dangerous situations. Jones et al. [JSC07] augmented a cyclist's helmet with both input and output methods. They tracked head tilts and utilized them to indicate turn signals on the back of a helmet. Similarly, a commercial product, Blink Helmet, utilized manual buttons on the sides of the helmet to indicate stop and turn signals.

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

2.3.3.2 Navigation cues

Navigation cues have been previously integrated on the handlebar, in a helmet, or projected in front of a cyclist. One of the earlier works in on-bicycle systems was TactiCycle [PPB09, PPHB12] which integrated vibration motors in the handlebar for turn-by-turn navigation. SmartGrips [3] further commercialized this idea and released two vibrotactile grips that could be easily integrated in the handlebar for navigation. Another on-handlebar LED-based navigation product, called Smarthalo [4], indicates distance and direction via different light patterns. Hammerhead [5] is a bike accessory that also can be fixed to the handlebar and indicates turn-by-turn navigation cues through directional LEDs. Both navigation devices, however, require pairing with a smartphone to receive routing information.

Tseng et al. [TLCC15] utilized peripheral light cues located inside the helmet, above the eyes, to navigate riders without introducing additional distraction. Since our aim is to assist child cyclists on the road without mental overload, a part of this thesis investigated the use of ambient light integrated in the helmet to represent warning signals, navigation and lane keeping cues, and safety gesture reminders. Another inspiring approach is the use of projection to indicate navigation cues and improve visibility. Dancu et al. [DVÜ+15] augmented a bicycle with a map projection in front of the bicycle to show navigational cues and projected turn signals at the back to show the turn intentions to other road users.

2.3.3.3 Lane keeping cues

Lane keeping assistance has been previously explored in the automotive domain. For example, Pohl and Ekmark [PE03] explored a torque feeling in the steering wheel, which mediated the correct lane position. They suggest that a multimodal assistance, for instance, combination of a haptic feedback with a HUD display might work better to increase driver's awareness. However, Kidd et al. [KCRK17] showed that driver's trust for an active lane keeping was the lowest among drivers' assistance technologies. We do not know how we can support child cyclists with a safe lane keeping in situations with missing cycling infrastructure, and therefore focus on this aspect in our work.

2.3.3.4 Traffic behavior recommendations

Different commercial systems have presented recommendations for a safe behavior on the road using helmet and projected interfaces. Newly introduced helmets with augmented reality look promising for representing information in a subtle and non-distracting way. For example, the SKULLY AR-1 [6] shows detailed infor-

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[3] `http://smrtgrips.com/`
[4] `https://www.smarthalo.bike`
[5] `https://www.dragoninnovation.com/customer-projects/hammerhead`
[6] `https://skullytechnologies.com/fenix-ar/`

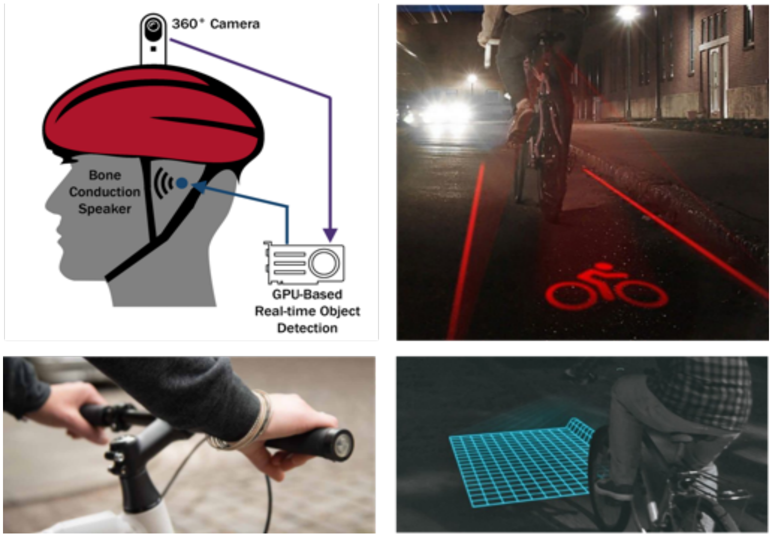

Figure 2.5: Examples of existing technologies to support cyclists: a helmet with a spherical camera mounted to a bike helmet to capture a user's surroundings, presented by Schopp et al. [SSH18] (upper left), Flashy Blinky Lights with a projected bicycle lane on the sides of the bike[11] (upper right), SmartGrips with two vibrotactile grips integrated in the handlebar[a] (lower left), and LumiGrids with projected grid to detect obstacles on the road[9] (lower right). The images were taken from the corresponding research papers and official web-sites. [a] *`http://smrtgrips.com/`*

mation about speed, navigation, and nearby vehicles in the corner of a helmet's visor. Another example is the Livemap helmet [7], which augments the environment with routing information, speed and safety features. However, it is unclear whether augmented reality helmets can enhance safe cycling and lane keeping for children. Additionally, we were inspired by VRscout project [8] that explores DIY solutions for building AR glasses, and decided to extend the functionality of a helmet with a similar HUD display in our evaluations.

Commercial systems have also focused on the detection of obstacles on the road, such as potholes [9], and project a bicycle sign in the front to indicate visibility [10]. Flashy Blinky Lights introduced a projected bicycle lane on the sides of the bike to increase the visibility of cyclists in the dark and assist car drivers in keeping a safe distance [11]. However, it is unclear how effective these systems are, due to the lack of empirical evidence. For instance, previously, researchers discovered that projected surfaces were harder to use and perceived as less safer than head-up displays [DVÜ+15]. However, from the perspective of child cyclists it is valuable to have a system which can be usable in both day and nighttime. Therefore, in

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

our evaluations we investigated both HUD display and a laser-based projection to support child cyclists with keeping a good lane position.

Given the lack of empirical evaluation for assistance systems with child cyclists, this work primarily focuses on the lab and controlled test-track evaluations with child cyclists to explore technological enhancements integrated into helmets and bicycles. However, before diving into the main part of this thesis, in the next chapter we outline the development of children's motor- and perceptual-motor skills as an important factor affecting their ability to cycle. This overview helps us to define challenges for designing multimodal assistance systems for child cyclists.

3 Cycling and Child Development

This chapter focuses on motor and peceptual-motor development of children, which plays an important role in mastering cycling skills. Cycling is a combination of motor activities, such as pedalling, steering, balancing, and braking, and cognitive abilities, which include perception of the surrounding environment, paying attention and making judgments and decisions about a traffic situation [BRSB04]. One of the reasons for the high accident rate in the age group under 15 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 [BRSB04, LFP+15].

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 [SM92]. Undoubtedly, some of these issues are related to the development of children's motor and perceptual-motor abilities [BRSB04, DDBL+13, CTPK05]. For example, cycling subskills, such as balancing, pedalling, steering, or braking, develop at different rates [AOWO]. 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 [DDBL+13], observing traffic signals [BRSB04], estimation of car speed [CPZ+10], understanding of road crossing behavior and gap acceptance [PKC04]. The issue here lies in the difficulties children face in synchronizing perceptual information with motor movements [CPZ+10, PKC07]. 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 [Com16, Ell14]. 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 [Sch12] and Wierda and Brookhuis [WB91], 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, warning children of potential accidents, navigating, or assisting with lane keeping and safety gestures, which we outline in details in Chapter 4-7. In this chapter, we outline cycling-relevant aspects of children's development, which include motor and perceptual-motor skills.

3.1 Motor Development

Motor development is a continuous process throughout life. It starts with the reflexive period of infants and adjusts with regard to injuries or aging the whole life [Cla07]. However, development of children's motor skills over time is not only maturation, but also adaptation and learning. Fundamental motor skills, such as running, jumping, catching, normally develop through interaction with environment and biological development. For example, at the age of seven, these skills can be refined and guided towards context-specific activities, such as swimming and cycling [BM98, GO05, PI17].

Motor coordination is often classified based on the group of muscles responsible for this movement: gross and fine motor skills. Gross motor skills refer to the whole body movement, such as running and jumping, and fine motor skills require more precision and dexterity, and often usually involves the manipulation of small objects, such writing and drawing [DDV$^+$11, DDG$^+$13]. Given that child cycling does not require particular precision and flexibility, a combination of different groups of gross muscles are responsible for children's motor cycling abilities. They focus primarily on the movement quality, coordination, and stability of movement.

Since motor skill development is a complex process happening during a lifelong journey, many researchers suggested developmental models to describe this process. For example, Seefeldt [See80] presented a *hierarchical model* of motor development with four phases. The first phase consists of involuntary reflexes in infants, followed by object control and locomotion skills included in the second phase. The third and fourth phases are based on the previous two and are responsible for development of transitional motor skills and sport-specific skills respectively, which include development of skills necessary for cycling.

Clark and Metcalfe [CM02] see the motor development process similar to climbing a mountain and suggested a *mountain metaphor*. Each stage of this mountain is responsible for a development of a particular motor skill and is built on top of each other. In addition to Seefeldt's model, this model also accounts for individual constraints, environment and tasks, which play an important role in shaping motor skills. Similarly to Seefeldt's model, it includes reflexive ($<$ 2 weeks), preadapted phase (2 weeks - 1 year), which include development of grasping and rolling, followed by fundamental motor skills (1-7 years), context-specific (7-11 years) and skilful motor development ($>$ 11 years). Children's high skilfulness is located on a mountain's peak.

Later on, in 2005, Gallahue introduced a *triangulated hourglass model* [GO05], where he used a metaphor with sand falling into the hourglass. In this representation sand represents different factors, which influence motor development. Similar to two previous models, it consists of four developmental phases, which include reflective, rudimentary, fundamental, and specialized movement phases.

Fundamental phase is subdivided into initial phase (±2-3 years), emerging elementary phase (±3-5 years), and proficient phase (±5-7 years). As in the mountain metaphor, this model accounts for individual, environmental and task constraining factors, which influence the rate at which children obtain motor skills.

From the three motor development models, we can see that this is a complex lifelong process, which depends on children's biological development, environmental and learning factors. The goal was to indicate the developmental phases of different models and to show that all of them reach similar conclusions, maturation years and influential factors. We also see that context-specific motor skills are still maturing between 7 and 11 years and a skilful phase starts after 11 years old. This fact underlines the necessity of cycling assistance for children in this age range. Therefore, this thesis focuses on the technological assistance of child cyclists, aiming to create safe cycling environment and increase learning in the early stages of cycling.

Zooming into motor cycling skills shows that they often require a complex set of movements, such as hand gestures, shoulder look, or turning. For example, previous research [DDBL+13] has identified thirteen components for motor cycling skills, which need to be mastered to ensure safe cycling: (1) walking with the bicycle, (2) mounting and starting the bicycle, (3) shoulder look left and right, (4) bicycling in a straight line over a small obstacle, (5) bicycling in a circle, (6) bicycling one handed in a circle, (7) bicycling a slalom in and out of markers, (8) looking over the left shoulder while bicycling in a straight line, (9) bicycling over obstacles, (10) bicycling on a sloping surface, (11) signalling left and right while bicycling in a straight line, (12) braking to come to a controlled stop, and (13) dismounting the bicycle. This set of skills is often to indicate for reaching a particular level of mastering the cycling in the experiments.

Normally mastering the bicycle skills depends on two factors: (1) children's physical and mental development and (2) cycling experience. At the age of five, children still have undeveloped psychomotor skills to handle most of the aforementioned situations, while a 9-years old can successfully handle most of the tests related to this set of motor skills. Cycling experience also plays an important role in acquisition of necessary cycling skills. For example, previous research has empirically shown that more experienced cyclists have a better control of their bicycles and are less prone to have an accident [WB91, Sch12].

One way to improve cycling experience is to attend cycling training courses, aimed to improve children's motor cycling skills [LNVH13]. Many western countries introduced cycling courses to improve children's motor abilities, such as Bikeability in Scotland [1], "Safe Routes to School" in New Jersey and US [2]. These initiatives are aimed to improve children's cycling skills, encourage them to cycle, increase children's knowledge of traffic signs. They usually start with traffic-free

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[1] `https://www.cycling.scot/bikeability-scotland`

[2] `http://www.saferoutesnj.org/`

trainings on the dedicated areas, where children practice braking and balancing, and progress over time to more complex situations, such as positions on the road, interaction with other road users, and cycling on a curve and intersections. Training programs normally do not include practising in real-traffic environments due to the safety and ethical concerns, and is often offloaded to parents, volunteers, or dedicated schools. They have also been shown to be successful in increasing children's both motor and cognitive skills. For example, Savill et al. [SBBH96] tested cycling skills of 12- and 13-years old children two years after attending a bicycle training, such as starting a bicycle, braking, turning, and overtaking parked cars. Trained children performed well on most of the tasks, but they still had difficulties with pedalling or showing hand gestures and performing shoulder looks before turning. This finding motivates a part of this thesis about reminders of safety gestures for child cyclists, presented in Chapter 7.

Although children improve their motor skills at training courses, they often have difficulties in mastering some skills, such as shoulder looks or hand gestures. Moreover, development and practising of motor skills are a time-consuming process, which normally evolves from childhood to adolescence. Ideally, children would start cycling on the streets after acquiring necessary motor skills, but unfortunately it is not always the case. These aspects encourage us to develop assistance for child cyclists "on-the-go", which will enable learning by doing, i.e., learning by cycling.

3.2 Perceptual-Motor Development

Within the scope of children perceptual-motor development we focus on visual, auditory, and cognitive aspects, which are relevant for our work. Children's ongoing cognitive and motor maturation between six and 13 years old is one of the main challenges of this work. This maturation strongly influences the developmental aspects vital for cycling, such as ability to fixate, static and dynamic visual acuity, selective attention, obstacle avoidance, and many more. In the following we will outline aspects of visual, auditory, and cognitive development.

Visual perception is vital for cycling. It is one of the most important channels for effectively perceiving the surrounding environment, looking for hazards, avoiding distractions and obstacles. In particular, these safety-relevant skills depend on the ability to fixate, saccades movement, and smooth pursuit eye movement. Normally, the ability to fixate is acquired within the first six months of life [AGHY07], however a fixation steadiness develops throughout adulthood [LVG08]. This suggests that duration of fixations on a target is longer for children than for adults, which might cause distractions or delayed reactions to external stimuli [HPSR14]. Eye saccades are responsible for simultaneous movement of both eyes between multiple phases of fixations and vital for visual search [SSE$^+$06]. Children's saccades are still less precise and shorter compared to adults. Moreover, their velocity increases until the age of 14 and the cognitive adult-like performance is reached at the age of twelve [HPSR14]. Another aspect of children's visual development is related to smooth pursuit eye movements. This ability of eye movement ensures fixation on a slowly moving small target on or near the fovea, and requires for high definition vision [SSE+06, LZ15]. Recent experiments with children report that smooth pursuit gains are lower in children compared to adults, approaching adult values in mid adolescence. Children have larger phases than reported adults values indicating that prediction in the smooth pursuit system is less mature in children [SSL+06].

Auditory perception is important channel of information for child cyclists. It plays an important role in increasing awareness of the road situation [SKHC+16], e.g., noise of a car approaching from behind, ringing a bicycle bell. Although at the age of six months infants already have an adult-like perception of auditory information [HG19], granular elements and patterns of auditory information, such as different intensity, frequency, pitch, develop through childhood [BLK+13, Boo97, PB96]. Perception of distance and direction of the sound of the upcoming car is essential for cycling safety. It depends on the difference of arrival time on both ears and sound intensity at each ear. Given that the perception of sound intensity is still developing, it is sometimes challenging for children to effectively estimate the direction and distance to the sound source. Even though children's auditory perception rapidly develops until the age of 8-10 years, in particular distance and direction estimation, however the refinements are still happening until the age of 13 years. Moreover, the ability to distinguish relevant sounds from the background noise is already present in infants, but it further improves throughout childhood. In general, similarly to visual perception children's auditory perception develops throughout the childhood and accounts for numerous refinements.

Similar to visual and auditory perception, other children's safety-relevant cognitive abilities, such as acquiring relevant environmental information, processing speed of received information, and working memory [HG19, LVG08], also develop throughout childhood. These abilities work together to support cognitive control of cycling behavior and depend on children's experience and development. For example, when children gain more cycling experience, executive functions and strategies require less mental resources needed to process big amount of information. Development in processing speed changes in working memory and shifts from concrete to abstract perception of the surrounding environment. Development of cognitive systems also depends on the environmental factors and biological development, such as brain maturation, and is a time-consuming process. Therefore, children tend to experience difficulties in perception an environment's global picture in the presence of distraction.

We have seen that perceptual-motor abilities, such as visual, auditory, and cognitive information processing, undergo changes from early childhood until adulthood. However, one more challenge for child cyclists is a synchronizing both motor and perceptual-motor abilities. Previous work has shown that children have difficulties in syncronizing motor and perceptual-motor information [CPZ+10, BRSB04] and have outlined the limitations of their attention capacity [EPS97, PTA95]. In comparison to child pedestrians, child cyclists move at the higher speed, which requires a more complex decision-making and faster reaction times to external hazards in addition to a simultaneous bicycle control.

