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Vibrotactile Motorcycle Navigation

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Abstract

Navigation devices for cars are ubiquitous and become increasingly popular for motorcyclists as well. The motorcycle navigation devices were optimized for motorcyclists regarding their range of functions, but the interaction with these navigation devices are not optimized for motorcyclists. In this thesis, we explore vibrotactile feedback for motorcycle navigation. We evaluated the vibration that is generated by the motorcycle with different motorcycles and riders, and found that the best location for providing vibrotactile feedback is the waist. We designed a prototype that is integrated into a kidney belt. We evaluated its usability in a real world driving study, comparing the vibrotactile approach to a visual approach. We found that the vibrotactile system outperforms the visual system in terms of errors made, as well as occurring distraction while driving.

Kurzfassung

Navigationsgeräte im Auto gehören mittlerweile zur Standardausstattung vieler Autos und werden auch immer öfter auf dem Motorrad eingesetzt. Die Motorrad Navigationsgeräte wurden zwar vom Funktionsumfang an das Motorradfahren angepasst, jedoch wurde die Interaktion mit dem Fahrer nicht angepasst. In dieser Arbeit verwenden wir vibrotaktile Signale für die Motorradnavigation. Dafür haben wir die Vibration während des Fahrens mit verschiedenen Motorrädern und Fahrern gemessen. Dabei haben wir festgestellt, dass sich insbesondere die Hüfte besonders gut eignet um vibrotaktile Signale an den Fahrer zu übertragen. Daraufhin haben wir einen Prototyp entworfen der in einen Nierengurt integriert ist. Wir haben diesen Prototyp in einer Fahrsituation auf öffentlichen Straßen mit einem visuellen Navigationssystem vergleichen. Mit dem vibrotaktilen System haben die Fahrer weniger Abbiegefehler gemacht und waren gleichzeitig weniger abgelenkt als mit dem visuellen System.

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1 Introduction

Car drivers usually plan a trip to be the shortest or fastest connection between their start and destination. In contrast, motorcyclists usually ride for the experience of the ride, therefore motorcyclists usually avoid the fastest route but plan a route via small unused, preferably bendy, roads. Finding and routing along these roads in unknown areas usually requires the use of a navigation aid. Therefore, motorcyclists use a diverse set of navigation tools. Some use the sun as directional orientation, others use maps or road-books. Over the last years, more and more motorcyclists started to use digital motorcycle navigation devices, that are comparable to car navigation devices. However, these motorcycle navigation devices have not really evolved from car navigation devices. Besides from minor interface changes, hardware changes (i.e., waterproof, mountable on the handlebar), and motorcycle specific functions (e.g., find curvy roads or import routes from third-party route planners like Kurviger.de[1]), the motorcycle navigation systems are not optimized towards the driver device communication. Similar to a car navigation device the rider has to regularly look at the navigation device's display to be notified about current turn instructions.

Motorcycling is different from car driving. On the one hand, this is due to the different road types that are used by motorcyclists. On the other hand, a rider's surroundings and physical conditions are completely different from a car. Motorcyclists wear protecting gear, for example, the helmet limits the field of view, the visor adds another barrier to the sight, the potential navigation device is not protected from the sun, which makes it even harder to perceive the content on the display (e.g., in a car, the roof protects the display). There is no built-in way of audio communication between the driver and the vehicle. Additionally, motorcyclists don't want to be distracted by any audio signals during their ride.

According to the research of the Great Britain Department of Transport, motorcyclists have an especially poor safety record when compared to other vehicles [CWBT04]. Even though motorcyclists make up less than 1% of vehicle traffic, they suffer 14% of

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[1] https://kurviger.de/

total deaths and serious injuries on Britain's roads. Since motorcycling is dangerous, it is important to not further distract the rider.

Several different subtasks need to be performed to operate a motorcycle. These tasks mainly use the visual and auditory senses of a driver. Visual aspects include scanning the road for other road users, dirt, and its' course. Auditory tasks are mostly listening to surrounding traffic and alarm sounds. Current navigational devices use auditory and visual cues to provide turn instructions. This has the potential drawback of overloading the driver´s senses and probably cause driver´s distraction [CN01]. Particularly in situations with high cognitive load (e.g., taking turns in high traffic situations), drivers tend to have fewer capacities for visual tasks [HNTE07].

According to the multiple resource theory [Wic02], adding more tasks to already occupied channels leads to a reduced performance and therefore to an increased accident risk [EV04]. There are applications that might not benefit from adding more visual stimulation, for example: cars, motorcycles, or aircraft [VVJD05]. Navigational systems for pedestrians [HHBP08] have already been realized with vibrotactile cues. A similar vibrotactile navigation system was evaluated in a car on busy urban roads [AB10]. Actuators mounted to the torso of a user vibrate and therefore provide a hint to the user where to turn. In contrast to the pedestrian navigation, the motorcycle domain possesses challenges that need to be investigated to create a usable and safe to use system. In the motorcycle domain, Prasad et al. started investigating this type of navigational system in their Haptimoto project [PTGH14]. However, they focus on the general feasibility of navigating a driver in a controlled environment through a sequence of turns.

We further explore the feasibility of vibrotactile feedback, for motorcycle navigation in a real-world driving situation. In contrast to a controlled setup, understanding driving in the real-world needs to take several aspects such as the vibration of the motorcycle and potential cognitive distraction of the driver into account.

1.1 Outline

In this thesis, we evaluate if vibrotactile feedback is a suitable mean for motorcycle navigation in a real driving situation. Therefore, we evaluate existing vibration on a motorcycle while driving, to find the position with the least vibration. The positions are selected with everyday usability in mind, to be able to integrate vibration feedback in an unobtrusive way to everyday motorcycle trips (see Chapter 3). We design and develop a fully working vibrotactile navigation prototype, that can be used for everyday motorcycle navigation tasks (see Chapter 4). The system is compared against a traditional visual navigation system in a real-world driving study (see Chapter 5). The vibrotactile approach significantly reduced the errors made during the navigation task. According to subjective feedback, the vibrotactile navigation system adds less distraction, compared to the visual navigation system.

2 Background and Related Work

This chapter provides an overview of work that was done in related areas. We start with giving an overview to the sense of touch in general (see Section 2.1), which is divided into a part about vibration and a part about electrical muscle stimulation (EMS). This is followed by a part about navigation systems (see Section 2.2), starting with visual and auditive approaches, which are followed by approaches using vibration EMS, and haptic feedback in general.

2.1 Sense of Touch

Touch is perceived with the skin (including hair follicles), tongue, throat, and mucosa. The skin covers almost all parts of the human body. This enables us to apply wearables, that provide feedback that triggers our sense of touch, to almost every part of the human body.

Today, there are two common ways to deliver touch feedback. The traditional approach is to use vibration. The other approach is to use EMS. Even though EMS has been evaluated since the 18th century, it is quite new in the HCI community as feedback technology [PSAR14].

Vibration is a mechanical phenomenon. It occurs when an object performs an oscillating motion. Usually, it is created using a direct current motor with a non-symmetric mass attached to it, called vibration motor. The mass is rotated and due to the asymmetric mass the centrifugal force is displacing the motor. If the rotation is fast enough the displacement is felt as vibration. The force of the vibration can be controlled by modifying the speed of the motor and the weight of the asymmetric mass.

EMS uses electric impulses to stimulate muscles in the same way the central nervous system would. Electrodes are used to create these electric impulses. Usually, the electrodes are adhesive pads. Muscles that are nearby an electrode are stimulated by the electric impulse. The stimulation causes the muscles to contract. When applying the electric impulses with a frequency of $60\mathrm{Hz}$ using a sawtooth waveform and an appropriate current (varies between users and part of the body), EMS can be perceived as haptic feedback [PSAR14].

Pfeiffer et al. [PSAR14] propose EMS as feedback technique in free-hand interaction on large displays. They compared their EMS approach to a traditional vibration feedback approach. In order to do so, they conducted a study that is intended to find out how feedback should be designed to best reflect the performed gesture as well as the properties of the object a user performs with. All users were able to distinguish both feedback types. Also, EMS was perceived better when interacting with hard materials compared to vibration. For soft materials, no significant difference could be found.

2.1.1 Vibration Feedback

This section presents the traditional form of touch feedback, namely vibration. Vibration has been used in a variety of fields. When learning a movement, vibration can add beneficial information. This has been shown by Lieberman and Breazeal [LB07]. They proposed a system called TIKL. TIKL is a wearable vibrotactile feedback suite intended to learn given arm movements. They can show a 27% increased accuracy of the movement and an accelerated learning rate of up to 23%.

Studies conducted in the lab often create different results compared to the findings of an in the wild study. Therefore, van der Linden et al. [LJB+11] conducted a long-term study on the learning effects of vibrotactile feedback. They built a wearable device that measures the body movements and posture while playing the violin. The system is called MusicJacket [VSBJ11]. MusicJacket is intended to support good bowing and posture while playing the violin. Therefore, the system provides vibrotactile feedback in real-time to pupils who learn to play the violin. There were two groups: novice and advanced violin players. They observed that the pupils were able to increase their playing skills and that the teacher and pupils liked the system. The straight bowing technique of the novice group improved significantly compared to novices who have not received vibrotactile feedback. However, the vibrotactile feedback seems to increase the cognitive load, as the pupils made more mistakes when using the system. In contrast, their technical skills like posture and bowing were better when using the system. After receiving the treatment their skill remained better compared to pupils that haven't worn MusicJacket. During high cognitive load, pupils reported that they did not feel the vibrations anymore.

The vibration feedback does not have to be used actively as shown in MusicJacket. Vibrotactile feedback was shown effective for passive learning, as well. In Mobile

Music Touch [HSD+10] a user is equipped with a glove that has vibration motors attached to each finger. A user can learn to play the piano by using passive learning techniques. A song is played and a finger vibrates when the user shall press the corresponding piano key. It was shown that a piano novice can replay an unknown song after perceiving the treatment for half an hour. After half an hour, the user was able to play the song without using the glove any more. Two studies were able to show the efficacy of Mobile Music Touch.