Children's difficulties with synchronizing motor and perceptual-motor information have been observed in the experiments with estimation of time-to-collision and gap acceptance. For example, Briem et al. [BRSB04] conducted an experiment with 57 children aged from eight to twelve on the training area, where they had to cycle in circles on the roads with traffic light changing to red from time to time [BRSB04]. It was shown that 52 out of the 57 participants either missed a signal or overshot the stop line at least once at the eight signal changes. Their outcome suggests that children cycling performance decreased due to the increased task load and generally depends on the combination of motor and perceptual-motor abilities. Moreover, the results have shown that children's cycling speed and a number of mistakes increased with age, e.g., mistakes at short stopping range, which required faster reaction times. Plumert et al. have shown that children underestimate the time-to-collision with approaching cars, because they base their decision on the distance instead of both distance and speed [PKC04]. The results showed that children left less spare time between themselves and the approaching vehicle when they crossed the intersection. Compared to adults, they needed more time to start cycling and reach the roadway. Most likely children had more difficulty in estimating time-to-collision, coordinating the movement related to traffic, or how long it would take the vehicle to reach the crossing line. However, in another experiment Plumert et al. [PKC+11] observed that cycling over a longer period of time led to an acceptance of smaller gaps and improves decision-making and perceptual-motor functioning. This finding indicates the importance of children's cycling practice and improvement of cycling abilities over time.

After looking at the high accident rate and ongoing development of children's motor and perceptual-motor abilities, in this thesis we aim is to assist children "on-the-go" with technological feedback, much like parents who guide their kids with instructions while cycling. We explore how existing modalities and feedback mechanisms can be used to help children while they master cycling skills. In the following four chapters we investigate how technological augmentation of bicycles and helmets can assist child cyclists.

4 Warning Signals

This chapter focuses on the design space of warning signals for child cyclists. In part due to the development of children's motor and perceptual-motor abilities, child cyclists are often at greater risk for traffic accidents. To facilitate road safety for children, we explored the use of multimodal warning signals to increase their awareness and prime action in critical situations. We conducted two laboratory experiments an instrumented bicycle simulator to ensure cycling experience in safe conditions. As a result from both experiments, we derived a set of on-bicycle and helmet locations for auditory, vibrotactile, and visual feedback suitable for child cyclists and an initial set of multimodal warning encodings for children's bicycle safety. We show that with the support of warnings child cyclists faced no accidents in the bicycle simulator and spent more time perceiving visual than auditory or vibrotactile cues. Our results also indicate that unimodal encodings were applicable for directional cues and multimodal for immediate actions. Lastly, trimodal warnings performed better for understandability and led to shorter reaction times.

The material in this chapter originally appeared in Matviienko, A., Ananthanarayan, S., Borojeni, S. S., Feld, Y., Heuten, W., & Boll, S. Augmenting bicycles and helmets with multimodal warnings for children. The 20th International Conference on Human-Computer Interaction with Mobile Devices and Services, 2018.

4.1 Background and Motivation

The number of cyclists worldwide has increased considerably over the last couple of years [PB17]. Most notably, cyclists comprise 26% of the population in the Netherlands, 18% in Denmark and 10% in Germany [PB12]. Even though the number of accidents with cyclists has decreased over the last two decades [ACW$^+$16, SW13], bicyclists still remain a highly underrepresented group and belong to the category of vulnerable road users.

A closer look at the statistical accident reports show that child cyclists aged between six and thirteen years suffer the most road related injuries of any age group [Com16, Ell14]. 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 [BRSB04, LFP$^+$15].

In recent years, researchers have augmented helmets, bicycles, and clothing accessories with ambient, vibrotacticle, and audio cues to improve rider safety. Notable examples include a vibrotactile belt to aid navigation [SB13], a display projected on the road surface to show cyclist intention [DVÜ$^+$15], a GPS-based collision detector [YHNS15], and a peripheral light display integrated in a helmet for distraction-free route guiding [TLCC15]. 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 in an understandable and intuitive way.

This chapter aims to fill this gap in increasing safety for child cyclists. We investigated how visual, vibrotactile, and auditory feedback situated in the helmet and bike can be used to convey warning signals. We explored a multimodal approach motivated in part by its success in the automotive domain, particularly in increasing driver awareness [LHB15a], and conveying navigation information [MLEA+16] and warning cues [PBP13]. 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 the investigation with children, especially since they aim to present information without additional mental load. We also adopted simulator based evaluations and showcased a bicycle simulator, which 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 [Com16, GSS+16a, KHL15].

4.2 Perception of Uni- and Multimodal Signals in a Bicycle Simulator

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.

4.2.1 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 anywhere from 2 to 20 times per week for school, fun, or shopping.

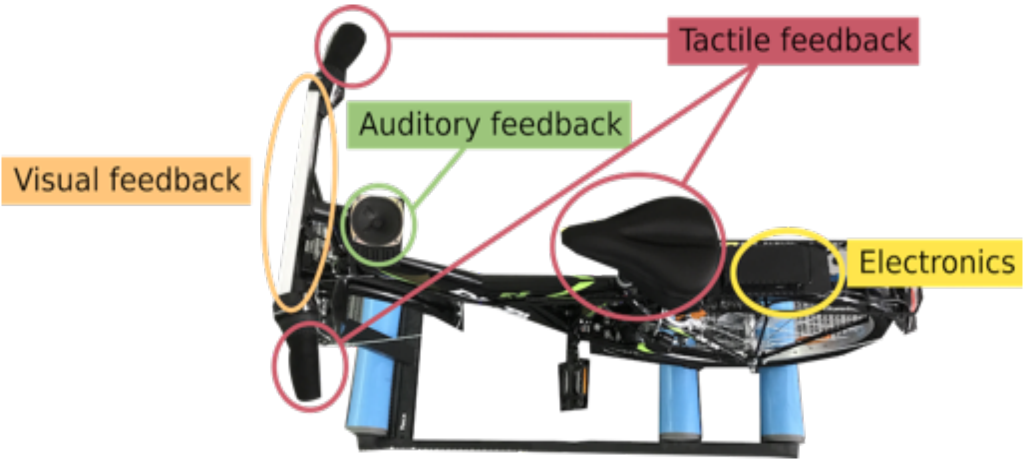

Figure 4.1: Bicycle on a stationary platform fitted with unimodal and multimodal feedback.

4.2.2 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 4.1). Actions on the bike such as braking and pedalling are reflected in a simulated environment projected on the wall in front of the bike. The environment was implemented using the Google Maps Street View API[1]. The simulation was limited to straight roads for the sake of simplicity (Figure 4.2). 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 [BARS12]. 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

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

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.

Figure 4.2: A child cycling through a street view simulation projected on the wall.

4.2.3 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 4.1). 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. 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 4.1.

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.

#	**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 red flashes	100%
5	Light	Right	3 green flashes	100%
6	Light	Left	3 green flashes	100%
7	Audio	Front	Speech: *"Please stop!"*	100%
8	Vibration	Left Right	3 pulses 3 pulses	82%
9	Light Vibration	Left Left	3 green flashes 3 pulses	96%
10	Light Vibration	Right Right	3 green flashes 3 pulses	100%
11	Light Vibration	Front Saddle	3 red flashes 3 pulses	93%
12	Vibration	Left Right Saddle	3 pulses 3 pulses 3 pulses	63%
13	Light Vibration	Front Left Right	3 red flashes 3 pulses 3 pulses	96%
14	Light Vibration	Front Left Right Saddle	3 red flashes 3 pulses 3 pulses 3 pulses	45%

Table 4.1: Summary of conditions and results of the exploratory study. The cues for conditions #8-14 were activated simultaneously.

4.2.4 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 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 [KHL15, GSS$^+$16a].

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.

4.2.5 Results

The exploratory study helped us 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.

4.2.5.1 Existing Problems

Despite the small sample size, we confirmed the previous work of Sandels [San70] 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).

4.2.5.2 Recognition rate

We found that unimodal signals (Table 4.1, #1-7) were recognized 100% of the time. 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.

4.2.5.3 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 [PPHB12].

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.

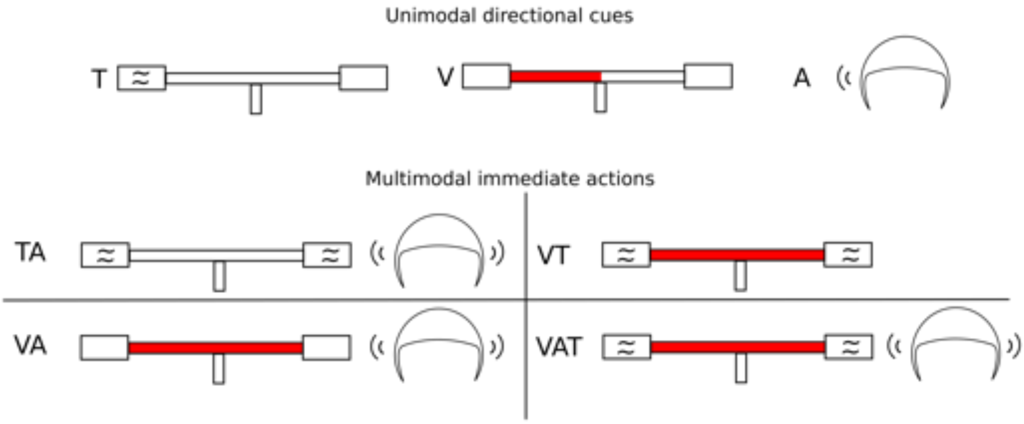

Figure 4.3: Overview of encodings for directional cues and immediate actions. Tactile and visual feedback were presented on the handlebar and auditory was integrated in the helmet. For example, the unimodal directional cue on the left a car approaching from that direction. V = visual, T = tactile, A = audio, TA = tactile + audio, VA = visual + audio, VT = visual + tactile, VAT = visual + audio + tactile.

4.3 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 [FKHK07] with unimodal encodings consisting of either auditory [HS05] or vibrotactile [HTS05] 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) [Com16, GSS$^+$16a, KHL15]. To 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 [MLA07] 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 [PBP13]. The summary of encodings for both directional cues and immediate actions are shown in Figure 4.3.

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 4.2.

#	**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 4.2: 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.

4.4 Efficacy of Uni- and Multimodal Warnings in a Bicycle Simulator

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.

4.4.1 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.

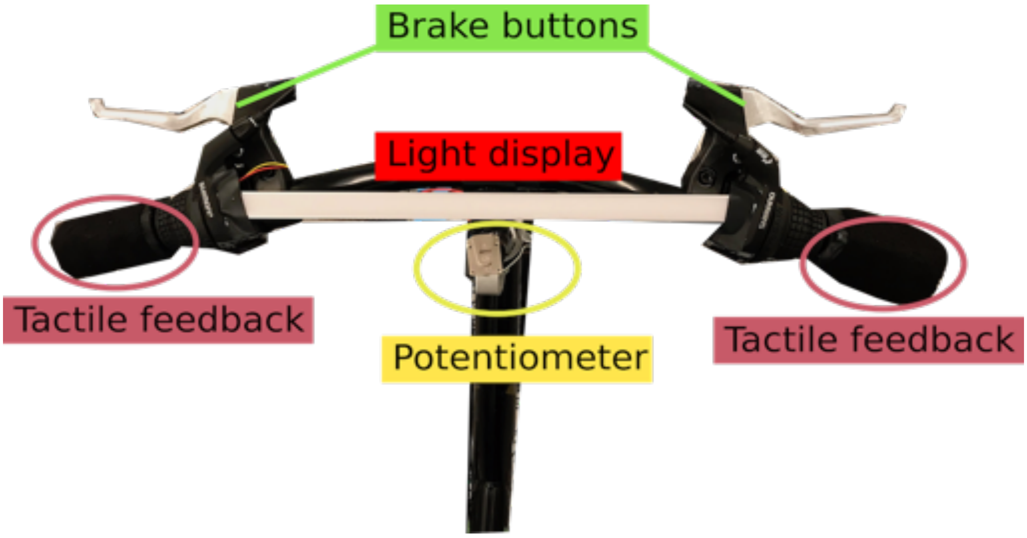

Figure 4.4: Front part of the bicycle simulator: a handlebar with visual and tactile feedback, a potentiometer for measuring rotation angle and buttons to detect braking activities.

4.4.2 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 4.4) and multiple magnets on the rear wheel for a better estimation of speed (Figure 4.5). Children could now turn left and right, which made their cycling experience more realistic.

The light display on the handlebar and the vibration motors on left and right grips remained the same (Figure 4.4). 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.

4.4.2.1 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 4.6). The speakers were connected to

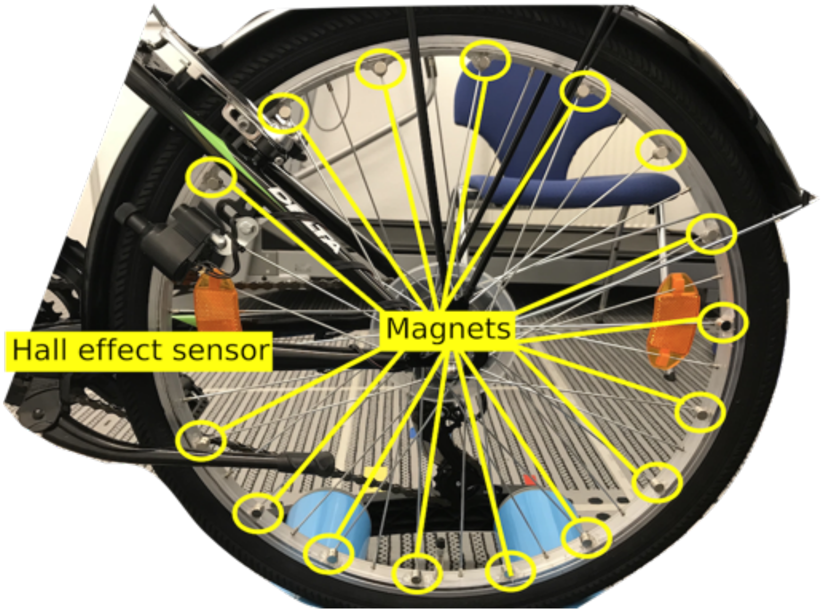

Figure 4.5: Rear part of the bicycle simulator: rear wheel with hall effect sensor and a set of magnets for measuring speed.

a NodeMCU 8266 board[2] 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.

4.4.2.2 Simulation

In order to create a more realistic simulation experience, we used SILAB driving simulator software[3]. While this simulation software is normally used for car simulators, we were able to customize it for our bicycle simulator (Figure 4.7). 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.

4.4.3 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 4.2). Within these thirteen conditions, we explored two types

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[2] `https://en.wikipedia.org/wiki/NodeMCU`

[3] `https://wivw.de/en/silab`

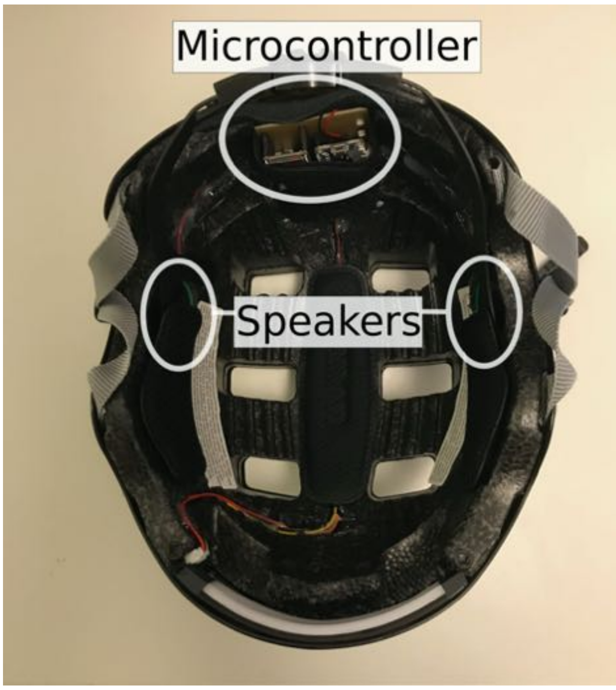

Figure 4.6: A helmet with auditory warning signals.

of dangerous situations for cyclists on the road based on prior statistical reports [Com16, GSS+16a, KHL15]. 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 per each condition: three with a directional cue followed by an immediate action and three with immediate action only. 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).

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.

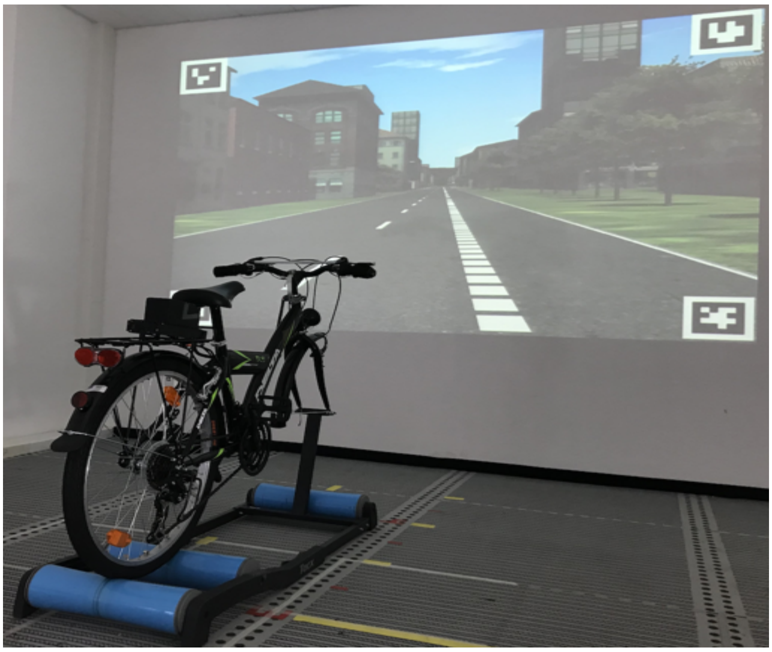

Figure 4.7: An indoor bicycle simulator consisting of a projected street view connected to a stationary bike. It was used to investigate on-bicycle and helmet locations for warning signals.

4.4.4 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 then had a chance to familiarize 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 children about their preferences for the different warning signals. The entire study lasted approximately one hour.

4.4.5 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 4.3), every participant estimated the understandability of each signal.

Distraction (Likert scale): for each condition (Table 4.2), every participant estimated the distraction of each signal combination.

We used Tobii Pro Glasses 2[4] 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 a cyclist's reaction time for immediate action signals with trimodal encodings (Table 4.2: condition #4, #8 and #12) would be shorter than bimodal. We based this hypothesis on previous work by Politis et al. [PBP13] that compared reaction times for various multimodal signals for car drivers. We also envisioned that cyclists would spend more time perceiving visual warning signals. Finally, we anticipated that children would consider non-visual encodings the least distractive for directional cues.

4.4.6 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%.

4.4.6.1 Reaction Time

The encoding with three modalities had a comparable *reaction time* (M = 474.96, SD = 230.83) to the encodings with two modalities: 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) (Figure 4.8). We did not observe a significant difference among them ($\chi^2 = 4.3$, p = 0.23). 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

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

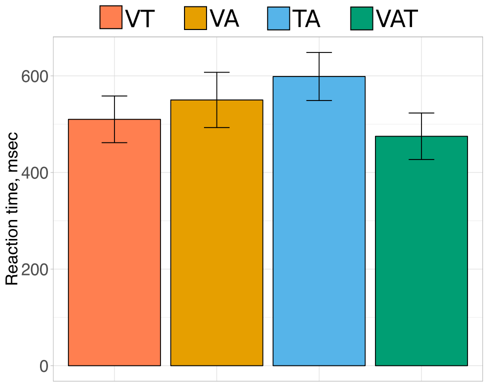

Figure 4.8: Reaction times for immediate action encodings.

at every junction before seeing a car.

4.4.6.2 Duration and Frequency of Glances

We discovered that the *duration of glances* was on average longer for conditions where two visual cues ($M \in (1.6, 2.7)$ sec) were presented rather than one ($M \in (0.5, 0.9)$ sec). Additionally, we found that the *frequency of glances* was on average higher for conditions with two visual cues ($M \in (1.2, 2.1)$) than with one ($M \in (0.4, 0.8)$). 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. We do not provide all pairwise comparisons using a post-hoc analysis with Wilcoxon signed-rank test, because the resulting table (12x12x3) would be too large. Instead, we present one example for conditions with two (V+VA), one (A+VA) and zero (A+TA) visual cues (Table 4.6). All post-hoc analyses were conducted with a Bonferroni correction to avoid type I errors.

4.4.6.3 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), auditory (M = 4.57, SD = 0.8) and visual (M = 4.19, SD = 1.14) encodings for directional cues were comparable for their understandability, based on Likert scale results (Table 4.3). 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.

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

Table 4.3:

Table 4.4: Understandability for all signals (5 - very understandable).

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 4.5). 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.

4.4.6.4 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.

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 4.5: Summary of descriptive statistics per condition. V = visual, A = auditory, T = tactile. Likert Scale (5 - very distractive).

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

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."*

4.4.7 Discussion

Broadly speaking, 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 [PPHB12] and on-body [BKAS11] 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 [HTS05]. 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.

4.4.7.1 “The more, the better”

When it comes to alerting children of immediate danger, multimodal encodings can be the most effective. Not only did children prefer these encodings, but they also performed better in terms of reaction time. As one child exclaimed, *“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 among bimodal and trimodal signals, the simultaneous activation of tacticle, 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. [PBP13]. 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 4.8). 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 [SMB14].

4.4.7.2 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 4.5), 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, 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 [TLCC15]. 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 [NEFL16]. 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.

4.4.7.3 Supporting Perceptual-Motor Learning

When we started work in this area, our goal 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 [SRRW13]. 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" [SRRW13]. The bicycle simulator in this case, can support coordination, teach children to recognize traffic scenarios, and raise situational awareness.

4.4.7.4 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.

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 [PLGM^{+}15] or external stimuli [BVCT17]. Apart from the simulator, 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.

4.4.8 Summary

This chapter reports from two laboratory experiments in an instrumented bicycle simulator, exploring multimodal warning signals for child cyclists. The outcomes provide insights into how warning signals can be represented for child cyclists multimodally, and in an understandable and non-distracting way to address RQ1: *How can we represent warning signals for child cyclists in an understandable and non-distracting way?*

In both experiments we investigated ambient light on a bicycle, vibrotactile feedback on a handlebar's grips and a saddle, and the auditory feedback on a bicycle and in helmets as speech- and beep-based instructions. In the second experiment we simulated two most dangerous situations: (1) at junctions, where a car was approaching either from left or right, and children were notified via directional cues, and if danger of collision remained, they were presented with a follow-up immediate action signal to prime braking; (2) 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. The main outcomes from the two studies are:

- We derived a set of on-bicycle and helmet locations for multimodal feedback applicable for warning representation and showed that with the support of the designed warnings child cyclists faced no accidents in the bicycle simulator. From the first experiment we derived that the auditory feedback needs to be placed in the helmet, close to the ears and without blocking them, to avoid a possible distraction to other cyclists and make the signals less invasive and more private. The results from the second experiment showed that ambient light signals need to located close the eyes to ensure a peripheral perception of the signals, for example, in the helmet.

- We discovered that children spend more time perceiving visual than auditory or vibrotactile cues. Since the visual signals were presented on the handlebar, children tend to glance at them more often, and therefore would need more time to react to them.

- We found that unimodal encodings were applicable for directional cues and multimodal for immediate actions. In this case, children could make a clear distinction between a less urgent signal (directional cue) and an urgent signal (immediate action).

- We observed that trimodal warnings performed better for understandability and lead to shorter reaction times. This outcome supports the results from previous works in the automotive domain, where drivers reacted faster to multimodal signals. In our experiment, a simultaneous activation of multiple signals ensured a better and faster perception of the signals.

  Therefore, to answer RQ1 we distinguish between two types of warning signals: directional cues and immediate actions. Based on the results of two experiments, we can conclude that directional cues can be best represented unimodally using acoustic signals in the helmet or vibration on the handlebar, and the immediate actions – using simultaneous activation of vibration on the handlebar and acoustic and visual signals in a helmet.

5 Navigation Cues

This chapter focuses on the design space of navigation cues for child cyclists. 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.

The material in this chapter originally appeared in Matviienko, A., Ananthanarayan, S., El Ali, A., Heuten, W., & Boll, S. NaviBike: Comparing Unimodal Navigation Cues for Child Cyclists. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 2019.

5.1 Background and Motivation

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 [MT13]. 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 [BRSB04, LFP+15]. Combined with undeveloped attentional skills of children aged from six to 13 [TJFS05, DB10, BM11], 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 [TLCC15], a vibromotor belt for navigation [SB13], and projected maps on the road [DVÜ+15]. 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

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

Figure 5.1: A mid-size tricycle and helmets equipped with auditory, light and vibrotactile navigational cues for investigation in an outdoor practice test track.

in an understandable and non-distractive way.

In this chapter, 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 [PPB09, PPHB12, SB13]. We conducted two experiments to compare these three navigation modalities in a bicycle simulator and in an outdoor practice test track (Figure 5.1). To simulate cognitive load, we employed an auditory distraction task [WB91] 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 chapter, we present an empirical evaluation of different unimodal navigation instructions for child cyclists.

5.2 Exploring Unimodal Navigation Cues in a Bicycle Simulator

We began our investigation in an indoor bicycle simulator. Based on previous works that explored navigation for motocycles [PTGH14] and cars [MLEA$^+$16], 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[2] and Google Maps. Specifically, we used the phrase *"Be ready to turn left/right*

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[2] `https://goo.gl/E9xjfY`

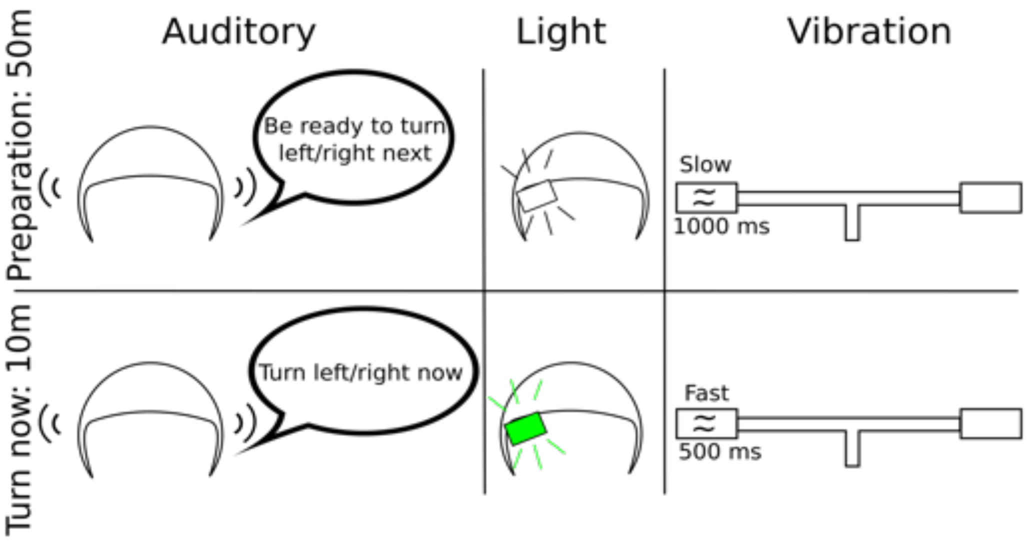

Figure 5.2: Overview of feedback encodings for navigation cues used in both lab and controlled test-track experiments. Children experienced speech and blinking light (white followed by green) in the helmet, and vibration on the handlebar with "preparation" and "turn now" phases, presented at 50m and 10m before turning respectively.

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 [TLCC15]. We used white and green blinking patterns based on previous work [MLEA+16], 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 [PPHB12], which utilized similar patterns for vibration patterns. The preparation and turning signals were shown 50 meters and 10 meters before the turn respectively (Figure 5.2), based on the work of Steltenpohl and Bouwer [SB13]. We excluded the comparison with screen-based Garmin navigation devices, given the results from Chapter 4 that showed that children were distracted by a visual feedback placed on the handlebar. However, we do not exclude the necessity to additionally evaluate Garmin devices with child cyclists.

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 [AOWO]. 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 [WB91]. 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.

5.2.1 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.

5.2.2 Apparatus

We used the same bicycle simulator as presented in Chapter 4. However, this time the simulation consisted 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. The only difference in the setup was adding the auditory distraction task and a helmet. We added a button on the right side of the handlebar (Figure 5.3) and a speaker mounted on a tripod behind the bicycle (Figure 5.5). Both the button and the speaker were connected to an Arduino Uno programmable board, which communicated with the simulation software via a USB-connection.

We 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. 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 5.4).

To determine the children's eye gaze during the experiment, we used Tobii Pro Glasses 2[3], which are light-weight and easy to calibrate, especially while working

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

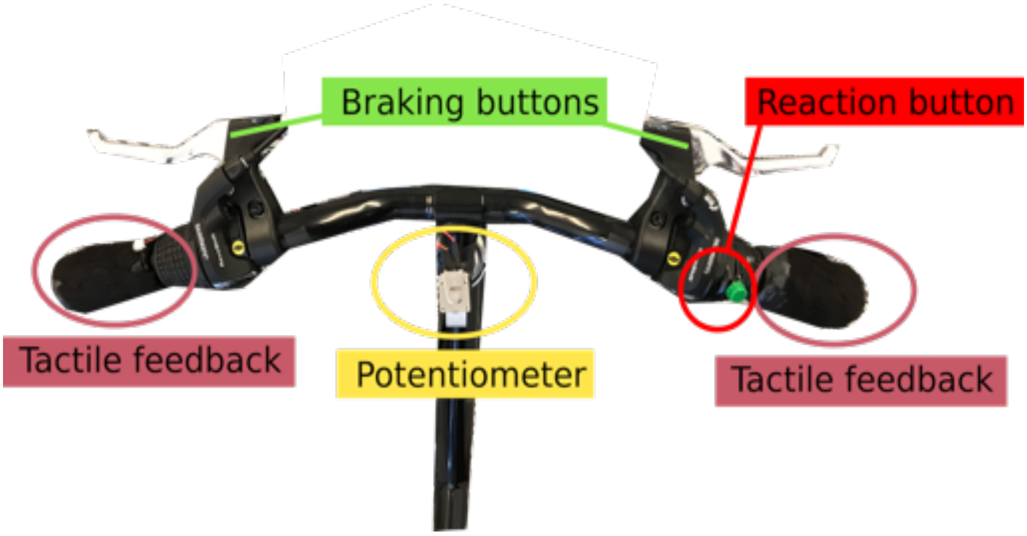

Figure 5.3: Bicycle simulator with a reaction button on the right side.

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.

5.2.3 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.

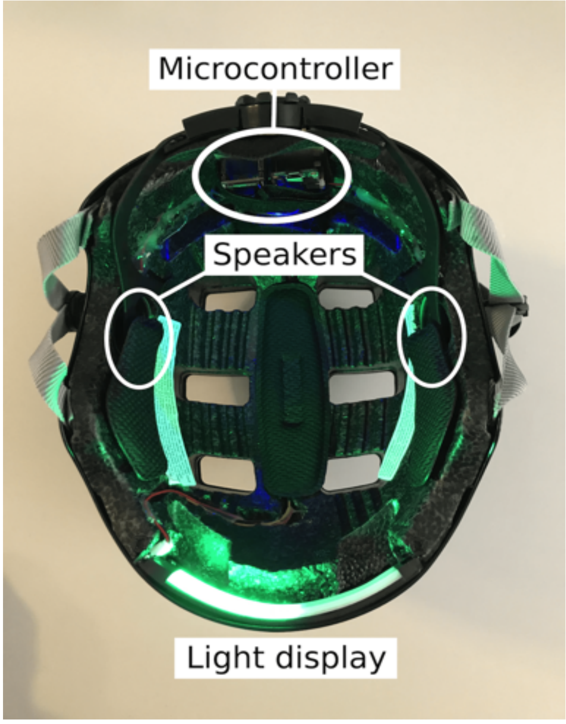

Figure 5.4: Helmet with auditory and visual navigation cues. Green light on the left side of the helmet indicates a turn left.

5.2.4 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 [WB91].

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.

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, ev-

	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 5.1: Summary of results for the laboratory experiment in a bicycle simulator. RT = reaction time.

ery participant estimated the required mental load while cycling with a given navigational aid.

5.2.5 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 5.5). 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.

5.2.6 Results

5.2.6.1 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 ($\chi^2 = 1.65$, p = 0.44) (Table 5.1).

5.2.6.2 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.

5.2.6.3 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 ($\chi^2 = 6.39$, p = 0.041). However, we found a statistical difference in error rate only between auditory and light-based navigation methods (Z = -2.77, $p < 0.01$).

5.2.6.4 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 [WB91], who also showed a 20% error rate for auditory distraction task.

5.2.6.5 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 ($\chi^2 = 19.32$, $p < 0.01$). 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 ($\chi^2 = 3.76$, p = 0.15).

5.2.6.6 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.

5.2.7 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 [CGW+16, DWNA07].

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 [PPHB12], the placement of the vibrotactile cues would be better served on the body, especially since children have to show hand signals while cycling [EU68]. 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 [DVÜ+15], 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

Figure 5.5: 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.

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 [WB91, SKLB08]. 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.

We confirmed the applicability of the auditory distraction task [WB91] 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 [LAK+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 [DB10, TJFS05]. By overly active children we refer to participants who had difficulties sitting calmly on the bicycle during the study and between the experimental conditions (N = 3). This observation underlines the challenge of designing a "one-size-fits-all" assistance system for child cyclists, given the wide age range.

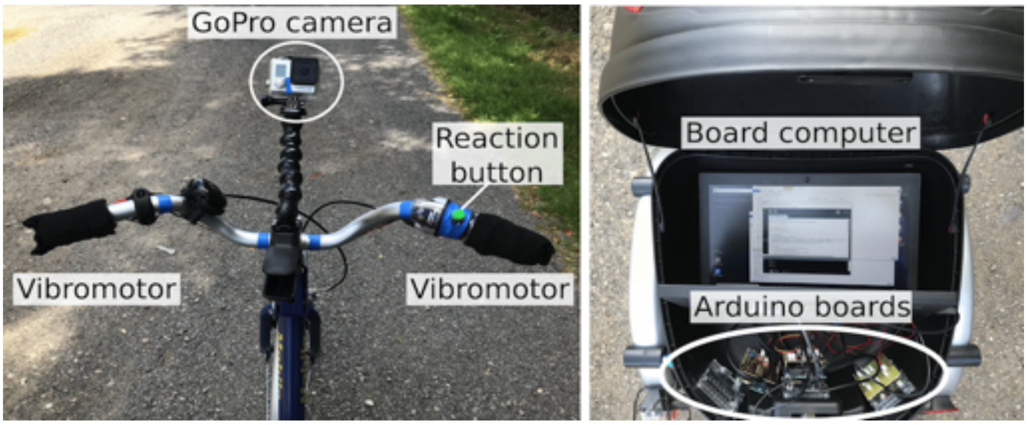

Figure 5.6: A tricycle equipped with a laptop in the rear cargo box, vibrtotacile feedback on the handlebar, a GoPro camera for in-field observations and a reaction button for the auditory distraction task.

5.3 Exploring Unimodal Navigation Cues on a Test Track

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.