Vibrotactile feedback was evaluated in the context of sport as well. Spelmezan proposes a system that provides real-time feedback while riding a snowboard [Spe12]. He compared the performance before and after a day of training. A snowboard instructor conducted the study. Participants used the system half of the day and on the other half participants trained without the system. Their skill level was checked before and after the day of training. However, the author cannot show a significant improvement in riding skill that can be related to the vibrotactile feedback. This is possibly because the author did not measure the performance of each rider before and after each condition. Whereas, each condition means either after training with or without the system. Additionally, some of the participants did not like the system as it did not always work flawlessly.

Vibration feedback has been used in all varieties. In general, most researchers were able to find significant improvements when using vibration feedback. However, it seems that sometimes no improvement could be found.

2.1.2 EMS

EMS is a novel way to provide haptic feedback. In contrast to vibrotactile feedback, EMS does not only allow providing simple feedback but also actuating the muscles and, thus, inducing movements [PSAR14]. PossessedHand [TMR11] uses EMS to control the movement of a user's hand. It can control 16 joints in the hand and is able to calibrate itself. The authors show that PossessedHand can support humans in learning a music instrument. However, the device is not able to create enough force to the finger to actually play a music instrument.

Lopes et al. [LBB13] propose muscle-propelled force feedback. They equip a mobile phone with EMS. Therefore, they are able to create force feedback without needing to equip a mobile phone with vibration motors. This results in smaller and lighter devices. The authors want to test the device in the context of gaming. The device actuates a user's forearm muscle which forces users to involuntarily tilt the device to one side. Users have to resist the involuntarily created force in order to successfully play a game. Lopes and Baudisch evaluated this device in a study [LB13]. They found that users were able to produce a maximum of $18.7\mathrm{N}$ of force.

Kruijff et al. [KSB06] used EMS as feedback modality when playing 3D video games. They added electrodes to the biceps to be able to control the arm movement. No electrodes were added to the forearm in order to control the finger movement.

REVEL [BP12] uses EMS to change the perception when touching an object in augmented reality. The authors were able to change the tactile feeling of objects without relying on gloves. REVEL creates an oscillating electrical field around a user's finger. When sliding his or her finger across the surface of an object, he or she perceives distinctive tactile textures. The tactile sensations can be changed per object.

EMS is an uprising technology that is more and more used in the HCI community. The use cases try to use the special properties that EMS can provide. For example, a user's hand is bent involuntarily, this would not be possible with vibration feedback. EMS provides new possibilities for research and commercial applications.

2.2 Navigation Systems

In general navigation systems aim to support the navigation task, usually by adding additional information. For example, these might be a digital map showing the current position and the destination, usually including the azimuth. In the automotive domain, the common approach is to use turn-by-turn instructions (e.g., "turn left in 300 meters"). Since the number of turns on a regular street is limited, humans are able to convert that information to the real-world. Another common approach is the use of a compass alike arrow that points towards the goal.

2.2.1 Visual Navigation System

Furukawa et al. [FYH+11] propose the usage of "vection fields" for navigating crowds of pedestrians. The authors can show that moving vection fields on the ground influence the moving direction of pedestrians and therefore they are suitable to navigate crowds of people. The technique works intuitively without further explanation, which therefore might be better suited for navigation compared to arrows typically found for navigating crowds of people.

Rukzio et al. [RMH09] developed public display for pedestrian navigation, the Rotating Compass. It features eight circular aligned lights that show the direction that a user should follow in order to reach a destination. When comparing their novel public display to traditional approaches, like a paper based map or phone navigation, they can show advantages using their system. Users were faster and had a better orientation using the Rotation Compass, compared to traditional approaches.

Elderly people with memory issues have issues navigating, therefore Rassmus-Gröhn and Magnusson [RM14] designed a visual navigation system that focuses on helping these people. They propose a multi-step approach for navigation. A user has to select the destination from a list of personalized goals. When selecting a goal, the user is shown pictures of important landmarks along the route. During navigation, a compass alike arrow shows the direction to walk.

Funk et al. [FBP+14] research finding lost objects using a real-world search engine. They compare two approaches for navigating towards an object: a compass alike arrow and a picture of the sought image at the location it has been seen the last time. Both visualizations are shown on a head mounted display. They can show that using the image of the item at the surrounding context is faster for objects that are not obviously placed.

Mativienko et al. [MLE+16] use ambient light for turn by turn car navigation, which aims to reduce the distraction that is typically found with visual car navigation systems. The ambient light was able to reduce the average distraction time compared to a traditional car navigation device.

Smarthalo is a commercial product that is mounted on the handlebar of a bicycle[1]. It is a circular device that can show turn-by-turn instructions by lighting a part of the circle in different light patterns.

2.2.2 Auditive Navigation System

Auditive feedback is often provided as sensor substitution or addition to sight in navigation scenarios. If a user feels uncomfortable using a display (e.g., while walking), information can be transferred using audio. AudioGPS [HMG02] proposes to project sound in three-dimensional space for navigation purposes. The human ear is able to project sound in three-dimensional space, this allows a user to “follow the sound”. This approach has been extended in GpsTunes [SEM+05], where the functionality of a music player and navigation device are combined. The currently playing music is

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

adapted to navigate a user towards a destination. Simple music alteration techniques like volume adaption and panning are shown to be an effective mean for navigation.

Auditive feedback is also a prominent choice for navigating blind or visually-impaired people. In Drishti, a user receives auditive walking guidance and also notifications if a possible obstacle arises in front of the user [RHM04]. The authors were able to navigate blind people in and outside of buildings using sound. Similarly, SWAN [WWL+07] allows tactile input and auditive output for navigating visually impaired. A different approach is taken in DroneNavigator, Avila et al. [AFH15] use a quadcopter for navigating visually impaired. The quadcopter emits noise while flying, users can follow the sound for navigation purpose.

Baus et al. [BWA+07] introduce the use of auditory landmarks in addition to visual landmarks commonly used for navigation purposes. For example, when passing a music hall, a landmark will describe that the user might hear music, so the user knows to be at the right position when hearing music coming from a music hall. When comparing the performance of auditory landmarks to visual landmarks the author found an equal performance for both modalities.

2.2.3 Haptic Navigation System

This thesis focuses on haptic navigation systems, so we provide a more in-depth summary of work in that area. We are starting with more general haptic navigation systems that do not rely on vibration or EMS and are mostly self explanatory. This is followed by a section on EMS and vibrotactile navigation systems.

Amemiya and Sugiyama [AS09] created a handheld haptic pedestrian navigation device for the visually impaired. They use an approach that they call “pseudo-attraction force”, which exploits the way humans perceive force. They use a strong force into one direction, and a weak force in the opposite direction, created by a mass that is accelerated either strong or weak. Humans only feel a strong force, but not a weak force, therefore the “pseudo-attraction force” creates a force into one direction that is followed by a user.

Kon et al. [SMHK09] use the hanger reflex for intuitive pedestrian navigation. The hanger reflex occurs when pressing against certain points of the head, the head turns as a reflex. This effect can be exploited for navigation purpose since the body follows the head movement, which is also a known phenomenon for cyclists and motorcyclists [Spi10]. Nakamura et al. could further proof the hanger reflex to work on the waist, wrist, and ankle [NNSK14]. When comparing the effect of the hanger reflex to the different body parts, Kon et al. found that the effect was the strongest at the waist [KNSK16].

CabBoots [Fre07] proposes to manipulate the height of the shoe sole while walking. The authors describe their approach as intuitive haptic pedestrian navigation. By tilting the shoe, a user is led into one direction, the authors use the metaphor of a well-trotted natural path, when a pedestrian is coming close to the edge of the path the topography leads one back to the middle of the path. Pull-Navi [KHFK09] is a head mounted haptic navigation system that presents turn instructions by pulling a user's ear. Whereas a user follows the pull, i.e. pull the left ear means turn left. HAPMAP [IAK+11] is a haptic pedestrian navigation system that uses the sensation of a handrail to navigate users along a path. The authors created a handheld device that creates the feeling of a curving handrail to steer a user.

Navigation Systems using EMS

Fitzpatrick et al. [FWT99] and Maede et al. [MAA+05] use galvanic vestibular stimulation (GVS) to influence the direction of human walking. GVS stimulates the vestibular system, by applying a low current to the mastoid behind the ear. When walking with GVS a user tends to walk towards the anode, to compensate the stimulation of the vestibular system. Users don't need to focus on any signals provided by the system, the stimulation works without attention towards the signal.

Figure 2.1: The cruise control by Pfeiffer et al. the user is steered in a certain direction by applying a small electrical signal to the inner leg [PDS+15].

Pfeiffer et al. [PDS+15] propose a cruise control for pedestrians. The authors use an EMS approach to reduce the workload while navigating. They send electrical impulses to the motor system to control a users' walking direction. It is not mandatory that the user is actively contributing to the navigation task. The system rotates the leg and therefore the walking direction of a user is changing (see Figure 2.1). In a lab study, the system was found to change users walking direction approximately $16°/\mathrm{m}$. A study in a park could show that the system is able to navigate users on a given route through the park.

Vibrotactile Navigation Systems

Vibration can be used for navigation purposes. Vibration might be even preferred compared to visual in-vehicle information systems because these visual systems are ofttimes found to be distracting or to reduce the safety [FM03; JKC99; Wie91]. Sklar and Sarter [SS99] showed that unexpected tactile instructions result in better response times and better detection rates than visual instructions.

Heuten et al. present the Tactile Wayfinder [HHBP08]. They propose a navigation system featuring a vibration belt that keeps the user on track. The belt is vibrating into the direction the user shall take. They validated their system on an open field, where a user had to follow a predefined route. Their findings show that the user is able to follow the route in a predefined corridor. In a follow-up study Pielot and Boll [PB10] compared the Tactile Wayfinder to a commercial pedestrian navigation system. Even though the Tactile Wayfinder could not catch up with the navigation performance of the commercial pedestrian navigation system, the participants' attention was freed using the Tactile Wayfinder.