5.3.1 Participants

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

Figure 5.7: LED helmet with LED strips integrated into the visor for the light navigation in the test-track study.

5.3.2 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 5.6). 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 5.7). 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 5.5). 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 5.6).

Figure 5.8: 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).

5.3.3 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 [WB91] 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 5.8). 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 sig-

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

nal – at two meters. Every participant cycled six random routes and experienced from six to eight turns per trial (Figure 5.8). 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 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.

5.3.4 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.

5.3.5 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

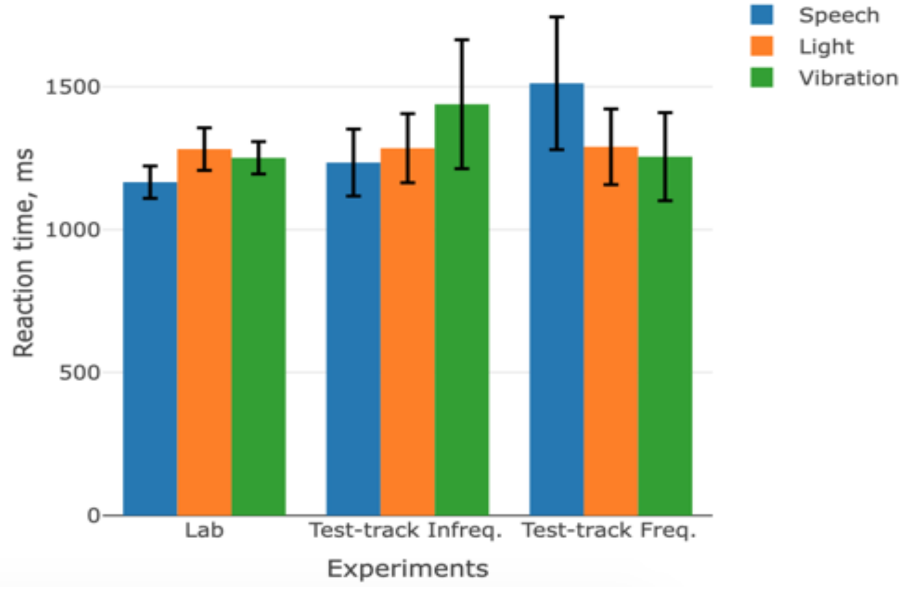

Figure 5.9: Summary of reaction times in laboratory and controlled test-track experiments.

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.

5.3.6 Results

5.3.6.1 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 5.9).

5.3.6.2 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 ($\chi^2 = 1.14$, $p = 0.57$). 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].

5.3.6.3 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 ($\chi^2 = 9.76$, $p < 0.01$). 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 ($\chi^2 = 7.5$, $p = 0.024$). 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: $Z = -1.66$, $p = 0.096$).

5.3.6.4 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].

5.3.7 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.

5.3.7.1 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 [BB04]. 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 [Com16, Ell14].

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 the previous chapter 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 chapter, where reaction time was higher, because children faced both the auditory distraction task and navigation signals simultaneously.

5.3.7.2 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.

5.3.7.3 Educating child cyclists

Looking over the shoulder and perfoming hand signals are an essential part of safe manoeuvring while navigating on the road [EU68]. 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 [JSC07] and hand gesture [DVÜ+15], we can remind children to perform the safety manoeuvres with vibration on the handlebar or on the wrist.

5.3.7.4 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 [PPB09, PPHB12], 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 [SKHW15]. 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.

5.3.7.5 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.

5.3.8 Summary

This chapter reports from one laboratory experiment in an instrumented bicycle simulator and one controlled test-track experiment, exploring unimodal navigation cues for child cyclists. The outcomes provide insights into how navigation cues can be represented for child cyclists uinimodally, and in an understandable and non-distracting way to address RQ2: *How can we represent navigation signals for child cyclists in an understandable and non-distracting way?*

In both experiments we investigated ambient light and speech in the helmet, and vibration on the grips of the handlebar to encode navigation cues for child cyclists. Except for the navigation cues, children experienced a secondary auditory distraction task, which we used to measure the reaction time of the participants and at the same time explore whether they have available mental resources for reacting to the external distraction.

The main outcomes from the two studies are:

- We found that the auditory navigation performs the best in the presence of the auditory distraction task. Despite the fact that both speech navigation and the auditory distraction task refer to the same auditory perception of the signals, children still performed better using auditory method in both laboratory and controlled test-track experiments.

- We propose that combination of light and auditory signals might be useful for children of younger age to distinguish between left and right. Given that some children might experience confusion between left and right while cycling, we find it essential to supplement future cycling assistance systems with light and speech, so that children can learn to distinguish the directions, especiallt in the beginning of their cycling experience.

- We 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. Similarly to the augmentation of speech navigation with light for learning left and right, we think that combination of vibration on the handlebar can facilitate hand gestures due to its high intuitiveness. Moreover, safety gestures play an important role in improving the safety for child cyclists, which we explore deeper in Chapter 7.

- 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. Since the usage of headphones are not recommended or even prohibited in some countries, we see helmets with auditory navigation cues as a suitable alternative for children. Moreover, from the technical point of view, coupling of smartphone to a helmet will reduce the computational power needed for the routing algorithms and will be done on the smartphone side.

Therefore, to answer RQ2 we claim that speech navigation integrated in the helmet can assist child cyclists with an understandable and non-distracting navigation way. Based on the results from two experiments, we also conclude that vibration and light can be used as a supplementary assistance to remind children about hand gestures and help them in distinguishing between left and right accordingly.

6 Lane Keeping Cues

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

The material in this chapter originally appeared in Matviienko, Andrii, Swamy Ananthanarayan, Stephen Brewster, Wilko Heuten, and Susanne Boll. Comparing unimodal lane keeping cues for child cyclists. In Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia. ACM, 2019.

6.1 Background and Motivation

The number of cyclists in some western countries has increased considerably over recent years [PB17]. For example, cyclists comprise 26% of the population in the Netherlands, 18% in Denmark and 10% in Germany [PB12]. Consequently, the risk for accidents is much higher; cyclists in North America are eight to 30 times more likely to be seriously injured than cyclists in the countries of northern Europe [PD03, PB06]. A lack of cycling infrastructure that separates motor vehicles from cyclists is one of the reasons for a higher accident rate in Canada and US compared to the cycling-friendly countries, like the Netherlands, Denmark or Germany.

A closer look at the statistical reports shows that cyclists aged between six and thirteen remain the most vulnerable age group [Com16, Ell14]. One of the reasons for the high accident rate among this age group lies in the motor and perceptual-motor developmental differences compared to adults, which affect children's performance of cycling activities. Motor, cognitive, and sensory information processing skills change from childhood to adolescence and influence children's capabilities for navigating complex traffic situations [BRSB04, LFP+15].

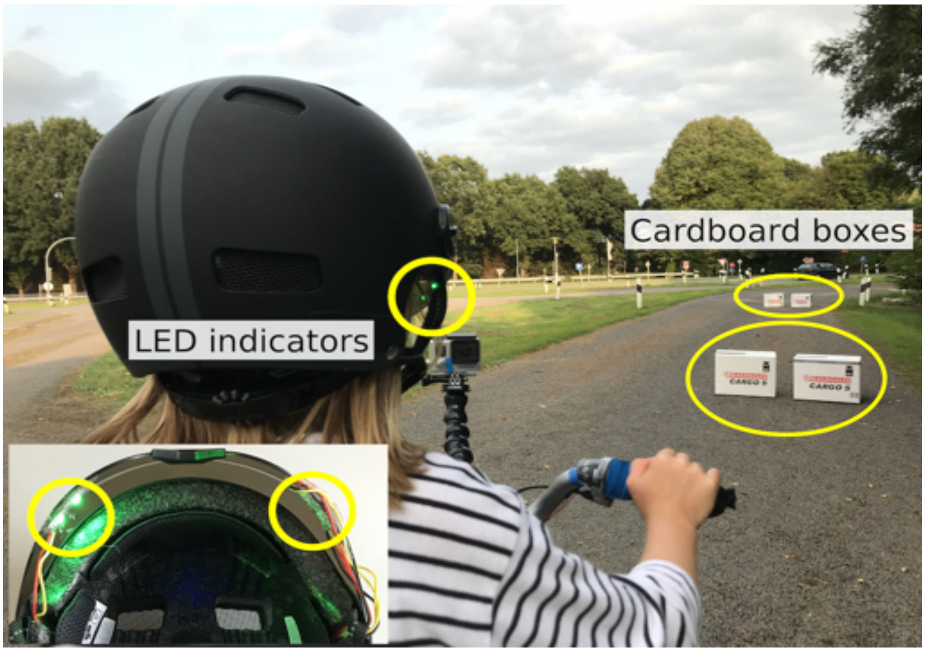

Figure 6.1: The LED helmet and road obstacles used in the controlled test-track experiment.

Recent enhancements to bicycles, such as 360° laser scanners (LIDARs)[1] and ultrasonic sensors[2], allow recognition of traffic and objects around cyclists [BZC+18]. This information is necessary for keeping safe distances to the obstacles within a virtual bicycle lane, especially in cities with missing cycling infrastructure [GGGC16]. These virtual bicycle lanes (i.e., not visible in environment) can serve as intermediary solutions while real infrastructure develops. In our work, we focus on how children can be supported to ride safely within these virtual lanes through different feedback cues. Our goal is not in the development of these virtual lanes using LIDAR or other sensors, but rather in the technology needed for children to stay within these dynamic virtual lanes.

Our goal is to ultimately increase the mobility of children by providing safety assistance systems on their bicycles and helmets. Multiple Resource theory suggests that usage of multiple modalities can potentially increase cyclists' attention without mental overload [Wic08]. We used this theory as a basis for creating unimodal feedback to present safety-relevant information for child cyclists to support lane keeping. Ultimately, we foresee using lane keeping system with accompanying ultrasound sensors on the side of the bicycle. This way we can correct the trajectories on-the-go in the absence of cycling infrastructure. We acknowledge that there are other solutions, such as making traffic members more aware of cy-

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[1] `https://www.borealbikes.de/wp-content/uploads/2018/09/Holoscene_JDE_Brochure.pdf`

[2] `https://interaktiv.tagesspiegel.de/radmesser/`

clists or extra bicycle training courses for children. However, we focus on tractable technological solutions to the problem given our present socio-economic culture. Unimodal cues for lane keeping is one possible approach in this broad research space motivated in part by its prior success in increasing driver awareness and conveying information unobtrusively in the automotive domain [LHB15b], motorcycling [TLCC15], skiing [NEFL16], and cycling with adults [PPB09, PPHB12].

To better understand children's issues while cycling, we first conducted an interview with twelve children. We then conducted a lab and controlled test-track experiment to explore how vibration on the handlebar, ambient light in the helmet, head-up display indicators, and on-road laser projection can assist child cyclists in maintaining a good lane position. For the lab experiment, we developed an indoor bicycle simulator and investigated the efficiency of lane keeping cues in the presence of a visual search task. In the subsequent controlled test-track experiment, we examined the generalizability of our findings in conditions closer to real world in an outdoor test track using a mid-size tricycle (Figure 6.1). Our main contribution is an empirical evaluation of unimodal lane keeping cues for child cyclists in both lab and test-track evaluations. Furthermore, we provide potential solutions for effective lane keeping for children, which can be easily and cheaply integrated into safety equipment (e.g., helmets), bicycles (e.g., vibration), and other accessories (e.g., projection).

6.2 Interviewing Children about Safety-Related Issues

Before starting the design and evaluation of lane keeping cues, we wanted to better understand any safety-related issues child cyclists faced and their behavioral patterns when encountering particular traffic situations, following a user-centered design approach [Coo00]. As can be seen from the related work, we lack empirical evaluation of lane keeping mechanisms for child cyclists. Therefore, we needed a deeper understanding of children's perceptions of road hazards and the way they deal with dangerous situations on the road.

6.2.1 Participants

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

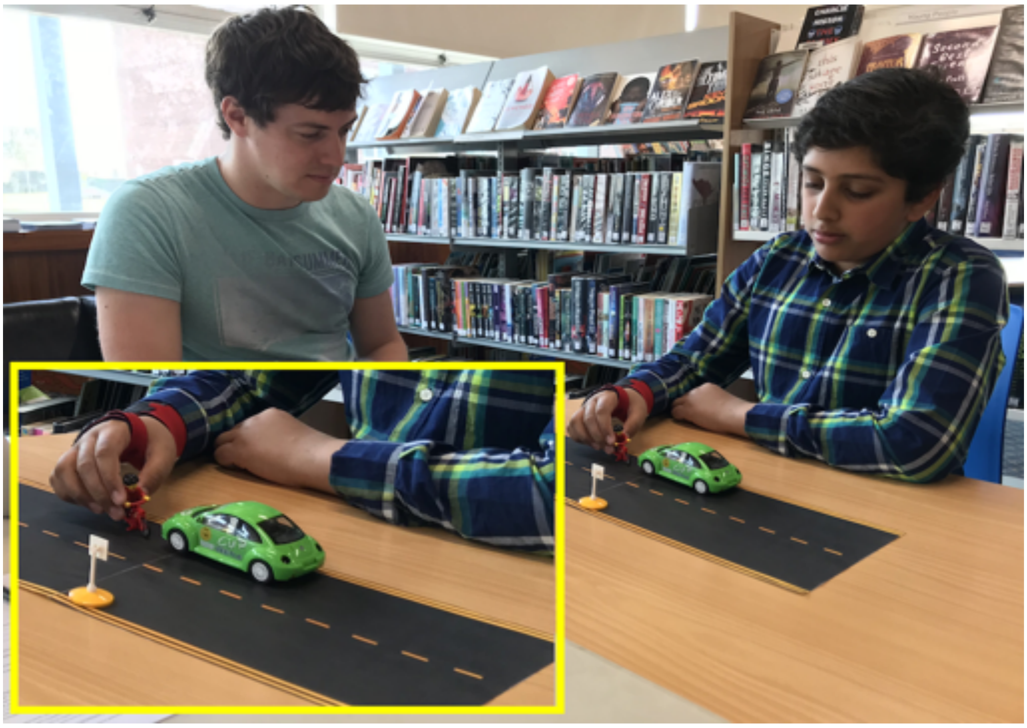

Figure 6.2: One of the participants is showing his cycling actions using Lego figures during the interview.

6.2.2 Procedure

After obtaining informed consent from participants' parents, we explained the purpose of the interview to children. We started by asking demographic questions followed by a brief semi-structured interview on any problems they experienced while cycling. Afterwards, children were presented with two situations: cycling on a road without cycling infrastructure with *static* obstacles, e.g., parked cars, trash containers, and *dynamic* obstacles, e.g., a dog, a ball, or a pedestrian on the street in front of them. For these situations, children were asked to describe verbally and demonstrate using a Lego cyclist figure the actions they would perform to avoid the obstacles (Figure 6.2). The entire interview lasted approximately 15 minutes.

6.2.3 Results & Discussion

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

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

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

As can be seen from this semi-structured interview, children are aware of the potential dangers of road traffic and avoid areas without infrastructure or cycling alone. However, they are hesitant and feel discouraged when cycling alone or leaving well-known residential areas. We observed that almost half of the interviewed children (N=5) forgot to return to the side of the road after overtaking an obstacle, or were unsure about the safe distance to the side of the road. Since children usually avoid dynamic objects on the road and wait until the danger is gone, we focus on lane keeping mechanisms around static objects with missing infrastructure for the rest of the chapter. Our focus is not on the generation of the lane with LIDAR or ultrasonic sensors but rather on lane keeping feedback cues. We therefore assume there is an already existing system that tracks surrounding objects.

6.3 Investigating Lane Keeping Cues in a Bicycle Simulator

Given children's problems of cycling on the road without infrastructure, discovered during the interview, we began our investigation in an indoor bicycle simulator. This allowed us to provide a safe environment and to collect first insights regarding children's performance with lane keeping cues. The idea was to provide

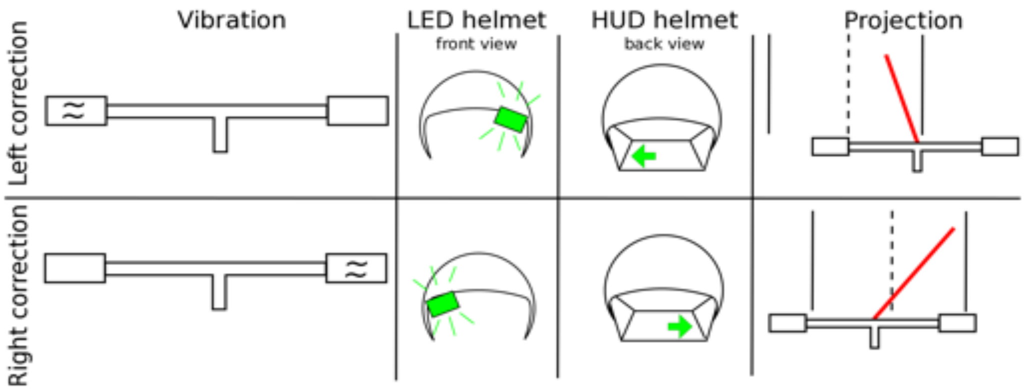

Figure 6.3: Overview of encodings for the lane keeping cues used for trajectory corrections. Children experienced each cue via vibration on the handlebar, blinking light in the LED helmet, blinking arrows in the HUD helmet, and a projected laser line indicating left and right in front of the cyclist.

path correction cues to guide the children left or right on the road with parked with cars on the side, as in the scenario from the interview. We developed four lane keeping mechanisms based on the previous works.

For the tactile lane keeping aid, we used vibration left and right on the handlebar grips. This was based on the results presented in Chapters 4 and 5, and previous work on vibrotactile navigation [PPHB12], which utilized similar vibration cues. For the ambient light lane keeping aid, we used a green flashing light on the left and right side of the helmet to indicate a direction. We used the location above the eyes to take advantage of the peripheral vision of cyclists [TLCC15]. For the head-up display cues, we used a green blinking arrow on the left and right, projected in front of the helmet to indicate a direction. Vibration, ambient light and HUD arrows consisted of three 500 ms pulses. As soon as a cyclist went too far left, a signal was presented on the right side, and vice versa. If a cyclist remained within the safe distance area, a signal was not shown. For the laser-based projection lane keeping cues, we used a laser beam mounted in the front of the bicycle. Since the laser beam projected on the screens was not visible, it was projected on the cardboard paper placed at the bottom of the screens, simulating a projection on the road in the simulation. The line turned left or right to indicate the direction to turn, and was always presented. Across all mechanisms, the direction a cyclist had to go was shown on the corresponding side : signal on the left – go to the left, signal on the right – to the right. The summary of the lane-keeping conditions is shown in Figure 6.3.

Two external factors compete for a cyclist's attention while cycling in the natural traffic environment . The first is related to the control of the cycling process, which includes pedaling, keeping the balance, and steering [AOWO]. The second factor is related to road distraction and situational awareness. To simulate real-world cycling conditions in the bicycle simulator, we introduced a secondary task together alongside the primary one. We chose a visual search distraction task applicable for children aged from six to thirteen [EC87]. The children had to spot an animal, which randomly appeared during cycling on the left and right side of the road, and to press a button attached to the handlebar as soon as they saw it. We specifically chose an animal (and not a car) as a traffic-unrelated stimuli to estimate the visual load of children's attention. Therefore, the goal was to estimate the level of distraction by measuring children's reaction time to this visual distraction.

6.3.1 Participants

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

6.3.2 Apparatus

We used the same bicycle simulator as presented in Chapters 4 and 5. The only difference was that cycling actions reflected in the simulation environment were displayed on three screens in front of the bicycle (Figure 6.4). The simulation consisted of a straight street with eight sets of cars parked on the left side of the road (UK). Based on the "Guide for the planning, design, and operation of bicycle facilities" [aas10], the virtual bicycle lane in the simulation corresponded to 1.5m (5 feet) width.

To represent the lane keeping cues, we fitted the bicycle with vibration motors on the left and right grips of the handlebar and a laser (5mW, 650nm) mounted on the servomotor in front of the bicycle to project a light beam under the screens (Figure 6.5). The vibromotors, hall effect sensor, potentiometer, buttons and servo were directly connected to an Arduino Primo microcontroller, which communicated with the simulation software via WiFi.

We also augmented a child's cycling helmet with LEDs on the left and right sides of the visor close to the eyes (LED helmet, Figure 6.1) as in the experiments with navigation and another one with a head-up display in the front (HUD helmet, Figure 6.6). LED strips in the LED helmet were directly connected to a NodeMCU 8266 board with an integrated Wi-Fi module and powered by a lithium ion (LiPo) battery. The microcontroller and the battery were integrated in the back of the helmet. For the HUD helmet, we added an Android smart-

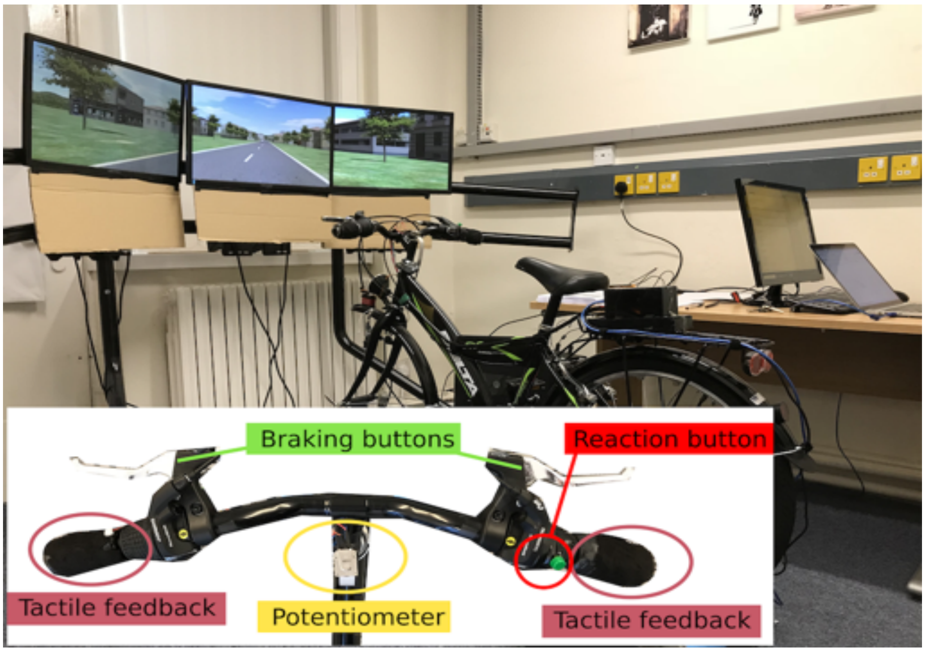

Figure 6.4: Bicycle simulator: handlebar with tactile feedback and a bicycle mounted on the platform with Hall effect sensor, magnets for measuring speed, servo with laser in the front and microcontrollers.

phone (Nexus 5) on a holder made of the transparent plexiglass in the front, and a battery power bank at the back of the helmet to balance the weight and charge the smartphone on the go. Visual cues displayed on the smartphone display were directly projected onto the plexiglass surface in the front. Communication between the simulation and both helmets, i.e., microcontroller and the smartphone, was accomplished via a WiFi connection.

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

6.3.3 Study Design

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

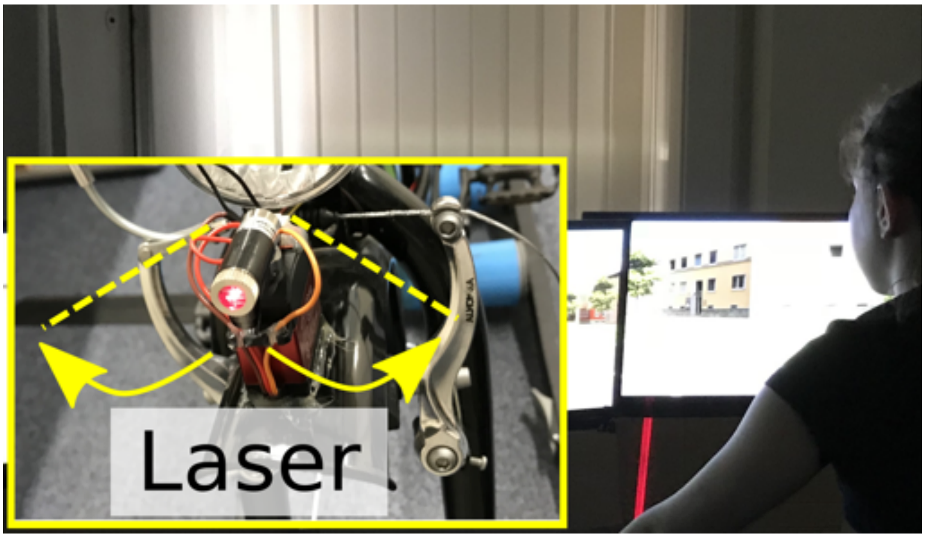

Figure 6.5: Laser projection: we mounted a laser on a servo in front of the bicycle to indicate lane keeping cues by turning it left or right and projected a line under the screens.

6.3.4 Measures

To compare lane keeping cues, we measured the following Dependent Variables:

Accumulated trajectory error left and right (in units of the bicycle simulator): we summed up the areas between the left and right side of the virtual bicycle lane and the cycled trajectories (Figure 6.7).

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

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

Reaction time (in ms): we measured the time between presentation of the animal and a button press, inline with previous work by Wierda and Brookhuis [WB91].

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

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

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

Figure 6.6: HUD helmet: visual cues displayed on the smartphone were reflected in the plexiglas surface of a holder in the front. A battery power bank at the back was used to balance the weight and change the smartphone.

6.3.5 Procedure

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

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

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

Table 6.1: Summary of descriptive statistics per condition. TE = trajectory error, RT = reaction time, SD = standard deviation of a trajectory, RO = response omissions, Under. = understandability, Distract. = distraction., Proj. = Projection, Pref. = preference.

6.3.6 Results

6.3.6.1 Trajectory and time within the lane

The trajectory error was comparable among all five conditions and we did not observe a significant difference using a Friedman test neither for trajectory error right ($\chi^2 = 6.5$, $p = 0.17$), nor left ($\chi^2 = 4.86$, $p = 0.3$). However, we observed that a trajectory error right was significantly larger than left for each lane keeping cue using Wilcoxon signed-rank test (see Table 6.1). We found a standard deviation of trajectories comparable among all five conditions and we did not observe a significant difference using a Friedman test ($\chi^2 = 4.84$, $p = 0.3$).

We found that the percentage of staying within the lane with vibration (46%) and LED helmet (46%) was higher than with projection (41%) and HUD helmet (40%), and comparable with no assistance (46%). We observed a significant difference for the percentage of staying within the lane using a repeated-measures ANOVA ($F(4, 21) = 3.99$, $p = 0.015$) and present all pairwise comparison using t-test in Table 6.2.

6.3.6.2 Reaction time

We found that cycling without assistance for the lane keeping had the shortest reaction time (M = 1206ms, SD = 555) in the visual search task, followed by vibration (M = 1356ms, SD = 551), LED helmet (M = 1478ms, SD = 588), projection (M = 1493ms, SD = 664), and HUD helmet (M = 1642ms, SD = 858) (Figure 6.8). There was a statistically significant difference between the

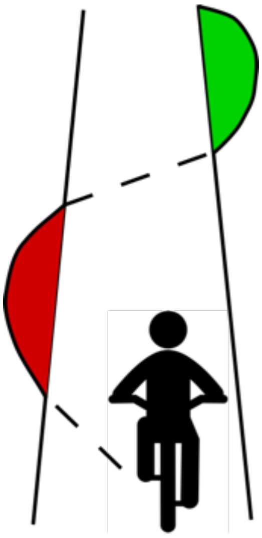

Figure 6.7: Accumulated trajectory error left and right: area on the left indicates trajectory error to the left and right area – to the right. We summed these areas along the cycling trajectory, estimating an accumulated trajectory error for each side.

conditions as determined by a Friedman test ($\chi^2 = 10$, $p = 0.04$). We found that children's reaction time with non-visual lane keeping cues was significantly shorter than with visual ones. We present all pairwise comparison using Wilcoxon signed-rank test in Table 6.2.

6.3.6.3 Response omissions

The percentage for response omissions in the visual search task was comparable among all conditions: vibration (19.3%), LED helmet (23.9%), HUD helmet (23%), projection (21.1%), and no assistance (23.7%). We did not find a sta-

	% within the lane	**Reaction time**
Vibration – LED	$t = 0.2$, $p = 0.84$	$Z = -1.03$, $p = 0.31$
Vibration – HUD	$t = 3.46$, $\mathbf{p < 0.01}^{**}$	$Z = -2.61$, $\mathbf{p < 0.01}^{**}$
Vibration – Projection	$t = 2.43$, $\mathbf{p = 0.02}^{*}$	$Z = -0.57$, $p = 0.57$
Vibration – No Assis.	$t = 0.17$, $p = 0.87$	$Z = -1.55$, $p = 0.122$
LED – HUD	$t = 2.23$, $\mathbf{p = 0.035}^{*}$	$Z = -1.1$, $p = 0.27$
LED – Projection	$t = 2.21$, $\mathbf{p = 0.037}^{*}$	$Z = -1.06$, $p = 0.29$
LED – No Assis.	$t = -0.03$, $p = 0.98$	$Z = -2.35$, $\mathbf{p = 0.019}^{*}$
HUD – Projection	$t = -0.32$, $p = 0.75$	$Z = -1.9$, $p = 0.057$
HUD – No assis.	$t = -2.13$, $\mathbf{p = 0.043}^{*}$	$Z = -2.65$, $\mathbf{p < 0.01}^{**}$
Projection – No assis.	$t = -1.76$, $p = 0.09$	$Z = -1.77$, $p = 0.077$

Table 6.2: Lab study results: Summary of pairwise comparisons for the time within the lane and reaction times. * ***<.05*** ** ***<.01***

tistical difference among the conditions using a Friedman test (χ^2 = 1.79, p = 0.78).

6.3.6.4 Understandability and Distraction

The understandability of the lane keeping cues was comparable among all methods: vibration (Md = 5, IQR = 1), LED helmet (Md = 5, IQR = 0), HUD helmet (Md = 5, IQR = 1), and projection (Md = 4, IQR = 1). We did not observe a significant difference for it using a Friedman test (χ^2 = 7.3, p = 0.063).

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

6.3.6.5 Problems and Preferences

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

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

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

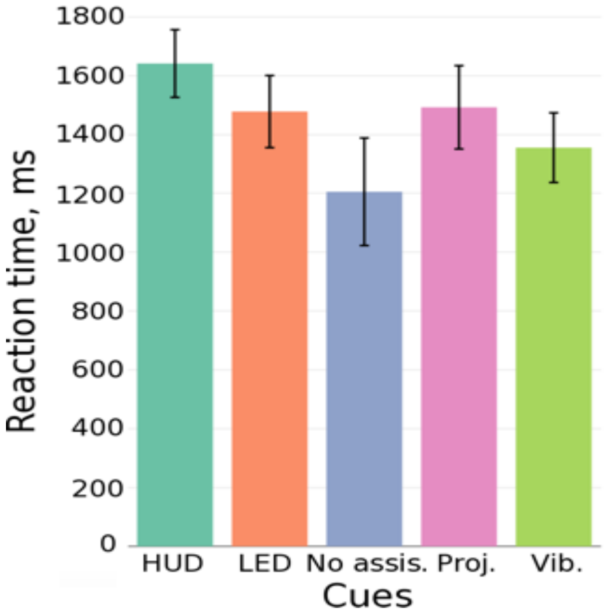

Figure 6.8: Reaction times to the visual search task for the lane keeping cues.

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

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

As we have seen from the lab experiments, vibration and LED helmet were the most preferred lane keeping mechanisms for child cyclists based on the qualitative data, despite the absence of statistical differences for some quantitative measures. We observed that with vibration and LED helmet children stayed within the lane longer than with HUD helmet or projection, but it was on the same level as without any cues. The results regrading the reaction time to the secondary task indicated that child cyclists tended to oversee one out of five external visual stimulus independent of the type of lane keeping assistance, which is inline with the reaction time to the auditory distraction task during navigation presented in Chapter 5. The reaction time to the external visual stimulus was shorter for the vibration method and no assistance in comparison to the visual lane keeping cues. Similarly to the results from Chapter 5 about navigation cues, we observe comparable reaction times to the external stimulus. We found that a trajectory error to the left and right with a lane keeping assistance was comparable to a condition without assistance. This was most likely caused by the high sensitivity of the potentiometer used for steering in the bicycle simulator and children's unfamiliarity with a bicycle simulator. Despite a test ride before the experiment, children needed time to adjust to a new cycling experience in the bicycle simulator, given its novelty. Moreover, children positively reacted to the use of lane keeping assistance during the post-study interview. Therefore, to avoid the limitations from the lab experiment, we decided to evaluate the lane keeping assistance in the follow-up controlled test-track experiment on the mid-size tricycle.

6.4 Investigating Lane Keeping Cues on a Test Track

The goal of the controlled test-track experiment was to confirm the results from the lab experiment on an outdoor track. From an experimental perspective, running the study in real-world traffic conditions would have been ideal. However, due to safety concerns this was not possible (or approved) by our institutional review board (IRB). Therefore, we aimed for an approximation with an outdoor test track. This marks a gradual shift towards ecological validity. We used a tricycle instead of a regular bicycle to avoid safety concerns due to balance and coordination issues based on recommendations from the IRB. Although not ideal, children still had to ride on a paved road, steer and maneuver a real bicycle, and experience multisensory perception of the environment. The tricycle also allowed us to focus on the steering aspect of lane keeping, without the potential influence of poor stability or cycling technique.

6.4.1 Participants

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

6.4.2 Apparatus

For this evaluation, we used a mid-size tricycle to prevent falls (Figure 6.1) as in the experiment with navigation cues. To represent the lane keeping cues, we fitted a tricycle with the same vibration motors on the left and right grips of the handlebar as in the simulator, and used the same LED and HUD helmets. To

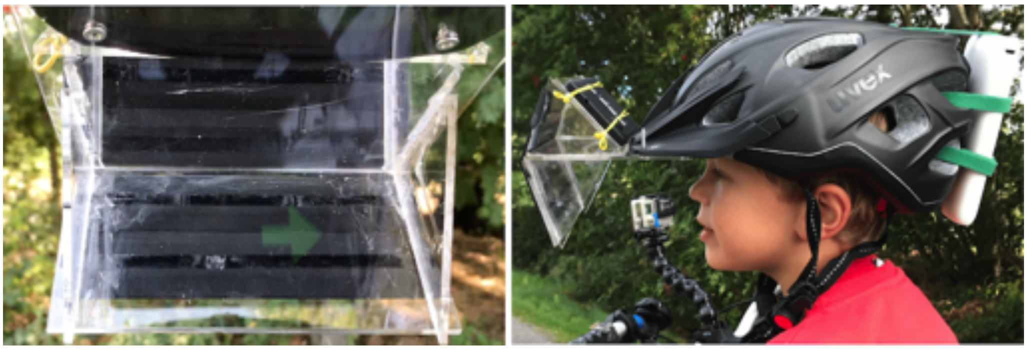

Figure 6.9: HUD helmet: we added black tennis grip bands in front of the helmet to increase the visibility of the reflected visual cues.

increase the visibility of the arrows in the HUD helmet, we added black tennis grip bands in front of the helmet (Figure 6.9). This change did not occlude much of the field-of-view, but would require looking upwards. The LED helmet remained unmodified from the lab experiment. We changed the laser to a ten times more powerful version (50 mW) to increase its brightness. However, due to the low visibility of the projection on the ground during the day time, we excluded this condition from the field experiment.