In Tacticycle, Pielot et al. [PPHB12] equipped a bicycle's handlebar with vibration motors. The system was designed to support touristic exploration trips on an island. The goal of touristic explorations is not to reach the destination but to enjoy the trip, hence vibration cues are provided for a coarse orientation towards a point of interest and not for turn-by-turn navigation. The system is designed to only provide minimal vibration cues. In a user study, the authors found that providing only minimal vibration cues is sufficient for exploratory bicycle trips. The concept was extended by smrtGrips [2]. SmrtGrips are basically vibrotactile grips that are mounted instead of the original bicycle grips. They can be connected to the user's smartphone and create turn-by-turn vibration patterns that are sent by the smartphone.

Steltenpohl and Bouwer [SB13] developed Vibrobelt, a vibrotactile belt for bicycle navigation. Using Vibrobelt, users were able to follow an unknown route towards

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[2] http://smrtgrips.com/

a destination. When comparing Vibrobelt to a traditional visual navigation system they found that while users wearing the vibrotactile belt made more errors, but encountered less dangerous situations. This is due to the increased visual focus on the screen, using the visual navigation system. This is also supported by the findings of Pielot and Boll [PB10].

Van Erp and Van Veen added eight vibrators to a driver's seat [EV04]. They compared the workload and reaction time of visual navigation instructions, vibrotactile navigation instructions, and a combination of both. They can show a significant decrease of the induced workload to the driver, when using the vibrotactile navigation instructions compared to visual instructions. The combination of both approaches shows the shortest reaction time. The biggest differences between visual and tactile instructions were found during high workload. According to the authors, the workload of the visual channel was moved to the tactile channel. Therefore, the workload and the reaction time was reduced using vibrotactile feedback, which is justified by the multiple resource theory. Vibrotactile navigation is not limited to cars, but can also be used for aerospace and nautical navigation [VVJD05]. The authors tested a helicopter and a speedboat, both vehicles create full body vibrations for the operator. Still, they can show that vibrotactile navigation works in high vibration environments.

Asif et al. [AHB10] compared three different distance encoding to be used in an automotive navigation system. They propose three different encodings: rhythm based encoding, rhythm & intensity based encoding, and rhythm & duration based encoding. The encodings were selected based on a pre-study and were evaluated using a vibration belt worn at the waist. The authors evaluated the encodings in a real urban environment using a wizard of oz experiment design. They found that vibrotactile stimulus is well suited to navigate along a pre-defined route and is indicated for use-cases where the eyes should not be put off the road. The study results indicate that rhythm & duration based encoding is most successful.

Asif and Boll compared a vibrotactile belt to a conventional car navigation system [AB10]. They found that the orientation performance was better compared to the traditional navigation system, whereas cognitive workload, performance, and distraction were not different. They showed that navigating a car during increased cognitive load induced by dense urban traffic is possible using only a tactile display [BAH11]. In TactiCar [LBHB15] the authors compare two vibrotactile patterns to be used with a vibrotactile belt to support car drivers during a lane change task. The first pattern is a rhythm based pattern and the second is an intensity based pattern. Both were compared in a driving simulator. They could not show a significant difference between both patterns.

Vibrotactile Navigation Systems for Motorcycles

Bial et al. provide a motorcyclist with vibrotactile feedback for navigation purpose [BKAS11]. They add vibration motors to a glove. Using the glove users were able to navigate in a lab study. They used vibration patterns that have to be translated by the user. Users were able to detect vibration patterns and figure the direction. However, their results show that the vibrations of the motorcycle itself make it hard to perceive the vibrations of the glove. Therefore, adding vibration motors to the glove might not work for real-world driving scenarios.

Prasad et al. [PTGH14] developed HaptiMoto, a vibrotactile motorcycle navigation system. HaptiMoto consists of a vest, that attaches three vibrational tactors to the back of a user. One tactor is attached to the back of each shoulder and one tactor is added to the lower back. They use an Android app to control the vibration cues and send them via Bluetooth to a LilyPad Arduino[3]. The vibrators are placed at the back of the shoulders since for the domain of walking user preferred the feeling of being tapped on the shoulder. There were no experiments that tried to find the optimal spot for attaching the vibrators. HaptiMoto used four different directional instructions: left, right, straight, and U-turn. For every instruction there are three intensities: approaching turn, get ready to turn, and take the next turn.

HaptiMoto was evaluated with speeds at around 50km/h and below. Users were asked to do single turns and consecutive turns in a controlled environment. The results show that using vibrotactile navigation cues work well for typical inner city navigation. They can show that a motorcyclist can feel and understand these instructions while riding the motorcycle in a controlled environment. However, it seems that there was an issue with fitting the HapitMoto vest to the users since the vest had to be refitted for some participants, because the vibration motors lost contact to the skin. Thus, the participants could not feel the vibration cues anymore. Also, some users had problems finding the correct road to turn (some turned an intersection too early and some turned an intersection too late).

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[3] http://lilypadarduino.org/

3 Measuring Vibration

Comparing the approaches of Bial et al. and Prasad et al. shows that vibrotactile motorcycle navigation can work if the tactors are not attached to body parts that are closely connected to the motorcycle. Body parts that are not closely connected to the motorcycle suffer less vibration than these parts that are closely connected [SS10]. Therefore we have to evaluate the existing vibration on a motorcycle to determine a good position to provide vibrotactile feedback.

This chapter evaluates where to place the vibration motors. A good spot place for vibration motors fulfills several properties. (1) It suffers low vibrations induced by the motorcycle. (2) It can be integrated unobtrusively into the motorcycle environment. (3) It allows to press the motors tightly against the skin, therefore the motors are always in good contact with the skin. Therefore, an evaluation of the generated vibration by the motorcycle is needed. Hence, we build a system using multiple accelerometers mounted on the body at different crucial positions. We evaluate the strength of the vibration at every position and compare it to the other positions.

3.1 Apparatus

We built a measurement system containing of an Arduino Nano[1] that is connected to ten MEMS-accelerometers (ADXL345[2]) via SPI[3]. The Arduino Nano uses an HC-06 Bluetooth module [4] (at 115200 BAUD) to send the acceleration data to an Android smartphone (Wiko Fever). The data is saved as comma seperated values with a time stamp and location information derived from the Android device. Every accelerometer

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[1] https://www.arduino.cc/en/Main/ArduinoBoardNano

[2] http://www.analog.com/en/products/mems/mems-accelerometers/adxl345.html

[3] http://www.epanorama.net/links/serialbus.html#spi0

[4] https://www.olimex.com/Products/Components/RF/BLUETOOTH-SERIAL-HC-06/resources/hc06.pdf

is placed in a case[5] that is sewn to different garments. Six accelerometers were sewn to a shirt and four accelerometers were sewn to straps.

3.2 Placement of the Accelerometers

The accelerometers are placed symmetrically at ten positions on the human body. The positions can be seen in Figure 3.1. We place all sensors symmetrically to determine if there is a difference between each side. The sensors are placed at the calf, the wrist, the side of the arm, the waist, and the back of the shoulder. We choose the calf as a reference for the legs. We did not use the thigh since the thigh should be always connected to the motorcycle [Spi10].

The wrist was successfully used for vibrotactile pedestrian navigation before [WSH+11], but integrating vibration motors to a glove for motorcycle navigation was found to be difficult to perceive due to the existing vibration of the handle bar [BKAS11]. Therefore, we choose the wrist as a reference for the vibrations that are created by the motorcycle and to understand the difference from vibration being very close to the motorcycle to vibration that was damped through the human body. The side of the arm and the waist are two spots that can be used for vibration feedback easily and could be integrated into the protection that is worn by a motorcyclist. The back of the shoulder is used to justify the placement of the vibration motors in Haptimoto [PTGH14] .

3.3 Validating the Vibration Measurements and Apparatus

In order to validate the vibration measurements, we created a test environment for the acceleration measurement. We use a speaker that is stimulated at a given frequency using a sinus signal. The accelerometer is attached to the speaker membrane. We evaluated the sensor measures using a spectral density estimation[6] that uses a Fast Fourier Transformation. We use R[7] to plot a periodogram of the measured

[5] We provide the design of the case for free here https://tinkercad.com/things/4cyG2cw4r86

[6] http://www2.ece.ohio-state.edu/~randy/SAtext/sm-slides-1ed.pdf

[7] https://www.r-project.org/

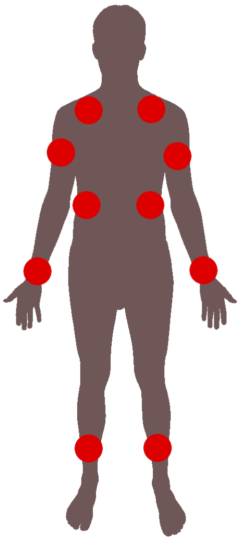

Figure 3.1: Placement of the accelerometers marked on the silhouette of a human.

vibration. R provides the `spec.pgram`[8] function to plot a spectral density estimation (periodogram). The induced vibration was clearly differentiable from the noise and harmonics. Figure 3.2 shows the periodic peak of the applied sinus wave and the peaks of the harmonic waves.

3.4 Quantifying the Strength of Vibration

In order to compare the strength of vibration, we need to be able to quantify the strength of the vibration that occurs at one position. We use *jerk*[9], the derivate of acceleration to accomplish that. *Jerk*, therefore, describes the change of acceleration and is ofttimes used by roller coaster engineers to ensure that a ride will not threat the safety of a passenger[10]. The *jerk* is also an important measure for rating the elevator riding convenience [How06]. Using the *jerk* for analyzing acceleration data is known to be robust [HJMM11] and widely used in analyzing vibration data in the automotive domain [Gri12; HW04].