We used a laptop placed into the rear cargo box of the tricycle as a WiFi hotspot and a power supply. The vibromotors were directly connected to an Arduino Uno microcontroller. All lane keeping cues were activated by experimenter using an Android application via WiFi communication two meters before an obstacle. The Arduino board in the rear cargo box of the tricycle was directly connected to the laptop via a USB cable. To observe the behavior and focus of the participants, a GoPro camera was placed in the middle of the handlebar facing the rider (Figure 5.6). To simulate parked cars on the side of the road as in the interview and bicycle simulation, we used eight cardboard boxes. However, this time the boxes were placed on the right side on the road, because the experiment was conducted in Germany. Due to the low precision of the GPS systems, we could not track the trajectories of cyclists. Instead, we focused on the qualitative responses to the cues in the real world, as we could not do the detailed recording that we did in the lab experiment.

6.4.3 Study Design

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

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

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

6.4.4 Procedure

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

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

6.4.5 Results

None of the children experienced an accident by cycling into the cardboard obstacles on the road and each safely overtook the obstacles. One child did not turn back to the side of the road after overtaking in the condition without assistance, which is lower in comparison to five children who took part in the interview. Another child reported that he did not want the lane keeping signals, because he felt more comfortable without them. *"I don't think I need such signals. I'd rather cycle without them. I think I was confident without the signals than with them."* The other 14 participants found the signals helpful and would like to have them in particular situations with a lot of traffic or all the time. As our participants remarked: *"In the cities like New York with lots of traffic, I would definitely need* *an additional support for my cycling. When there is a lot going on the street, I would definitely need them, but not all the time."* [P12, 9 years old]. *"I find the signals helpful. I can also imagine myself relying on them, if the bicycle "know" that it is safe to overtake a car."* [P14, 12 years old].

6.4.5.1 Understandability and Distraction

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

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

6.4.5.2 Problems and Preferences

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

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

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

6.4.6 Discussion

Interestingly, children's performance without any lane keeping assistance was comparable to situations with vibration and LED helmet lane keeping assistance. Thus, lane keeping assistance can potentially children's awareness without negatively affecting their cycling performance. However, it must be noted that both the lab and controlled test-track studies were conducted in safe environments without much exposure to real traffic conditions. In a real traffic situation, especially in an unfamiliar neighborhood, children may face a higher mental load and increased arousal. This is where our work can play an important role, especially since lane keeping cues did not perform worse than no assistance. However, we observed that vibration and LED helmet performed better than HUD helmet and laser-based on-road projection. We also think that a larger trajectory error to the right was due to children's aim of keeping a safer distance to the cars while overtaking.

6.4.6.1 Multimodal feedback vs. projected surfaces

The lane keeping cues did not introduce additional distraction and demand. In particular, vibration signals on the handlebar were shown to be the most applicable to keeping a good lane position in both lab and test-track evaluations. This finding is inline with the results from Chapter 4 regarding the representation of directional cues and turn-by-turn navigation [PPB09, PPHB12]. Ambient light in the helmet was also positively perceived due to its peripheral and non-demanding information representation, which fits with previous work about ambient light in helmets [TLCC15]. However, the brightness of the light signals needs to be adjusted depending on the outside brightness. Based on the results from Chapters 4 and 5 regarding warning and navigation cues, we think that by further combining vibration and LED helmet cues we might avoid limitations of both modalities and increase children's performance for lane keeping, which is inline with previous work for car drivers [PE03].

The HUD indicators were perceived better in the test-track than in the lab experiment due to better visibility, in part due to the black contrast material added to the helmet. We believe that the HUD helmet was outperformed by other modalities due to its current implementation and needs further exploration. For example, EverySight[3] has recently introduced AR glasses for cyclists based on microLED technology for adult cyclists, which provides a better visibility of the signals in comparison to the current implementation of our prototype. It leaves an opened question regarding its performance with children. The laser-projection has visibility limitations in bright environmental conditions, similar to previous work on projected surfaces for cyclists [DFF14, DVÜ+15], but can be potentially used when it is dark and might be useful for other road users, given

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[3] https://everysight.com

that they are getting cheaper and widely available. We envision that they can be used around bicycles to improve safety by providing assistance and increasing cyclists' visibility during the night-time. In this case, the projected interface can transform the physical environment around cyclists into a safety zone.

6.4.6.2 External distraction and reaction time

We observed that the reaction time to visual distraction task from the lab experiment lies between 1,3 and 1,7 seconds, which is comparable to the reaction times to the auditory distraction task presented to child cyclists during navigation in (Chapter 5). However, the reaction times to both auditory and visual distraction tasks were shown to be 2-3 times longer than to the multimodal warning signals, which were between 500 and 600 ms (Chapter 4). We assume that this difference in the reaction times might be caused by the following two reasons: (1) method of reaction and (2) priority of the task. As for the method of reaction, children pressed an additional button placed on the handlebar for the distraction tasks, and braked for the warning signals, which is most likely was a more natural way of reacting to an external danger. As for the priority of the task, children's primary task with the warning signals was to react to them, and not to an external distraction. For example, in our lab experiment, similarly to the experiments with navigation (Chapter 5), children's primary task to follow a lane keeping cue and to react to a distraction had a lower priority.

6.4.6.3 Towards trust in cyclist assistance systems

It was clear from our interviews with kids that confidence was a key issue when riding on unknown streets or neighborhoods. Children naturally avoided traffic situations where they felt uncomfortable with some children even going so far as walking the bicycle on the sidewalk when encountering an obstacle. Therefore, if children are to use lane assistance systems, trust is critical to adoption. Even for adults, in the field of autonomous vehicles, it has been shown that trust is necessary for a driver to give up control [CJ15]. Developing trust in the system with children, therefore, may take time and require a graded and transparent approach that requires further study. However, as more children trust the system, the more they will intend to use it [PSW08], thereby increasing the number of children riding on the roads. This can potentially contribute to "safety in numbers" [Jac03] and expand the rage of mobility for child cyclists. Thus, in this respect, we see our work as playing a role in improving the confidence for child cyclists to become increasingly mobile.

6.4.6.4 Encouragement through Gamification

To encourage children's use of the lane keeping system and thereby build trust, a gamification approach could be used to promote safety. By gamification, we mean, “the use of game design elements in non-game contexts” [DDKN11, LKG11]. Previously, this principle has been used in health and wellness with both adults [LML+06] and children [MPM13, KAL+12]. We see rewards as a component of gamification that can motivate children to use safety technology on the roads without cycling infrastructure. For example, a child may receive, gold, silver or bronze badges at the end of each ride depending on how well they followed the feedback cues and maintained the intended virtual lane. These badges could be recognized by schools where the top badges earn a toy or snack.

6.4.6.5 Lane assistance as an intermediary technology

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

Ultimately, the construction of cycling infrastructure with dedicated bicycle lanes is the ideal solution to increase cyclists’ safety [DNHTKK18, HRW+13]. More countries around the world aim to support the use of bicycles for the safety, health and ecological reasons. However, this is a time consuming process, which is not always in the list of priorities in some countries around the world. In this sense, we hopefully see our unimodal lane keeping assistance work with children as an intermediary technology. Coupled with recent low-cost bicycle enhancements [BZC+18], such as laser scanners and ultrasonic sensors, we can support safe maneuvers “on-the-go” and promote “safety in numbers” [Jac03], making cycling attractive for children.

6.4.6.6 Limitations

Since we conducted the controlled 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. Moreover, we conducted the test-track experiment during the summer, which might have influenced how quickly children finished the experiment. 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 lane keeping cues for child cyclists in the presence of an external visual distraction.

6.4.7 Summary

This chapter reports from one laboratory experiment in an instrumented bicycle simulator and one controlled test-track experiment, exploring unimodal lane keeping cues for child cyclists. The outcomes provide insights into how lane keeping cues can be represented for child cyclists uinimodally, and in an understandable and non-distracting way to address RQ3: *How can we represent lane keeping cues for child cyclists in an understandable and non-distracting way?*

From both experiments we found out that both ambient light in the helmet and vibration on the handlebar can effectively support child cyclists in keeping a good lane position. However, we still observed advantages of using projected surfaces, such laser-based projection on the road and a projected HUD indicators in the helmet. HUD helmet has a potential to perform better for lane keeping, given a different technology with a better visibility on the sunny day. The same applies for laser-based projection, which in the current implementation can be used in the night-time.

The main outcomes from the two studies are:

- From the semi-structured interview we found that children feel discouraged cycling alone and have problems on the roads with parked cars and no cycling infrastructure. For example, we observed that children either forgot to return to the side of the road after overtaking an obstacle, or were unsure about the safe distance to the side of the road. This outcome showed a need to provide path correction cues to guide the children left or right on the road with parked with cars on the side,
- We discovered that cycling performance with lane keeping cues was comparable to situations without them, but children found them helpful and expressed subjective preferences for the LED helmet and vibration on the handlebar. However, in the follow-up controlled test-track experiment, we discovered that ambient light has visibility limitations on the sunny days, and the multimodal combination of ambient light with vibration might be a better solution.
- We empirically showed that children have mental capabilities of reacting to the external visual distraction and can follow lane keeping cues simultaneously. Given that three of the evaluated methods were visual, children still could follow lane keeping cues, react to the visual distraction task, pedal and steer. It indicates that proposed unimodal lane keeping cues do not overwhelm child cyclists and they have available mental resources for the primary task of cycling.

Therefore to answer RQ3, we conclude that a combination of ambient light in the helmet with a vibration on the handlebar has a potential to serve as an efficient assistance for lane keeping on the road with missing infrastructure. We also think that projected surfaces, such as a laser-based projection in front of a cyclist, or a HUD helmet can be used in the night-time, but the technical implementation of these methods would require improvements to reduce the visibility limitations during the day-time. In Chapter 7, we explore a HUD glasses based on the microoled technology and show they provide an effective assistance without big visibility limitations.

7 Safety Gestures

This chapter focuses on the design space of safety gesture reminders for child cyclists. Child cyclists, in particular, might have difficulties performing safety gestures on the road or even forget about them, given the lack of cycling experience, road distractions and differences in motor and perceptual-motor abilities compared with adults. To support them, we designed two methods to remind about safety gestures while cycling. The first method employs an icon-based reminder in heads-up display (HUD) glasses and the second combines vibration on the handlebar and ambient light in the helmet. We investigated the performance of both methods in a controlled test-track experiment with 18 children using a mid-size tricycle, augmented with a set of sensors to recognize children's behavior in the real time. We found that children prefer HUD glasses over a multimodal system due to its higher general understandability and personal subjective preferences.

7.1 Background and Motivation

Looking over the shoulder and performing hand signals are an essential part of cycling and safe manoeuvring on the road [EU68, EU68, EURb, cyc]. Even though safety gestures are not mandatory road regulations in some countries, cyclists are expected to obey road rules that are in place for everyone's safety. This is particularly important for child cyclists, given their still developing motor and perceptual-motor skills, lack of cycling experience and knowledge of traffic rules. One possible way of improving children's literacy on the road is through cycling courses that help children practice cycling over an extended period of time. However, the disadvantage of this approach is that children might forget what they learnt, especially when they cycle irregularly. Occasionally, many children still need to be reminded about the right sequence of actions by their parents before performing a turn, namely looking over the appropriate shoulder and showing hand signals.

To address this issue, we explore ways of reminding child cyclists about safety gestures using technological augmentation of cycling accessories. This is illustrated by the following scenario: a 9-year old Liam has not perform a shoulder check and/or a hand signal at the particular junction on his way to school over the last two days. His bicycle logs this behavior and activates a reminder system that recommends the appropriate safety gestures next time he is at this junction. With this, we aim to remind children about safety gestures on demand, and not before every manoeuvre.

To assist cyclists, researchers have previously augmented cycling accessories with vibrotactile, visual and auditory feedback [PPB09, PPHB12, DVÜ+15].

Figure 7.1: Participants wearing a helmet (left) and HUD glasses (right) for the controlled test-track experiment using a mid-size tricycle.

Recent commercial products, such as Everysight [1] and helmet SKULLY AR-1 [2], introduced head-up displays integrated into helmets and glasses to show important information for cyclists. Due to the lack of empirical evaluation of these systems with child cyclists, we explore both multimodal systems and head-up displays in this paper. Particularly, we investigate how icon-based and mutimodal feedback integrated into a helmet, bicycle and heads-up display (HUD) glasses can be used as reminders about safety gestures for children. We focus on multimodal feedback, because of its success with child cyclists for warning signals (Chapter 4) and navigation cues (Chapter 5), and on the head-up displays due to their granular presentation of information. To compare these methods, we designed mutlimodal and icon-based reminders and conducted an experiment on an outdoor practice test track using a mid-size tricycle (Figure 7.1). We found that children prefer HUD glasses over a multimodal system due to its higher understandability and lower distraction level. In this paper, we contribute an empirical evaluation of reminders about safety gestures for child cyclists and a technical bicycle setup to facilitate cyclists' assistance.

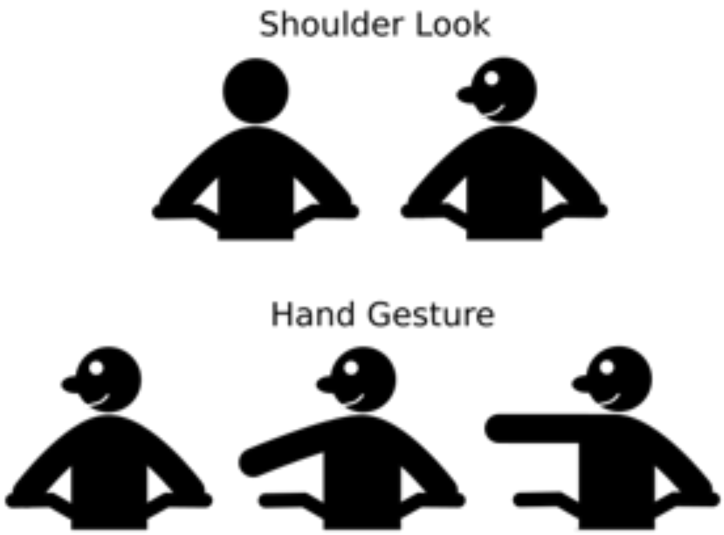

Figure 7.2: Overview of animations for HUD glasses. A shoulder look animation consisted of two images: looking straight and looking aside (above). A hand gesture animation consisted of three images: looking aside, stretching a hand 45°and stretching a hand 90°to the body (below).

7.2 Safety Gestures Signal Design

Shoulder checks and hand signals are an essential part of safe manoeuvring while navigating on the road [EU68, EURb, cyc]. While not mandatory in some countries, they help to increase awareness and alert other road users of cyclists' intentions, and therefore increase safety on the road. Normally children learn about safety gestures from cycling courses or their parents, however, sometimes they might forget about them. Therefore, within the scope of our work we explore methods of reminding child cyclists about safety gestures. Based on the assisting cues presented in Chapter 4 and 5, we designed two types of reminders for safety gestures: icon-based and multimodal.

For the icon-based representation, we used HUD glasses with a projected animation in front of the eyes. This animation consists of an upper part of a cyclist on a bicycle, who is turning his head to the left and right to indicate a shoulder check or stretching his arm to the left or right to indicate a hand gesture. We used a two-image animation for a shoulder check (looking forward - looking aside) and a three-image animation for a hand gesture (looking aside - a hand is 45°to the body - a hand is 90°to the body). For each signal, an animation consisted of three repetitions, i.e., a projected cyclist turned his head three times or stretched his arm three time to a side. The visual overview of both signals is shown in Figure 7.2.

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[1] `https://everysight.com/`

[2] `https://skullytechnologies.com/fenix-ar/`

For the multimodal representation, we combined an LED helmet with vibration on the handlebar grips. We used peripheral visual feedback placed in the helmet's visor to remind about a shoulder look. A pulsing green light on the left or right side of the helmet indicated the direction, in which children had to perform a shoulder check. To remind kids about hand signals, we employed vibrotactile feedback integrated in the left and right grips of the handlebar. Vibration in a corresponding grip indicated the direction in which children had to show a hand signal. Similar to the icon-based representation, each light and vibration signal consisted of three repetitions, i.e., a handlebar grip vibrated three times and the helmet pulsed three times.

According to cycling rules, the reminders were represented sequentially: a shoulder check was followed by a hand signal. We created two experimental conditions, based on each type of reminder.

7.3 Safety Bicycle

To evaluate both types of reminders, we used a mid-size tricycle augmented with cameras and sensors to recognize cyclists' behavior. The tricycle was equipped with five RGB-D cameras, perceptual pedals, GPS-module, an odometry system, and an on-board computer placed in the rear cargo box (Figure 7.4). In the following subsections we outline each component in details.