The measures contain some noise of the sensors. To reduce the noise from the acceleration data we calculate the average acceleration for each axis and subtract

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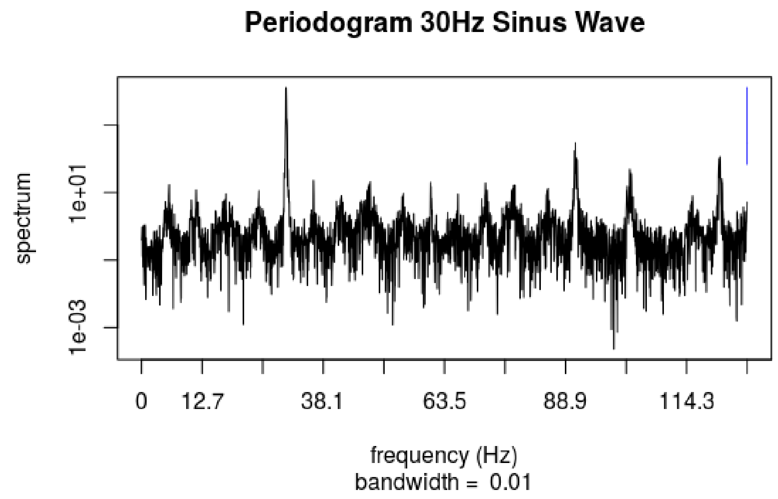
[8] https://stat.ethz.ch/R-manual/R-devel/library/stats/html/spec.pgram.html

[9] http://math.ucr.edu/home/baez/physics/General/jerk.html

[10] http://thetartan.org/2007/4/16/scitech/work



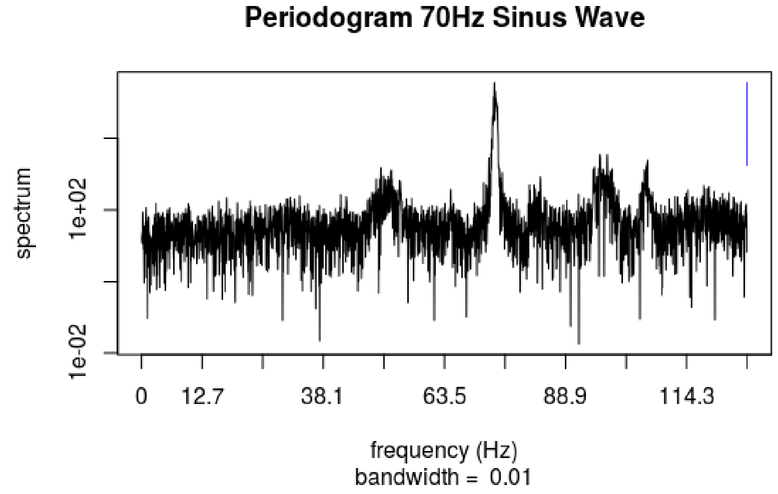


Figure 3.2: Sample Periodograms of a 30Hz (top) and 70Hz (bottom) sinus wave. Also showing the peaks of the harmonics of the applied frequency.

that value from every measurement of that axis. For calculating the overall *jerk* we calculate the *jerk* for every axis and use the Pythagorean Theorem for three dimensions (see equation 3.1) to get the overall *jerk*. Whereas j is the *jerk* and jx is the *jerk* that occurs for the x-axis.

$$(3.1) \quad j = \sqrt{jx^2 + jy^2 + jz^2}$$

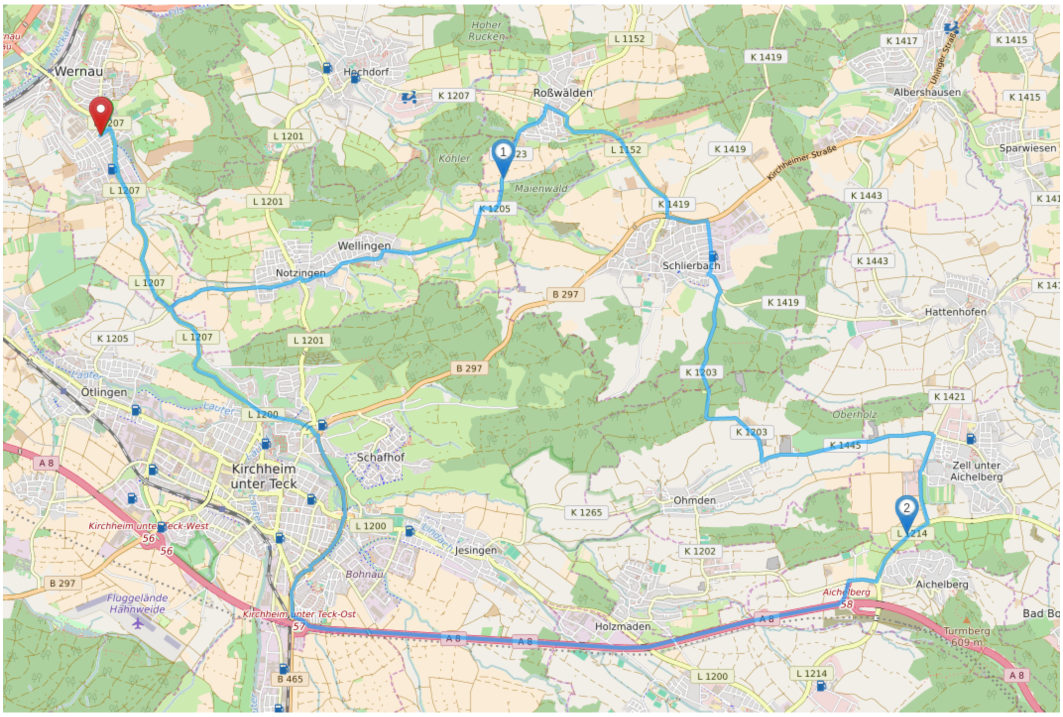


Figure 3.3: The route used for the measurement study. © OpenStreetMap contributors openstreetmap.org/copyright

3.5 Route

We chose a route that covers typical road types that are used by motorcyclists. The planned route is 35km in distance, takes approximately 40 minutes to ride, and contains 524 meters of altitude[11]. When planning the route we considered the road types described by Schneegaß et al. [SPB+13]. They classified five different road types: 30 km/h zone, 50 km/h zone, highway, freeway, and tunnel. We believe that the vibrations in a tunnel are not significantly different from the vibrations outside of a tunnel, hence we did not use a tunnel for the route. Additionally, we added rural roads to the road type classification of Schneegaß et al., since rural roads are one of the roads that are preferred by motorcyclists[12].

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[11] https://goo.gl/ZRhAr7

[12] e.g., https://kurviger.de/about/en

Participant	Calf L	Calf R	Waist L	Waist R	Shoulder L	Shoulder R	Arm L	Arm R	Wrist L	Wrist R
1	3.25	3.37	1.90	2.15	2.03	2.09	3.27	3.59	5.07	6.84
2	3.43	3.07	2.37	2.62	2.45	2.97	3.73	4.51	4.46	4.88
3	2.87	2.45	1.46	1.85	1.64	1.90	3.20	3.62	4.23	4.50
4	2.54	2.67	1.71	2.05	1.65	1.79	4.05	3.53	4.82	4.44
5	2.34	2.44	1.09	1.36	1.23	1.41	2.76	2.70	4.49	4.42
Average	2.89	2.80	1.71	2.01	1.80	2.03	3.40	3.59	4.61	5.02

Table 3.1: Average jerk per participant and body part.

3.6 Participants and Procedure

For the vibration measurement, we hired experienced motorcyclists with at least two years of experience. Volunteers have to own a motorcycle and have to ride their own motorcycle. The volunteers were recruited using our university mailing list, social media, and word of mouth. In total, five participants (5 male) aged between 25 and 66 years ($M = 33.2, \mathrm{SD} = 18.34$) took part in this study. All of them owned a valid driver's license and brought their own motorcycle. The participant's motorcycles were all 4-stroke engines, with one two-cylinder bike, two three-cylinder bikes, and two four-cylinder bikes. On average the motorcycles had $95.6\mathrm{hp}$ ($\mathrm{SD} = 25.3$). The participant was first equipped with the accelerometers (as described in Section 3.2) by the experimenter. The participant was instructed to drive a specific route (see Figure 3.3). The experimenter accompanied them with his own motorcycle.

3.7 Results

We evaluated the results of the five participants. The average *jerk* of both sides combined at the calf is 2.84, at the waist is 1.86, at the shoulder is 1.92, at the arm is 3.50, and at the wrist is 4.81 (see Figure 3.4). The detailed results for each side and each participant can be found in Table 3.1. On average, more *jerk* occurred on the right side for the waist, shoulder, arm, and wrist. In contrast, for the calf, more *jerk* occurred on the left side.

A map visualization of the strength of the occurred *jerk* on the right arm is provided in Figure 3.5. The visualization is created using CARTO[13] and available here[14]. Most

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[13] https://carto.com/

[14] https://boldtrn.carto.com/viz/fd44a684-5663-11e6-9de7-0e3ff518bd15/public_map

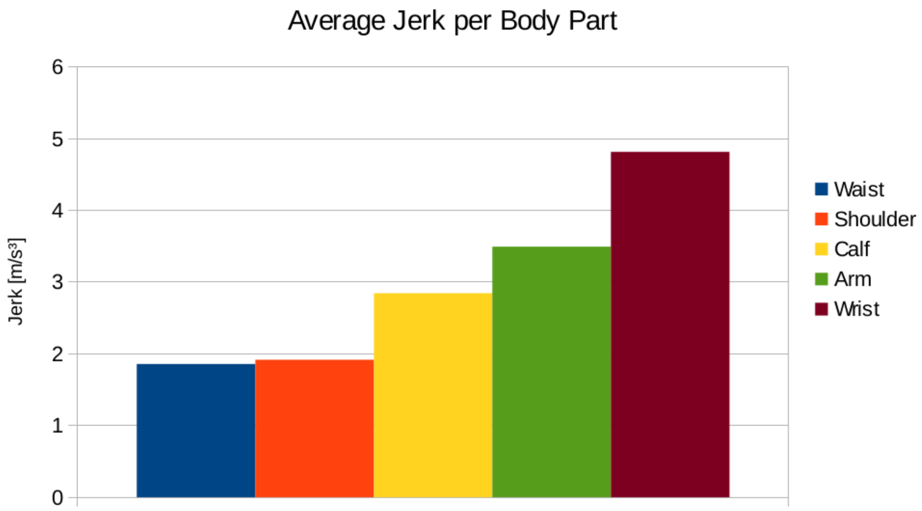

Figure 3.4: Average jerk occurred per body part

jerk at the right arm occurred at the freeway (the A8 is the street that goes from east to west in the south). That part of the freeway is built mostly with concrete plates, with small parts that are already renovated. The second most vibration occurs on the street from Schlierbach to Ohmden (K1203). The K1203 is a small street with a bad surface and several bumps, due to the bad surface, but no pot-holes.