7.3.1 Recognition cameras

RGB-D cameras belong to the type of cameras, which provide both color (RGB) and depth (D) information for every pixel in the image. We equipped the tricycle with five stereo based RGB-D cameras (Intel RealSense D435[3]): three facing a cyclist to recognize cyclist behavior and two pointing to the front for environment recognition. Two of the behavior recognition cameras were placed on the left and right side of the handlebar and the third one on the bicycle frame. The environment recognition cameras were mounted above the wheel in front of the bicycle. All cameras were connected to the on-board computer via a USB-hub and powered by a lithium-ion battery (16000mAh) placed in the rear cargo box.

To recognize cyclist behavior, such as shoulder look and hand gestures, we used the open source OpenPose library, normally used for real-time multi-person keypoint detection for body, face, hands, and foot estimation [4]. We used this library due to its previous success in research projects of hand keypoint detection in single images [SJMS17] and real-time multi-person 2D pose estimation [CHS+18, CSWS17]. The library ensures real-time recognition of arm joints and head movements necessary for safety gesture reminders. The environment

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[3] `https://www.intelrealsense.com/depth-camera-d435/`

[4] `https://github.com/CMU-Perceptual-Computing-Lab/openpose`

recognition cameras have a total view angle of approximately 120°and are designed to recognize other road users, road obstacles, and traffic signs. Two examples of head movement and hand gestures are shown in Figure 7.3.

Figure 7.3: Recognition of head movement (left) and hand gestures (right) of cyclists using the OpenPose library.

7.3.2 Pedals and Tilting

We augmented the pedals with inertial measurement units (IMU) and strain gauges to measure acceleration and pressure on the pedals. Each pedal contained a single point load cell with precision of 50 kg and NodeMCU 8266 directly connected to the strain gauge sensor. This allows us to measure a weight distribution between the left and right pedals while cycling and use it as an additional measure for cyclist behavior, e.g., cycling while standing.

To calculate bicycle tilting, we used an Arduino Primo board, which receives data from two NodeMCU boards placed in the front and in the back of the bicycle. We calculated the tilt using IMUs placed in the front and in the back of the bicycle and connected to the NodeMCU boards. Even though the tilting of tricycle is smaller in comparison to the two-wheeled bicycle, with this set of sensors we were able to measure the tilting while cycling on the curve.

7.3.3 GPS and Odometry System

To measure the position of the bicycle at any point in time we used a ROS-based (Robot Operating system) odometry system and a GPS module (NaviLock 62531). For this, we augmented the front and two rear wheels with a set of magnets and added reed switches on the frame of a bicycle. We used the odometry system and IMUs in the pedals to calculate the velocity of the bicycle.

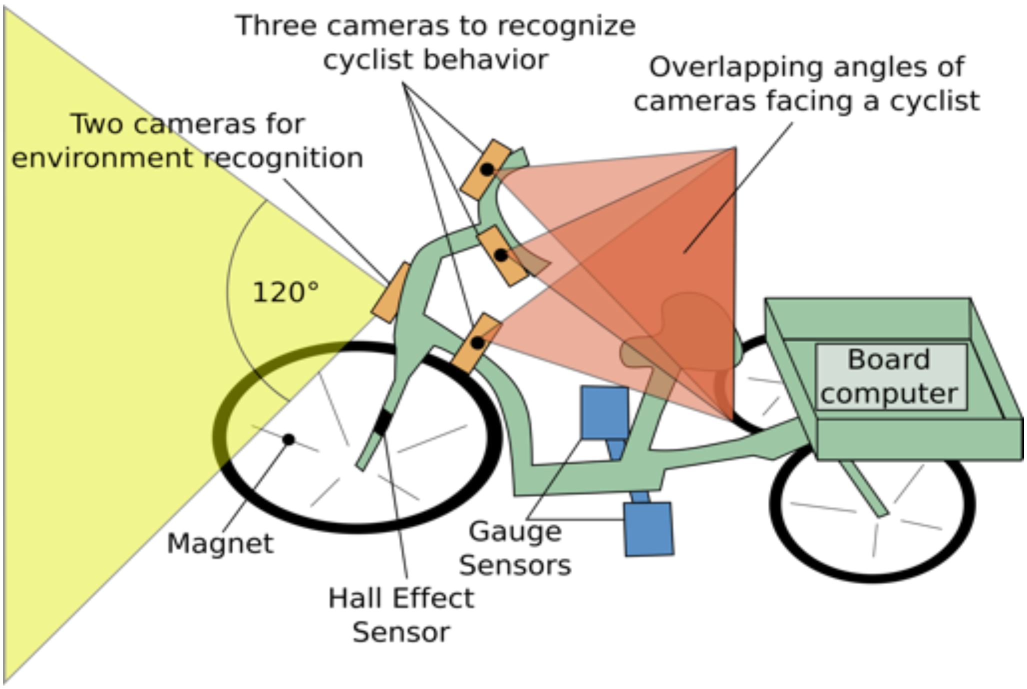

Figure 7.4: Schematic representation of the tricycle.

7.3.4 Board computer

We placed an on-board computer and a power supply in the rear cargo box. For the on-board computer we used NUC INTEL 8 (16 GB RAM, 1 TB storage) with Ubuntu operating system (16.04 LTS) running ROS server for real-time processing of video and logging data from the pedals, GPS coordinates, speed and tilting. The on-board computer was also used as a Wi-Fi and Bluetooth access point to connect the different peripheral components, such as helmets, handlebar grips, HUD glasses, and the experimenter's tablet for the Wizard-of-Oz signal activation during the test-track experiment. The schematic overview of the bicycle is shown in Figure 7.4.

7.4 Investigating Safety Gestures on a Test Track

The goal of the controlled test-track experiment was to investigate the efficacy of the two reminding methods for showing safety gestures. 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

Figure 7.5: The HUD glasses and its components. The microcontroller is powered by the battery and connected to a projector. The projection is reflected by the mirror and seen in the front.

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.

7.4.1 Participants

We recruited 18 children (5 female) aged between six and thirteen (M = 10.11, SD = 2.05) years. They had between two to ten years of cycling experience (M = 6.33, SD = 2.11). All of the participants had normal or corrected vision without color blindness. Majority of participants (14 out of 18) knew that one has to perform a shoulder look and a hand signal before making a turn. However, only 11 of them knew that a shoulder look must be followed by a hand signal.

7.4.2 Apparatus

For this evaluation, we used a mid-size tricycle, described in previous section, to prevent falls (Figure 7.7). To represent vibrotactile reminders, we fitted a tricycle with the vibration motors on the left and right grips of the handlebar. The vibromotors were directly connected to an Arduino Uno microcontroller. All reminding cues were activated by experimenter using an Android application via WiFi communication five meters before a turn. To observe the behavior and focus of the participants, a GoPro camera was placed in the middle of the handlebar facing the rider.

We used a helmet with a visor and integrated the LED strips on the sides of the visor (Figure 7.6). The LED strips were directly connected to a NodeMCU 8266 and powered by a lithium ion (LiPo) battery. Both vibrotactile and visual signals were activated via Wi-Fi by the experimenter using an Android application.

For the HUD glasses, we used microoled's MDP05DK microcontroller directly connected to a mini projector and powered by a lithium ion (LiPo) battery. The HUD glasses are based on the ActiveLook technology [5], which includes a miniaturized, light and powerful display module with ultra high brightness and very low power consumption. Cyclist images stored on the microcontroller were activated via Bluetooth by the experimenter using an Android application and projected in front of cyclist's eyes reflected by a mirror (Figure 7.5). An overview of the animations is shown in Figure 7.2.

7.4.3 Study Design

We conducted the controlled test-track experiment on an outdoor practice track in Germany, normally used as a training facility by novice car drivers. The test track consisted of a network of gravel roads with intersections, old stationary parked cars, traffic signs and lights. The roads on the test track did not have any cycling infrastructure. For safety reasons, no other traffic (except for parked cars) were presented during the experiment. The experiment was conducted over the course of six days: four of the days were sunny and other two were cloudy. Every participant had to cycle with both types of reminders for 15 minutes. The order of two conditions was counterbalanced. To activate the signals, the experimenter walked behind or next to the participant. The entire study was approved by the ethical review board of our university. Each child received €10 for participation.

7.4.4 Procedure

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

The children's task was to cycle, do the shoulder look and hand gestures every time they saw a reminder. After performing safety gestures they had to turn left or right correspondingly. After each condition, children were asked to estimate the understandability (5 – very understandable) and the demand (5 – very demanding) of the reminders using a 5-point Likert scale. At the end of the study, we interviewed children about their preferences and the problems they experienced with safety gesture reminders. The entire study lasted approximately 40 minutes.

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[5] `http://www.activelook.net/index.html`

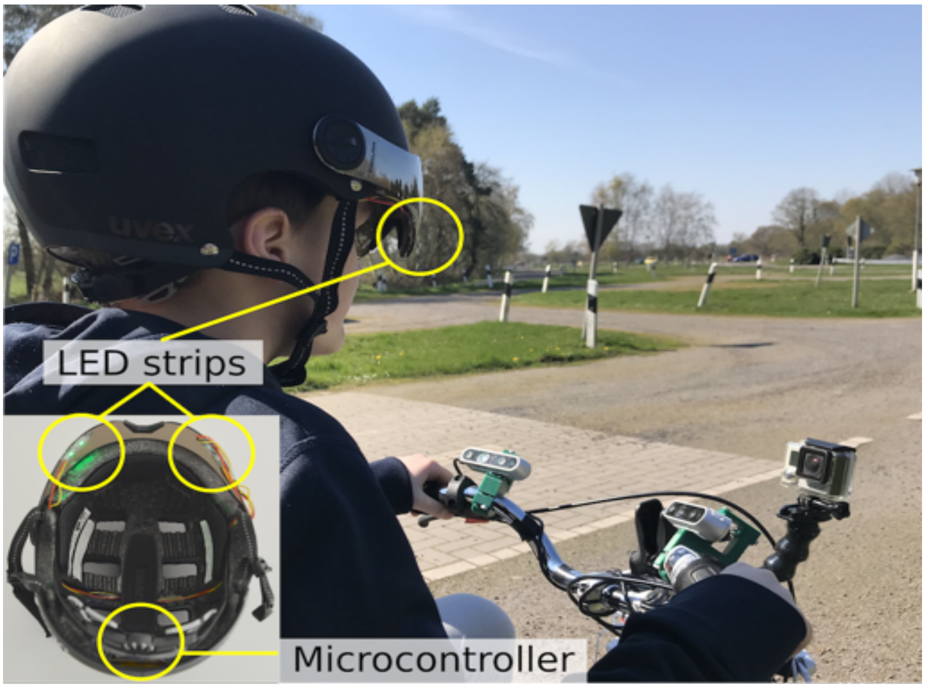

Figure 7.6: LED helmet with LED strips integrated into the visor for the ambient light cues.

7.4.5 Measures

To compare the types of reminders for child cyclists in the training area, we measured the following dependent variables:

Error rate: for each type of reminder, we counted the number of errors a child made when a reminder was presented. We counted an error, when children did not show a signal, showed it wrongly, or in the wrong sequence.

Understandability (5 - point Likert scale, 5 - most understandable): every participant estimated the understandability of each type of a reminder.

Demand (5 - point Likert scale, 5 - most demanding): every participant estimated the required mental load while cycling with a given type of a reminder.

7.4.6 Results

7.4.6.1 Error Rate

All participants could always see and follow the instructions regarding a shoulder check and a hand signal. Despite the fact that not all of participants (only 11 out 18) knew the correct sequence of safety gestures, all of them performed the gestures in the correct order: a shoulder check followed by a hand signal.

Figure 7.7: The tricycle used in the experiment on the outdoor test track.

7.4.6.2 Safety Gestures Recognition

We observed that head movement and hand gestures were recognized at 100% rate using Intel RealSense cameras in combination with OpenPose library in the real time.

7.4.7 Understandability and Demand

Understandability was comparable between multimodal system (M = 4.33, Md = 5, IQR = 1) and HUD glasses (M = 4.28, Md = 4, IQR = 1). Similarly, demand for both multimodal system (M = 1.72, Md = 2, IQR = 1) and HUD glasses (M = 1.56, Md = 1, IQR = 1) was comparably low. We did not observe statistically significant differences between both methods for both understandability (Z = -0.28, p = 0.78) and distraction (Z = -0.69, p = 0.49) using a Wilcoxon test.

7.4.7.1 Problems and Preferences

During the post-study interview, all children mentioned that they found the digital feedback useful and helpful, and would need them in the cases, when they forgot to show the safety gestures. With respect to the children's preferences for reminder types, we found that children preferred the HUD glasses more (n=10) than a multimodal system (n=8).

Despite the fact that eight children preferred the multimodal system, their decision was justified by the location of the signal (helmet over glasses) and not by its encoding. For example, P14 (7 years old, F) mentioned *"The helmet is quite fixed on my head, while the glasses can fall down."* or P11 (8 year old, F) commented *“The helmet can also hold better on my head.”*. Therefore, both children preferred the multimodal system, because it was integrated in the helmet, which they liked. Additionally, one child (P4, 12 years old, M) suggested to combine vibration with HUD, but when answering the question he decided for a multimodal system: *“I think the combination of glasses with vibration would be even better. One feels vibration very well and directly.”*. This makes a preference for the head-up display even higher.

The majority of children, who preferred the HUD glasses reported that it was very easy to see the projection in front of their eyes and it was clear to them what they had to do by mimicking the actions of a projected cyclist. *“I can see a human and I am also a human, so I just mimic his gestures”* [P6, 10 years old, M]. Another child also mentioned that it was a good reminder about what one has to do now: *“If one forgets or does not think about showing a hand signal, then a man reminds a cyclists about it very well.”* [P8, 10 years old, M]. Other children mentioned good visibility during a sunny day and no problems with obscurity. *“In the beginning I thought it would block my way, but it was good and clear.”* [P17, 13 years old, M]. *“I could always see it and it was also very good to see in the sun.”* [P16, 11 years old, M]. Additionally, we found that children had difficulties feeling vibration on colder days. For example, one child mentioned: *“After some time it was harder to feel the vibration, because my hands became cold”* [P9, 8 years old, M].

7.4.8 Discussion

We evaluated two methods for displaying safety gestures reminders and presented one technical solution of a bicycle augmented with a set of sensors for recognition of environment and cyclist behavior. Based on the quantitative results from a controlled test-track evaluation, we have shown that both reminders about safety gestures were successful, and the difference between the systems is negligible. However, both systems have their unique advantages and disadvantages.

HUD glasses have advantages of intuitive icon-based representation and high visibility of icons on sunny days. Besides that, the head-up display was considered easy to understand, non-distracting, and effective for reminding children about safety gestures. This finding supports the previous research that shows that information should be presented in the close proximity to the normal line of sight [WHBP15]. Unlike the results from previous work [DVÜ+15] regarding the head-up displays to assist cyclists, our results have shown that the glasses with a head-up display marginally outperformed the multimodal approach based on subjective measures. We assume that the difference in the results with previous work can be explained by the technology used and the placement of the display. The head-up display in the previous work [DVÜ+15] was based on a mini-projector mounted on the handlebar that projected an image on the plexiglass in front of a cyclist. We used OLED technology integrated in the glasses and showed that it provides a high visibility of icons even on sunny days. We assume that since the projection in the glasses was located in front of the eyes and not at the level of the handlebar, children found it less distracting and easy to use. Moreover, HUD glasses has a smaller form factor compared to the system in the previous work [DVÜ+15], which can benefit from a better individual fit, i.e., the size of the glasses can be adjusted depending on the age.

The placement of the head-up display might be reconsidered even further in the future. We think that placement of the head-up display should be shifted to a helmet, given that some children felt more comfortable and safer with a helmet than with the glasses. Moreover, helmets are advisory and in some countries even mandatory cycling accessories. Similar to the glasses, the head-up display can be placed in the visor of a helmet. Unfortunately, due to the technical limitations we did not augment a helmet with a head-up display within the scope of this work.

We have shown that ambient light in the helmet and vibration on the handlebar is a valuable combination. Compared to HUD glasses, which require focal visual attention, vibration and ambient light cannot be simply missed on the busy streets. In this case, a multimodal system might be useful in the situations with heavy traffic situations, while HUD glasses might be more applicable for light traffic scenarios. The multimodal system can provide an efficient guidance for child cyclists, which is in line with the previous results about navigation for child cyclists (Chapter 5). Similarly, vibration is a promising modality, but in our experiment we found that low outside temperature reduces hand sensitivity, which makes it difficult to perceive the signal. Alternatively, vibration feedback can be integrated in the gloves to avoid this limitation.

Within the scope of this test-track experiment, we focused primarily on the representation of reminder for safety gestures. However, we also showed that the current camera-based recognition system is sufficient to recognize the safety gestures in the real-time. Even though we have seen that gestures can be recognized without delays, we see the necessity in conducting an experiment with child cyclists in a more realistic scenario over a longer period of time, e.g., over one-two weeks during school period. Moreover, given that e-bicycles are becoming popular and have an energy source, it will be possible to supply power for all technical components.

7.4.9 Summary

This chapter reports from one controlled test-track experiment about safety gesture reminders for child cyclists. The outcomes provide insights into how safety gesture reminders can be represented for child cyclists in an understandable and non-distracting way to address RQ4: *How can we represent safety gesture re-*

minders for child cyclists in an understandable and non-distracting way? We showed that both HUD glasses and the multimodal system were successful for showing safety gesture reminders, but have their unique advantages and disadvantages. HUD glasses have an intuitive icon-based representation and high visibility of icons on sunny days. On the other hand, the multimodal system does not require as much visual attention and can be valuable on the busy streets. Additionally, we presented one possible technical solution of a bicycle augmented with sensors and showed how these sensors can be used.

The main outcomes of the study are:

- We found that children marginally preferred the HUD glasses over a multimodal system due to its higher understandability and lower distraction level. We contribute an empirical evaluation of reminders about safety gestures for child cyclists and a technical bicycle setup to enable cyclists' assistance.

- We present a possible technical solution for an instrumented bicycle, which enables recognition of the environment, traffic signs and cyclist's behavior. To ensure the activation of the signals investigated in Chapter 4-7, this technical solution can be used for conveying the data needed for the activation of other assistance signals.

8 Conclusions

This chapter concludes and summarizes the work presented in the thesis. It outlines the contributions to the field, discusses the limitations of the work, provides design recommendations for cycling assistance systems, and describes future research directions.

8.1 Contributions

This thesis contributes empirical evaluations of multimodal assistance systems for child cyclists in a stationary bicycle simulator in a laboratory and a tricycle on a test track. Based on the results from the reported experiments, we showed that multimodal assisting cues can be used for different purposes and can effectively assist child cyclists in the presence of external distractions. This section summarizes the contributions of this work.

8.1.1 Warnings

We derived a set of on-bicycle and on-helmet locations for multimodal feedback applicable for warning representation and showed that with the support of the designed warnings child cyclists faced no accidents in the bicycle simulator. From the first experiment we derived that the **auditory feedback needs to be placed in the helmet**, close to the ears and without blocking them, to avoid a possible distraction to other cyclists and make the signals less invasive and more private. The results from the second experiment showed that **ambient light signals need to be located close the eyes** to ensure the peripheral perception of the signals, for example, in the helmet. We also discovered that children needed more time to perceive visual than auditory or vibrotactile cues. Since the visual signals were presented on the handlebar, children tend to glance at them more often, and therefore would need more time to react to signals.

We found that **unimodal encodings were applicable for directional cues** and **multimodal for immediate actions**. In this case, children could make a clear distinction between a non-urgent signal, i.e., directional cue, and an urgent signal, i.e., immediate action. Additionally, we observed that **trimodal warnings performed better for understandability and led to shorter reaction times**. This outcome supports the results from previous works in the automotive domain [PBP13], where drivers reacted faster to multimodal signals. In our experiment, a simultaneous activation of multiple signals ensured a better and faster perception of the signals.

8.1.2 Navigation

We found that **navigating with auditory cues was the best in the presence of the auditory distraction task**. Despite the fact that both speech navigation and the auditory distraction task refer to the same auditory perception, children still performed better using auditory cues in both laboratory and controlled test-track experiments. Moreover, we propose that **the combination of light and auditory signals might be useful for children of younger age** to distinguish between left and right. Given that sometimes children experience confusion between left and right while cycling, we found it essential to supplement future cycling assistance systems with light and speech. In this case, children can learn to distinguish the directions, especially in the beginning of their cycling experience.

We found that the vibration feedback coupled with the speech navigation instructions can be used as a reminder to show hand signals before performing a turn. Similar to the augmentation of speech navigation with light for learning left and right, we think that vibration on the handlebar can facilitate hand gestures due to its high intuitiveness. As we have shown in Chapter 7, safety gestures can be effectively represented using a vibrotactile feedback.

Off-the-shelf solutions, such as Garmin bicycle GPSs and Google Maps, can be potentially used by children, if the speakers are placed in the helmet and the ears are kept open. Since the usage of headphones is not recommended or even prohibited in some countries, we see helmets with auditory navigation cues as a suitable alternative for children. Moreover, from the technical point of view, coupling a smartphone to a helmet will reduce the computational power needed for the routing algorithms.

8.1.3 Lane Keeping

From the semi-structured interview we found that children feel discouraged cycling alone and have problems on the roads with parked cars and no cycling infrastructure. For example, we observed that children either forgot to return to the side of the road after overtaking an obstacle or were unsure about the safe distance to the side of the road. This outcome showed a need to provide path correction cues to guide the children left or right on the road with parked cars on the side.

We discovered that **vibration and ambient light in the helmet perform the best for the lane keeping assistance** in the presence of a visual search task. However, in the follow-up controlled test-track experiment, we discovered that ambient light has visibility limitations on sunny days, and the combination of ambient light with vibration might be a better solution.

We empirically showed that children were able to react to external visual distractors and that they could follow lane keeping cues simultaneously. Given that three of the evaluated methods were visual, children still could follow lane keeping cues, react to visual distractors, pedal, and steer. This indicates that the proposed unimodal lane keeping cues do not overwhelm child cyclists, and they can cycle without a problem.

8.1.4 Safety Gestures

In another test track experiment we found that **children prefer HUD glasses over a multimodal system** due to its marginally higher understandability and lower distraction level. We contribute an empirical evaluation of reminders about safety gestures for child cyclists and a technology to enable cyclists' assistance. Along with the empirical evaluation of safety gesture reminders, we presented a possible technical solution for an instrumented bicycle, which enables recognition of the environment, traffic signs and cyclist's behavior. To ensure the activation of the signals investigated in Chapter 4-7, this technical solution can be used for conveying data needed for activation of assisting signals, e.g., warnings, navigation and lane keeping cues, reminders about safety gestures.

8.1.5 Summary

The goal of this thesis was to explore the design space of assisting cues for child cyclists and study technical possibilities to design these cues following a multimodal approach. We see it as a supplement to existing cycling education programs, aiming to assist child cyclists and ideally to increase road safety. Within the scope of this work we focused on some aspects relevant for cycling assistance. In particular, we studied the presentation of warning, navigation, lane keeping cues, as well as safety gestures for child cyclists. Our aim was to design these assisting cues without additional mental load, i.e., in an understandable and non-distracting way. We showed that these types of assistance can be represented via multimodal cues. We also demonstrated that these cues can be perceived and understood by child cyclists in the presence of auditory and visual distractions in a simulator-based and test-track experiments. The results from the conducted experiments provide evidence that multimodal signals have the potential to support child cyclists, can effectively notify about dangerous road situations, navigate, assist with lane keeping, and remind about safety gestures. Based on the results from the reported experiments, we summarize this work by presenting the following design recommendations of assistance systems for child cyclists:

1. Auditory feedback needs to be placed in the helmet close to the ears, but without blocking them (Studies about navigation cues, Chapter 5).

2. Ambient light signals need to be located close to the eyes to ensure a clear distinction between left and right (Studies about navigation cues, Chapter 5).
3. Acoustic and vibrotactile encodings are the most applicable for directional cues and a combination of a visual, auditory and vibrotactile feedback – for immediate actions (Studies about warning signals, Chapter 4).
4. Speech-based navigation performs the best in the presence of the auditory distraction task for children above nine years old (Studies about navigation cues, Chapter 5).
5. A combination of light and/or vibration with auditory signals is useful for educating younger child cyclists, e.g., learn to distinguish between left and right (Studies about navigation cues, Chapter 5).
6. A multimodal combination of ambient light with vibration is helpful for lane keeping assistance in the absence of cycling infrastructure (Studies about lane keeping cues, Chapter 6).
7. Both HUD glasses with an icon-based representation and a combination of ambient light and vibration are recommended to represent safety gesture reminders due to their higher understandability and lower distraction level (Studies about safety gestures, Chapter 7).

8.2 Limitations

This section provides the limitations of the presented approach, experimental environments and discusses generalizability of the results.

8.2.1 Approach

We addressed the problem of assistance for child cyclists from the engineering perspective by designing, implementing and evaluating assisting cues for child cyclists. However, this is one possible way to address the problem of cycling assistance. For example, cycling educational programs or technological advances in integrating sensors on bicycles and helmets can be complementary methods to improve cycling. While designing cycling assisting cues, we used the channels that do not compete for mental resources necessary for cycling, i.e., vibration, ambient light and sound, and showed that this approach can effectively support child cyclists. However, a single experiment, which, for instance, showed that a trimodal warning can prevent collisions between cars and cyclists, does not necessarily prove that it will successfully prevent collisions in all kinds of situations. With this work we started exploring the possibilities of assisting cues in bicycle simulator studies to avoid putting participants at risk and control key aspects of the cycling environment. We also made a step further and conducted test-track evaluations on a tricycle. However, this body of research will need deeper explorations in more complex scenarios. For example, it might need to account for the effectiveness of the assisting cues in the presence of other road users under different weather conditions and different levels of background noise.

8.2.2 Bicycle Simulator and a Test Track

The main limitation of our laboratory experiments 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. We assume that these aspects might influence the perception of the assisting cues, which need detailed investigations. However, we aimed to mimic road distractions via auditory and visual distraction tasks. More so, the bicycle simulator was sometimes perceived in a playful, game-like way. In the case of experiments with warnings, 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 trajectory. It would be interesting to explore these cycling strategies in real-world conditions. We conducted other three experiments on the test track study during spring and 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 face. Children had to cycle on the tricycle without a need to keep the balance based on recommendations from the institutional review board.

8.2.3 Generalizability

All the experiments presented in this thesis were conducted exclusively with children aged between 6 and 13, given the highest accident's rate for cyclists within this age group. In our design solutions we accounted for developing motor and perceptual-motor abilities and adjusted the design of assisting cues accordingly. However, one of the remaining questions is: How generalizable are the results to other age groups and which differences in implementation we might account? Ideally, to answer this question, future researchers will have to explore derived assisting cues with different age groups. In our opinion, some of our solutions might also work efficiently with other adults, given the results from previous work, but future investigations are necessary. The reaction times to the external distractors might be shorter due to a different level of development for motor and perceptual-motor skills.

8.3 Discussion

In this section, we elaborate on uni- and multimodal encodings, how these encodings can be combined into one assistance system for smart bicycles and helmets, reflect on the design space, external distractions and a sample size.

8.3.1 Uni- or Multimodal?

We showed that some of assisting cues for child cyclists are better represented unimodally and some – multimodally. For example, warning signals were split into directional cues (unimodal signals) and immediate actions (multimodal signals) to ensure a clear distinction between the types of warnings. In experiments with navigation, lane keeping and safety gestures, we started the exploration of encodings with unimodal signals. The general idea was to explore the efficacy of unimodal signals avoiding signal overload and unnecessary complex signal designs. As we have seen from the results, navigation for older children worked sufficiently with unimodal signals, while younger might need a multimodal solution. Similarly, representation of lane keeping cues needs to consider a multimodal design. As for the safety gesture reminders, we have also seen that HUD glasses outperformed a multimodal reminder, which consisted of vibration on the handlebar and ambient light in the helmet. Therefore, urgent warning signals or lane keeping cues are better presented multimodally to minimize the probability of missing them. It is less likely that a child misses all signals, given three perceptual channels. On another hand, navigation signals, safety gestures and directional cues can be sufficiently presented unimodally, which can be seen more as recommendation signals, given their lower criticality. This leads us to a conclusion that **every modality or a combination of them works better for a particular purpose**.

8.3.2 Design Space

As mentioned in the introduction, within the scope of this work we focus on the signals to assist a cyclist, but the design space offers more possibilities of cycling assistance. For example, wearable technology focused on the increase of a cyclist's visibility or assisting cues presented in the environment around a cyclist can cover other research areas. We focused on four particular types of information to assist child cyclists, given accident reports, missing cycling infrastructure, and children's developing motor and perceptual-motor skills. This led us to focus on warnings, navigation, lane keeping cues, and safety gesture reminders as "on-the-go" assistance cues. These types of assistance are a subset of possible information which can be presented to children and investigated with them. Moreover, each type of presented assistance can be explored deeper, e.g., when or how frequent the signals should be presented.

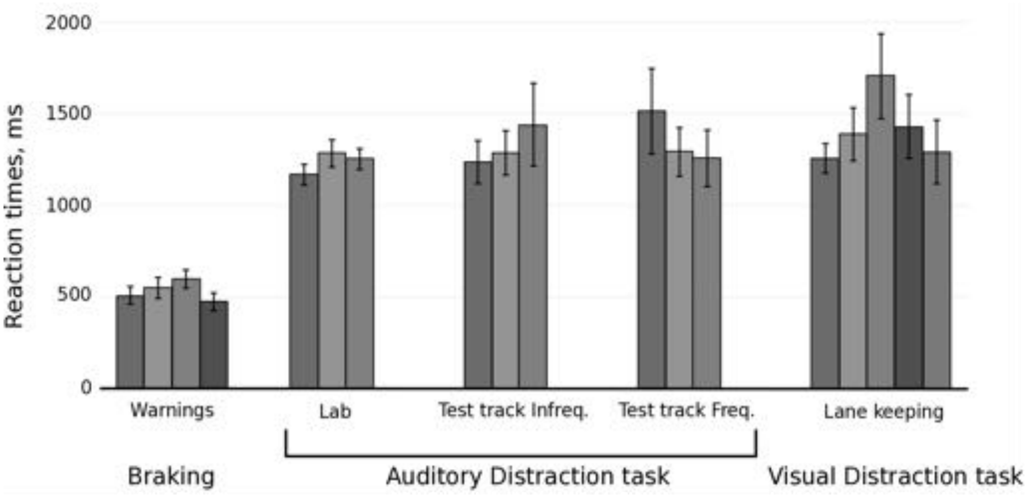

Figure 8.1: Overview of the reaction times from experiments with warnings, navigation and lane keeping.

8.3.3 Combining Sensors and Actuators

Recognition of the dangerous situations is an essential part of cycling assistance. In Chapter 7, we outlined a possible technical solution for an instrumented bicycle, which was already partially evaluated for safety gesture reminders. The design of the presented bicycle ensures the recognition of the surrounding environment, cyclist's behavior (sitting or standing), and cycling trajectories using integrated cameras. This is one possible technical solution, which can be used to facilitate safe cycling. This prototype can be augmented further with sensors for measuring distance to the side of a road and integration of Car2X technology[1] to ensure a reliable communication between bicycles and cars by sharing velocities and distances. While integration of Car2X communication might need a long time to integrate with existing vehicles and infrastructure, we envision our design solutions to become a part of helmet designs in a shorter time. Existing helmet design primarily focus on a head protection and increase of visibility of cyclists, and our solutions might be used for a third purpose – assistance of a cyclist "on-the-go".

8.3.4 External distraction and reaction time

We added a distraction task to simulate real-world conditions and explore available mental resources necessary to react to external stimuli. We explored auditory and visual distraction tasks and measured reaction times to them. In particu-

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[1] `https://www.vector.com/de/en/know-how/technologies/autonomous-driving/v2x/`

lar, we observed that the reaction time to the visual distraction task from the laboratory experiment with lane keeping was between 1,3 and 1,7 seconds, which is comparable to the reaction times to the auditory distraction task presented during experiments with navigation. We also measured the reaction time to immediate actions in the experiment with warnings. We observed that the reaction times to encodings for immediate actions were between 500 and 600 ms, which is 2-3 times shorter than to auditory or visual distractions (Figure 8.1). We assume that this difference in the reaction times might be caused by the following two reasons: (1) method of reaction and (2) priority of the task. As for the method of reaction, children pressed an additional button placed on the handlebar for the distraction tasks, and braked for the warning signals, which was most likely a more natural way of reacting to an external danger. As for the priority of the task, children's primary task with the warning signals was to react to them, and not to an external distraction. For example, in the laboratory experiment with lane keeping cues and navigation, children's primary task was to follow a lane keeping cue and to react to a distraction had a lower priority.

8.3.5 Sample Size

Given the sample size and cultural background of all participants, it is hard to generalize our results to a wider group of children. However, in total 141 children (72 of them were distinct) from Germany and the United Kingdom participated in the reported experiments. Some children participated in multiple studies, but we had 4-6 months breaks between the experiments to avoid learning effects. With these findings we provide first empirical evaluations of multimodal assistance systems for child cyclists in bicycle simulator and on a test track with the presence and absence of an external visual and auditory distraction.

8.4 Future Directions

This work is not the end of the journey with a multimodal assistance for child cyclists and there are other questions worth exploring in the future. For instance, in this thesis, we focused on the evaluations addressing a particular type of signals, but we have never explored the combination of signals with different purposes. One future research direction might be an exploration of simultaneous information representation and whether children can differentiate among different signals without a confusion. For example: *How many types of signals can be combined into one assisting system for child cyclists without mental overload?*

Another future direction might need to focus on a deeper exploration of cycling *environments* and *contexts*. In our work we used a bicycle simulator and a test track. In the experiments conducted in a bicycle simulator, we employed either a 2D projection on the wall or three screens in front of a cyclist. Both setups of bicycle simulators lacked immersion, which can be increased, for example, using a virtual reality headset. We think it is worth exploring cycling environments based on virtual reality caves to facilitate a higher immersion and a better peripheral perception of the environment. An advantage of bicycle simulators is that it provides a safe experimental environment and allows customization of road situations. The future work might need to take another step further towards increasing the ecological validity of the results and explore a real traffic scenario with cars and pedestrians on the road. Such evaluations have to be carefully designed, given ethical complications regarding safety. As for the cycling contexts, children in our experiments cycled alone, however their behavior might change in the presence of a friend, group of friends or strangers. We envision it as another future direction, which focuses on the efficiency of the cycling assistance systems in the presence of other cyclists. Availability of other cyclists can also introduce additional distraction and change the interaction with the system.

This work focused only on the interaction part of assistance systems for child cyclists. Future researchers might need to closer investigate the sensor part, responsible for recognition of the environment, calculation of the speed and distance to a car on a road crossing, or distance to the side of the road. The sensor part is essential for our solutions and requires a high reliability and precision of the environmental recognition.

Figures

Tables

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