3.8 Discussion

The results indicate that the most vibration while riding the motorcycle occurs at the wrist, followed by the arm and the calf (see Figure 3.6). The least vibration occurred at the back of the shoulders and the waist. Bial et al. [BKAS11] reported high vibration at the hands that make it hard to perceive vibrations provided by a vibration motor mounted in a glove. Similarly, we found that the most vibration occurs at the wrist. There was less vibration at the back of the shoulders compared to the wrist. The Haptimoto [PTGH14] project reports that the vibration was easily perceivable at the back of the shoulders. Since there is less vibration at the waist compared to the shoulders vibration provided at the waist should be also perceivable.

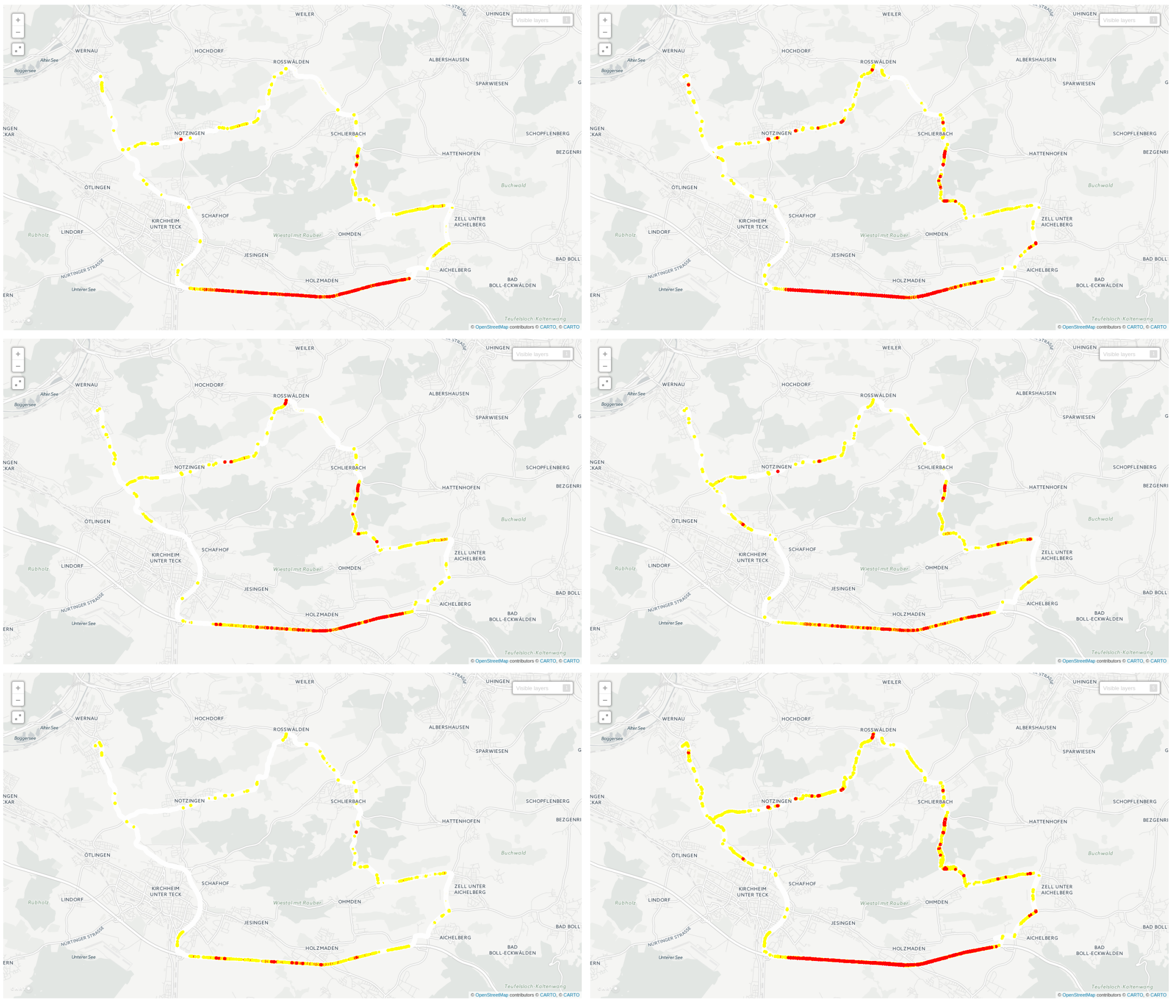

Figure 3.5: A visualization of the occurred vibration for each participant and a merged view. Top-left shows participant one. Top-right shows participant 2. Bottom-left shows participant 5. Bottom-right shows all participants merged. The red areas visualize the road segments with a high amount of *jerk*. © OpenStreetMap contributors openstreetmap.org/copyright

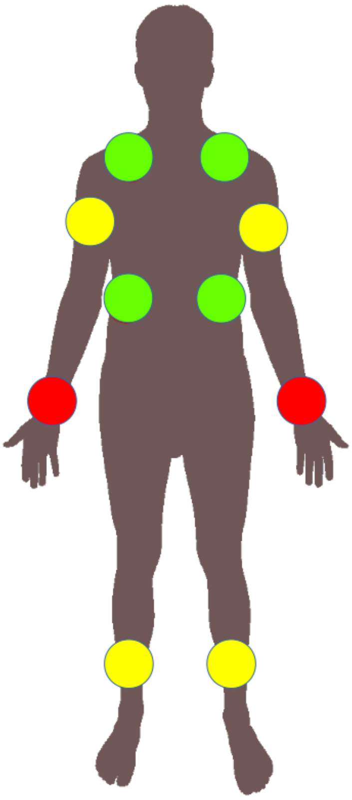

Figure 3.6: Visualization of occurred vibration on a human silhouette. Red means high vibration, yellow medium vibration, green low vibration.

3.9 Summary

When looking at the results it becomes clear that most vibration exists at the extremities. The torso suffers the least vibration. Thus, vibrotactile feedback should be applied to the torso. HaptiMoto [PTGH14] applied vibrotactile feedback at the back of the shoulder. In our measurements, the back of the shoulder suffered slightly more vibration compared to the waist. Additionally, the authors of HaptiMoto report that there were issues with the contact of the vibration motor to the skin. The HaptiMoto vest had to be refitted during the experiment. Some participants were not able to perceive the vibration feedback, due to sensor displacement.

Motorcyclists typically wear a kidney belt, while riding the motorcycle. Kidney belts are usually worn tight around the waist. When attaching vibration motors to the kidney belt, due to the pressure of the kidney belt, the vibrators should be in good contact with the skin at all time. Additionally, vibration belts are successfully deployed in other domains like pedestrian navigation [HHBP08], aerospace navigation [VVJD05], bicycle navigation [SB13], or car navigation [BAH11]. Hence, we propose building a vibrotactile belt for motorcycle navigation. The next chapter describes the design and implementation of the kidney belt vibration system.

4 System Design

We measured the vibration while riding the motorcycle at different positions of the body. We found that the waist is the most suitable position for providing vibrotactile feedback. The decision was made due to the results that indicate that the least vibration occurred at the waist, that there were issues with the skin contact of the vibrators with HaptiMoto, and motorcyclists already wear a kidney belt, therefore they would not need additional clothing, like a vest.

4.1 Design Goals

There are two important design goals for the system. The system should not influence road traffic safety in a negative way, therefore it should be unobtrusive and a user should be always able to ignore it. On the other hand, the system should be easily perceivable and understandable, at all usual driving situations. Traditionally, there are five senses [JS07]: hearing, vision, smell, touch, and taste. Visual and auditory sense is highly demanded by the primary driving task and is perceived as a distraction while riding the motorcycle. When riding the motorcycle the environment is loud, with the engine and wind, therefore if one would use auditive feedback for navigation, the sound has to be loud to be perceivable, hence the sound is hard to ignore and very disturbing if the instructions cannot be followed[1]. Thus, secondary tasks should mainly involve other senses so that the driver can (1) focus on the driving task and (2) perceive the navigation cues. Vibrotactile stimulation is unobtrusive and can be ignored. There are reports that under high cognitive load vibrotactile feedback is not perceived anymore [LJB+11].

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[1] Might be due to local restrictions, like a construction site.

4.2 Evaluation of Existing Navigation Frameworks

In order to build a fully working prototype, we need to provide a rider with vibrotactile turn instructions. We conducted a market analysis of existing navigation frameworks and found two frameworks that allowed receiving turn instructions from outside the application. In particular, we found an open source framework called Osmand[2] and a closed source framework called Cruiser Navigator, that is produced by Talent[3]. After several test rides with both solutions, we decided to use Cruiser Navigator instead of Osmand. Both support importing of routes, which is important for us to be able to always ride exactly the same routes for the use of the system in a user study. But Osmand had problems with navigating on imported routes, sometimes a waypoint was not marked as visited and therefore Osmand would try to navigate back to that point, this would have led to issues during the study, as this appeared frequently. Another issue of Osmand was that there were turn instructions at curves that were only curves and not a turn. Unfortunately, that effect happened frequently as well. Cruiser Navigator provides a sophisticated turn instruction calculation that only creates a turn instruction if there is actually a turn, keep, or exit and not just a curve. Adding too many turn instructions will confuse the rider and lead to incorrect turns. Therefore, we decided to go with Cruiser Navigator.

4.3 Design Space for Vibrotactile Feedback on a Motorcycle

The following design space focuses on the specialization of vibrotactile feedback on a motorcycle. Most parts of the design space are identical to the design space of regular vibrotactile feedback. The motorcycle creates limitations to the design space, thus we are discussing these limitations. The limitations described in the following issues are based on informal preliminary tests. We tried different vibrotactile patterns and vibration motor positions in various situations to explore the design space of vibrotactile feedback on a motorcycle. The preliminary tests were conducted using different motorcycles and several riders during the design phase of the prototype. The design space is useful for designers of vibrotactile motorcycle navigation systems. The design space is centered around three main dimensions: position on the body, feedback patterns, and feedback context.

[2] http://osmand.net/

[3] http://talent.gr/

4.3.1 Position on the Body

As discussed in Chapter 3, the placement of the vibration motors on the body should be selected with regard to the vibration of the motorcycle, because the vibration of the motorcycle makes it hard to perceive vibrotactile feedback [BKAS11]. Therefore, we measured the vibration of the motorcycle and found the waist to be the most suitable position on the body. Besides the vibration of the motorcycle, there are two important points to consider when choosing a position for the vibration motors. (1) It should be possible to create constant pressure on the vibration motors, so they are pressed onto the skin and their vibration is transfered to the skin of the rider. (2) It should be possible to integrate the vibration motors into the existing environment.

Distribution of the Vibration Motors

Once an area is located to place the vibration motors, the exact distribution of the vibration motors needs to be considered. The typical approach is to scatter the vibration motors symmetrically on both sides of the body or if attached to only one limb, symmetrically on both sides of the limb [SEWP10]. Vibrotactile belts that are used for navigation purposes usually contain a linear array of vibration motors with vibration motors scattered equally distributed around the waist [HHBP08; SB13]. However, for automotive navigation tasks, less vibration motors are required. One vibration motor per side is sufficient for navigating a car in an urban environment [ABH12] and was found to be sufficient for inner city motorcycle navigation, in a controlled environment [PTGH14][4].

4.3.2 Feedback Patterns

Even when placing the vibration motors at a position that suffers a low amount of vibration, the motorcycle is still a high vibration environment. Therefore, vibrotactile patterns need to be easy to perceive and easy to differentiate. Related studies propose to use a single or a pair of vibration motors per direction [BAH11; PTGH14]. By using a single vibration motor one can modify the rhythm, duration, and intensity of the vibration, whereas using a combination of rhythm and intensity seem to provide the

[4] Haptimoto used a third vibration motor to signal u-turns, however, a u-turn can be substituted by multiple turns into one direction. Additionally, current navigation frameworks try to avoid u-turns, as they might lead to dangerous situations and might create stressful situations for the driver [LU11].

best results [AHB10]. Another approach is to use a linear array of vibration motors, which allows moving patterns in one dimension [CC00]. Other studies propose to use a matrix of vibration motors that allow patterns to move in two dimensions [EV04]. This leads to four variables a pattern can use: rhythm, duration, intensity, and movement.

Rhythm and Duration

Rhythm and duration are the baseline for every vibrotactile feedback pattern. Using them on the motorcycle requires special attention by the pattern designer. Motorcycles create a high amount of vibration and are sensitive for street surface irregularities, such as potholes. According to our preliminary tests, street irregularities create an impact during which vibrotactile feedback is not perceived. Two vibration pulses with a short break might be felt as one, for example, when hitting a street irregularity during the break. The same applies for a long vibration pulse, which might be felt as two vibration pulses, when hitting a street irregularity during the vibration. Even though both situations seem unlikely to occur, both situations occurred regularly during our preliminary tests. Motorcyclists prefer untrafficked rural roads that are usually not as well maintained as highly trafficked urban roads. Thus, street irregularities are very common. When designing patterns for motorcyclists it is important to design patterns that are robust against street irregularities. One possible design pattern is to create time-outs between vibrotactile pulses that are perceivably longer than a common street irregularity.

As discussed earlier, motorcycling induces high cognitive workload. The navigation task in an automotive environment is referred to as tertiary task [KS09]. Whereas the primary task is referred to maneuvering the vehicle, the secondary task contains functions that increase the safety of the driver. Therefore, it is important that the pattern can be perceived subconsciously. In our preliminary tests, we found that patterns which require to either count vibration pulses or contain only small duration differences[5] are increasingly harder to perceive with growing cognitive workload of the primary and secondary task. A possible design pattern would be to create patterns with a different pace, e.g., a very fast paced pattern that jumps from one vibration motor to the other with almost no breaks and short vibration pulses can be easily differentiated to a very slow pattern that uses one vibration motor for a long time before jumping to the next vibration motor.

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[5] Small duration differences are differences that are smaller than approximately 20%

Intensity

The general approach to intensity is that the vibration intensity should increase the closer the rider comes to a turn [AHB10]. The vibration intensity itself can be easily adjusted by adding more vibration motors. It is also possible to weaken the intensity of the vibration by applying less current to the vibration motor. According to our preliminary tests, a single shaftless vibration motor might not always be felt while riding the motorcycle. Related studies showed that intensity based patterns do not work as good as patterns based on rhythm and duration [AHB10].

Movement

Movement of a vibrotactile pattern adds another variable to differentiate patterns. When using a linear array of vibration motors, movement can be performed in one dimension. Using a matrix of vibration motors, patterns can move in two dimensions. Movement of the vibrotactile pattern is not as easily irritated by the vibrating environment created by a motorcycle. Our preliminary tests showed that the direction of the movement is hard to perceive using three vertical aligned vibration motors, i.e., it is hard to perceive whether a pattern moves from left to right or from right to left. It is also hard to differentiate the direction of a circular movement using six vibration motors aligned in a circular shape, i.e., differentiate between clockwise and counter-clockwise movement. On the other hand, it is comparably easy to differentiate the orientation of the movement, i.e., vertical movement compared to horizontal movement and circular movement.

4.3.3 Feedback Context

When providing vibrotactile feedback for navigation purposes the cognitive workload of the driver is unknown. As discussed earlier, riding the motorcycle induces a high amount of cognitive workload, which makes it hard or even dangerous to actively focus on navigation instructions. However, a typical motorcycle ride consists of high cognitive workload phases and medium to low cognitive workload phases, whereas the workload depends on the situation. Riding along an unknown unwieldy mountain pass is exhausting, whereas riding a straight road is rather relaxing. When receiving a turn instruction during a phase of high cognitive workload a driver should be able to perceive a turn instruction subconsciously to understand its meaning once the high workload phase ends. For example, when receiving a turn instruction in a challenging curve, the rider is able to understand the meaning of the instruction after the curve.

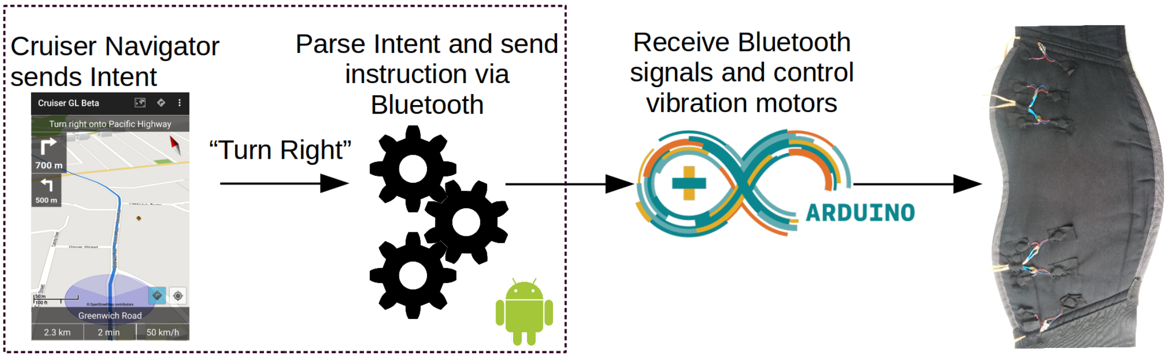

Figure 4.1: The system architecture of the prototype. Cruiser Navigator broadcasts intents to the Android platform. Our Android app receives and parses these intents to forward them via Bluetooth to an Arduino Pro mini. The Arduino Pro mini controls the vibration motors that are sewed to a kidney belt. The Android Robot is © by Google Inc. The Arduino Community logo is released under CC BY-NC-SA 3.0 https://creativecommons.org/licenses/by-nc-sa/3.0/.

4.4 Design of the Prototype

The following section describes the system architecture of the prototype and the evolution of the design. This chapter is closely related to the design space section. Abstract statements about issues and limitations of the motorcycle made above are shown throughout the actual development of the prototype. We start by describing the system architecture in general and follow with describing the different design stages.

As mentioned above we use the Cruiser Navigator navigation framework to calculate the routes and calculate the turn-by-turn instructions. Cruiser Navigator runs on Android and is broadcasting intents[6] whenever an instruction is played via Audio (e.g., "In 250m, turn left"). Broadcast intents can be received across the Android platform from any app that registered for the intent. We built an app that receives the intents sent by Cruiser Navigator, parses them, and sends turn instructions via Bluetooth to an Arduino Pro mini[7]. The Arduino is connected to an HC-06 Bluetooth module [8]

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[6] https://developer.android.com/reference/android/content/Intent.html

[7] https://www.arduino.cc/en/Main/ArduinoBoardProMini

[8] https://www.olimex.com/Products/Components/RF/BLUETOOTH-SERIAL-HC-06/resources/hc06.pdf

Figure 4.2: Simple vibration pattern prototype featuring four vibration motors

(at 9600 BAUD). An abstract overview of the system architecture can be found in Figure 4.1.

We use three classes of turn instructions: *far* (turn in 750m-1500m), *near* (turn in 250m), and turn *now* (turn in 70m). Theses classes are adopted from the classification of level crossings by Fukuda et al. [FISH99]. We worked closely with Talent to ensure the three classes are created consistently for every turn by Cruiser Navigator.

4.4.1 Pair Vibration Pattern Prototype

We built a first prototype (see Figure 4.2). We sewed four shaftless vibration motors[9] to a Büse Taslan[10]. Haptimoto [PTGH14] uses one vibrator on each side of the shoulder for communicating left and right turns. Therefore, we decided to add a vibrator on each side as well. However, we use two vibration motors on each side, both connected in parallel, this increases the intensity of the vibration. A single vibration motor was not always felt in our preliminary tests. The vibration motors are connected to the Arduino Pro Mini. We decided to create easily understandable patterns, similar to the "rhythm & duration based encoding" patterns presented by Asif et al. [AHB10]. Therefore, we increased the intensity of the vibration when coming closer to the turn. *Far* creates three vibration impulses that last 400ms with pauses of 400ms each. *Near* creates two vibration impulses that last 600ms with pauses of 600ms each. Turn *now*

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[9] https://www.pololu.com/product/1638

[10] http://katalog.buese.com/index.php?page=product&info=25558

Figure 4.3: Prototype with 3 vibrator pairs on each side.

creates one vibration impulse that lasts 1400ms. The closer the driver gets to a turn the intensity of the vibration should be increased [LBHB15; VVJD05]. Additionally, we provided a pattern to notify the user about roundabouts and which exit to take. Roundabout instructions don't need a distance encoding since the user drives towards it and only needs to know what exit to take. The system vibrates on both sides with pulses of 500ms duration. The number of pulses is equal to the exit to take, for example, two pulses mean that the rider has to take the second exit. This instruction is provided at the same distance categories as described above. Therefore, the rider has several opportunities to count the vibration pulses and to make sure to take the right exit.

We tested the first prototype for ten hours on typical motorcycle routes. However, under high cognitive load and perceiving vibration from the motorcycle, we felt that differing between the patterns is hard. When only perceiving low to medium workload it was easy to distinguish the different patterns. However, due to vibration of the street and the motorcycle, it was sometimes hard to perceive every vibration impulse clearly, so it happened that a three pulse vibration was perceived as a two pulse vibration. Thus, we decided to add more vibration motors to create add another parameter to the vibrotactile pattern: movement.

4.4.2 Array Vibration Prototype

We extended the prototype described in Section 4.4.1 to contain 3 individually controllable pairs of vibration motors per side (see Figure 4.3). We used the same categories

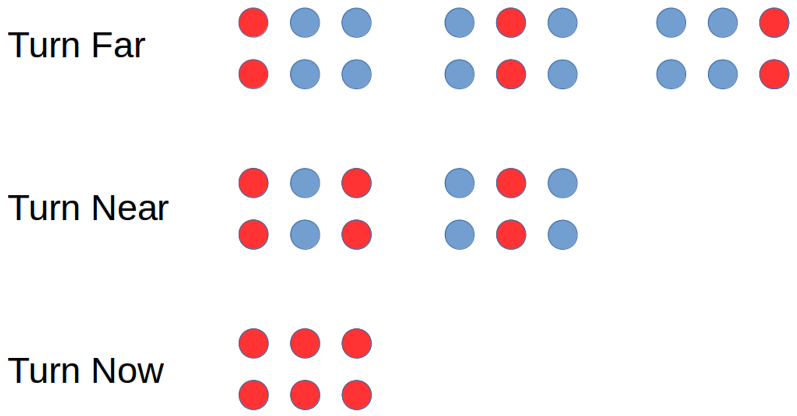

Figure 4.4: The vibration motor activation order of the array prototype's vibration patterns. A red dot shows a vibrating vibration motor, a blue dot shows an idle vibration motor.

as described above, but changed the vibration patterns for these categories. Since the patterns were hard to differentiate, we decided to add more vibration positions to further differentiate the patterns. *Far* creates a running pattern that triggers each vibration motor one after another. Each vibration impulse lasts 500ms. The pattern is repeated three times. *Near* creates a pulsing pattern, it starts by triggering the outer two vibration motors of either the left or right side and afterwards triggers the vibration motor in the middle of the corresponding side. Each vibration impulse lasts 300ms. The pattern is repeated six times. Turn *now* creates one vibration impulse for all three vibration motors of the corresponding side that lasts for 1.7s. The patterns are visualized in Figure 4.4. The roundabout instructions stayed the same, but trigger only one vibrator pair of each side instead of all 3 pairs.

We tested the array prototype on typical motorcycle roads for ten hours. It was easy to differentiate the turn *now* pattern from the other two patterns. However, the *near* and *far* pattern were not always distinguishable. The *far* pattern is different from the *near* pattern in its rhythm, duration, intensity, and direction. During our test rides, we figured that it is hard to feel the different directions of the vertical movement of the *near* and *far* pattern. Whereas most of the time it was easy to feel the difference, it was almost impossible to subconsciously understand the pattern during high cognitive load.

4.4.3 Matrix Vibration Prototype

We modified the array prototype to be able to control every vibration motor and not just a pair of vibration motors[11]. This allows creating even more distinct vibrotactile patterns. Before, we were only able to create horizontally moving patterns. The matrix structure of 3x2 vibration motors allows us to add vertical and circular movement.

The *far* pattern creates a circular movement that contains six steps, in every step one vibration motor is activated. The sequence of activation is clockwise. Every vibration pulse lasts 500ms, with 75ms between each pulse. The pattern is repeated two times. The *near* pattern contains seven steps: activate the upper three vibration motors of one side, activate two left vibration motors of one side, activate the lower three vibration motors of one side, activate two middle vibration motors of one side, activate the upper three vibration motors of one side, activate two right vibration motors of one side, activate the lower three vibration motors of one side. Every vibration pulse lasts 300ms, with 75ms between each pulse. The pattern is repeated two times. The turn *now* pattern stayed the same as before: all six vibration motors of one side vibrate for 1700ms. The patterns are visualized in Figure 4.5.

The patterns are designed to provide different rhythms and durations (300ms, 500ms, and 1700ms). The intensity of the vibration can be changed by activating a different number of vibration motors. By activating more motors, the intensity is increased. We increase the intensity from *far* with one vibration motor, to *near* with two to three vibration motors, to turn *now* with six vibration motors, as proposed in related studies [LBHB15; VVJD05]. Whereas the *far* pattern creates a circular motion, the *near* pattern creates a vertical motion and feels like a turn indicator, and the *now* pattern has no motion at all. Thus, every pattern uses a different orientation of motion, different rhythm, different intensity, and different duration. We tested the array prototype on typical motorcycle roads for ten hours. The patterns were almost always differentiable, even during high cognitive workload.

4.5 Summary

We applied well working approaches for vibrotactile car navigation to the motorcycle and found that due to the external factors these approaches do not work well on the motorcycle. In particular vibration patterns that rely on counting impulses as

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[11] In the previous prototypes, two vertical aligned vibration motors were connected in parallel.

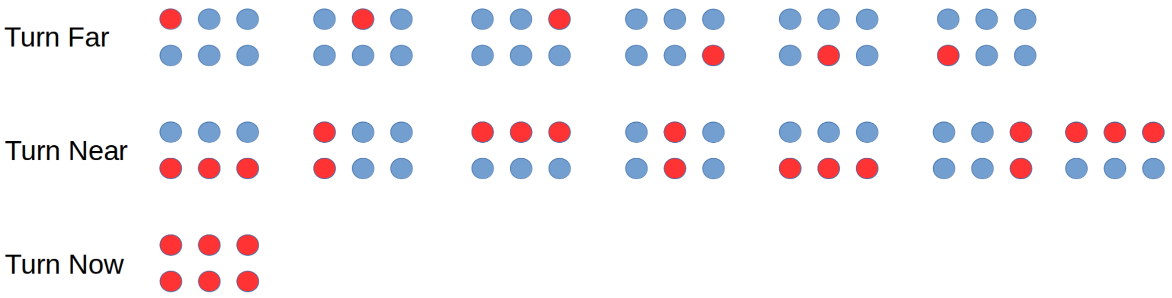

Figure 4.5: The vibration motor activation order of the matrix prototype's vibration patterns. A red dot shows a vibrating vibration motor, a blue dot shows an idle vibration motor.

proposed in related studies [BAH11; PTGH14; SB13], do not work well according to our preliminary tests in a real-world motorcycle driving scenario. There are two major reasons for this. (1) Counting needs attention. As described earlier, motorcycling is demanding and dangerous, therefore the driver needs to pay attention to the primary and secondary driving task. Therefore actively counting the vibration pulses is not always possible. (2) Motorcycles create a high amount of vibration. Due to the vibration of the motorcycle itself (see Chapter 3) and road irregularities, some of the impulses might not be perceivable in some situations or the number of impulses was not properly perceived. In contrast, the orientation of a moving vibration pattern was unconsciously perceivable and understandable. Differentiating between the patterns of the matrix prototype (see Section 4.4.3) was possible even during high cognitive load and suffering bad street conditions. The next chapter evaluates the matrix prototype in a real-world driving scenario.

5 Driving Study

In this study, we investigate if vibrotactile instructions are a feasible mean to navigate a motorcyclist in a real-world driving situation. In particular, we explore if using vibrotactile turn-by-turn navigational cues are easier to follow compared to visual instructions. For this purpose, we conducted a real-world driving study in which we collected the driver's performance (number of missed turns), as well as subjective feedback from the user.

We developed two different navigation systems that present navigational cues using different modalities to the participant while driving the motorcycle on a pre-defined route. Participants either used a vibrotactile navigation system (as proposed in Chapter 4) or a traditional visual navigation device mounted on the handlebar (i.e., a baseline). Every condition started with an in-depth introduction to the used system which is followed by a training phase to ensure a user feels comfortable using the system. We opted for a training session for both devices to ensure that participants are comfortable with both systems. The actual study route won't start before the participant feels comfortable using the system. After both feedback methods, there was an interview.

The study took approximately 150 minutes. Every route took about 45 minutes to ride. The routes were typical motorcycling routes covering a diverse set of road types (i.e., rural roads, motorways, inner city, etc.). There were about 60 minutes left for the introduction, preparing the participant's motorcycle, and interview.

5.1 Hypotheses

Motorcyclists suffer high workload, hence adding another distraction is not a good idea. We are researching possible improvements to the current motorcycle navigation approaches. Our approach is to use a different modality, instead of adding a display for navigation purpose. Therefore, we have to assure that using a vibration navigation system instead of a visual navigation system works equally well in a real-world driving scenario, as well as adding less distraction while driving.

$H1$: Navigating a motorcyclist along a predefined route using only vibrotactile feedback, in a real-world driving scenario, results in fewer routing errors compared to a visual navigation system.
$H2$: A motorcyclist that is navigated with vibrotactile navigation cues is less distracted compared to being navigated with visual navigation cues, in a real-world driving scenario.

5.2 Design

This study used a repeated measures design. There was one independent variable, the navigation system (with two levels: vibration or visual). The order of navigation modalities was counterbalanced, whereas the order of routes was always the same. The dependent variable was the errors made. We counted an error if the participant missed a turn or made an incorrect turn (e.g., turn too early).

5.3 Participants and Motorcycles

For this driving study, we hired experienced motorcyclists with at least two years of experience. Volunteers have to own a motorcycle and have to ride their own motorcycle. The volunteers were recruited using our university mailing list, social media, and word of mouth. Before taking part in the driving study, participants had to read and sign a consent form explaining the driving study and prototype as well as the risks involved. They received €15 as a compensation for their expenses due to participating in the study.

There were 16 participants, aged between 18 and 66 ($M = 34.5, \mathrm{SD} = 15.46$), with six students, three policemen (one of which already retired), and seven employees (mostly technical work, like construction and engineering). The participants had at least two years of motorcycling experience and a maximum of 37 years ($M = 11.88, \mathrm{SD} = 11.74$). They ride between $1000\mathrm{km}$ and $15000\mathrm{km}$ per year ($M = 5968.75, \mathrm{SD} = 3626.15$) using the motorcycle. Ten participants have used a navigation device on a motorcycle before, of which eight use only visual and two only uses audio instructions. No participant uses more than one modality for the purpose of motorcycle navigation. Every participant has used a navigation device in a car before, of which twelve use a combination of visual and audio and four use only visual.

Figure 5.1: The apparatus of the driving study: showing a user wearing the system (left) and the handlebar equipped with a smartphone and a GoPro (right).

Each participant used their own motorcycle during the study. Therefore, we collected data of a wide range of different motorcycle manufacturers: Suzuki, Triumph, BMW, Moto Guzzi, Kawasaki, Husqvarna, and Yamaha, as well as a wide range of different motorcycle classes: sports bike, street fighter, sport touring, dual-sport, supermoto, naked, and chopper. We tested common numbers of cylinders: one, two, three, and four, as well as a wide range of engine sizes, from $400\mathrm{ccm}$ to $1200\mathrm{ccm}$ ($M = 866.07, \mathrm{SD} = 263.41$).

5.4 Apparatus

The participants wore the kidney belt as described in Chapter 4 at all time during the study, but the system was only active during the vibration condition. The Arduino and Powerbank were placed in a hip pocket above the protection clothing, to make sure that in a case of an accident the damage due to wearing the system is as minimal as possible. The navigation software ran on an Android smartphone (Wiko Fever), that was mounted on the handlebar. The screen of the smartphone was covered during the vibration condition. The navigation software was the same in both times, therefore participants always received the same turn instructions at the same time with either modality. A GoPro Hero 3 White Edition [1] was mounted on the handlebar if there was sufficient space beside the smartphone and was directed at the participants head (see Figure 5.1).

The planned routes used streets, that are commonly used by motorcyclists. However, we tried to order the streets in an uncommon order and mixed uncommon turns between common turns to reduce any prediction effects (e.g., the driver suspects to take the next turn since this is the usual path motorcyclists take). Both routes are comparably long (route 1: 34 km, takes 38 minutes; route 2: 38 km, 40 minutes), see Figure 5.2. The end of route 1 was selected because a parking space is close by and the street has only low level of traffic to ensure a safe switch of the systems and a safe familiarization with the new system. The routes were not a perfect round trip since the start of route 1 was not the same as the end of route 2. Therefore, participants were not able to predict the end of route 2.

5.5 Procedure

The participants were instructed to follow the local laws and signs along the road. It was clearly stated that they would use a navigation prototype, which means that they should always judge the situation wisely and not follow an instruction if it may be unsafe. Participants were instructed to stop at a safe parking space whenever they felt unsure about the system or an instruction, or due to any other situation that might influence the road traffic safety or distract the participant from the driving task.

After introducing each participant to the study and preparing the participant's motorcycle (mounting smartphone and GoPro), the participant was introduced to the system that would be used in the first condition. For the vibration system, the different patterns were demonstrated and explained to the participant. For the visual system, the different aspects of the visual system were explained to the participant. Once the participant stated that they fully understood the system, they were asked to complete a test route. They were allowed to ride as many test routes as necessary to feel safe with the system.

Once the participant feels safe with the system, the actual route was loaded. The display of the smartphone was covered if in vibration condition. The vibration system was disabled if in visual condition. The participant was asked to navigate along the

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[1] https://de.gopro.com/support/hero3-white-support

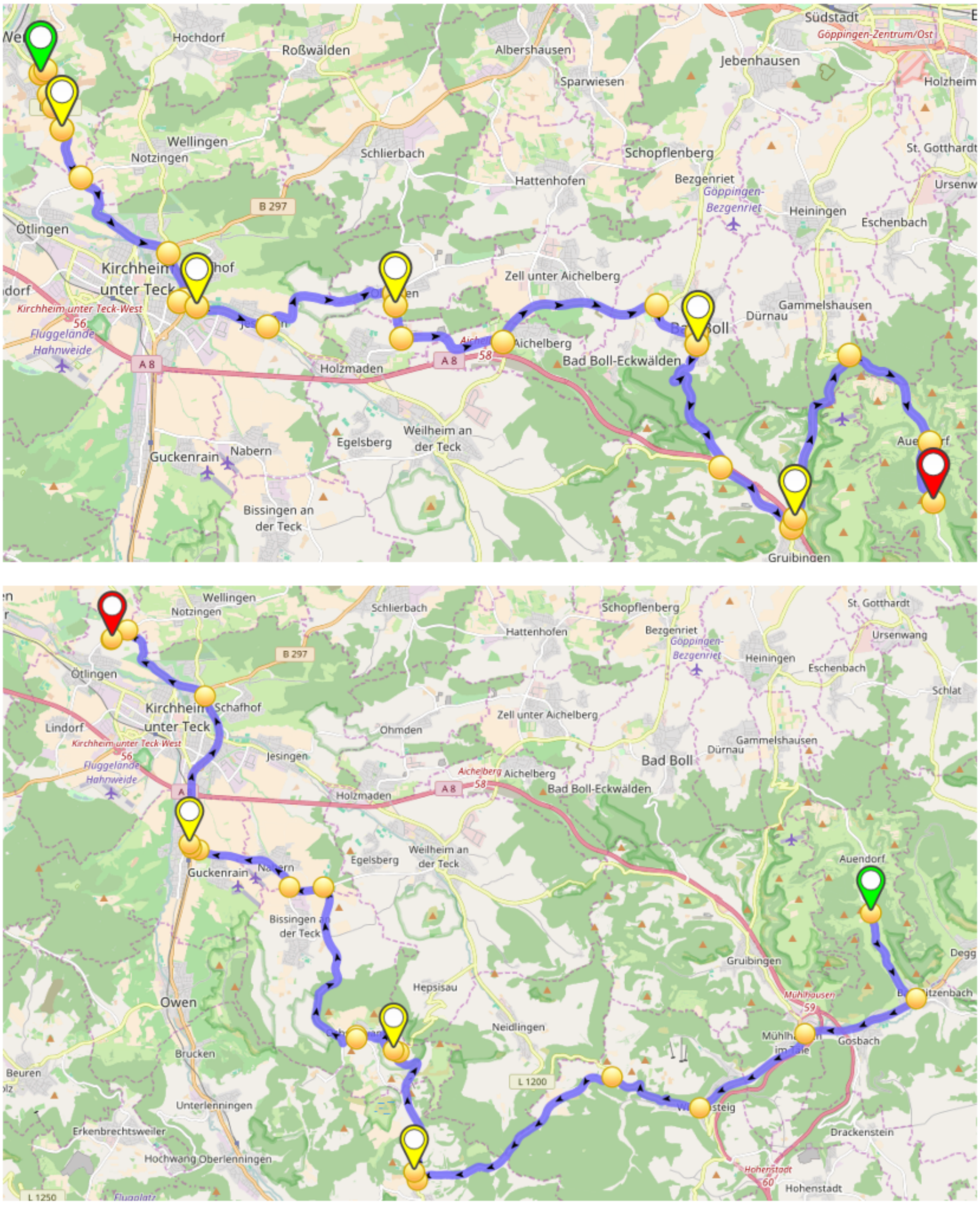

Figure 5.2: The routes used in the driving study. Top: route 1 of the driving study, bottom: route 2 of the driving study. Green marker indicates the start, red marker indicates the end, yellow marker indicates via points, yellow bubbles indicate a turn instruction. © OpenStreetMap contributors openstreetmap.org/copyright

given route. The experimenter followed the participant on his own motorcycle. Whenever a participant made a routing mistake, the experimenter signaled the participant to turn around and led the participant back on the correct route. The signaling of the participant was only done during low workload situations, with road traffic safety in mind. The first route ended at a parking space that allowed to switch the system. Before the second route starts the participant was again introduced to the new system and allowed performing as many test routes with the new system as were required to feel safe with the system.

5.6 Results

Overall the participants made eleven turn mistakes using the visual system ($M = 0.69, \mathrm{SD} = 1.08$) and one turn mistake using the vibration system ($M = .06, \mathrm{SD} = .25$). A Shapiro-Wilk test showed that both datasets are not normally distributed (visual: $p < 0.01$, vibration: $p < 0.01$). In 25 of the 32 error measurements the participant made zero errors, therefore 78% of measurements contains a duplicated value. Ten participants made no errors at all. The Wilcoxon Signed-Rank Test ranks each value to each other, but with duplicated values, no unique ranks can be build and therefore the p-value cannot be calculated exactly, Wilcoxon proposes to drop all 0's, but this would remove 78% of the data, therefore we used the Wilcoxon-Pratt Signed-Rank Test [Pra59]. A Wilcoxon-Pratt Signed-Rank Test revealed a significant difference between both samples ($Z = 2.23, p = 0.01$).

During the interview, 14 participants stated to prefer the vibration system, whereas two participants preferred the visual system. The main reasons for preferring the vibration system were the reduced distraction, increased concentration on the driving task and the road, and not needing to take the eyes of the street. Reasons for preferring the visual system were: knowing that a turn might be far away, therefore knowing that one might be able to focus on the driving task for the next kilometers and being able to see the course of the next curve.

15 participants stated that it was easy to differentiate the vibration patterns from each other while riding the motorcycle. One participant stated that it was not easy to differentiate the patterns. All participants stated that the visual system would be more distracting compared to the vibration system (see Figure 5.3). All participants would want to use the vibration system regularly when navigating on a motorcycle.

Figure 5.3: A participant using the visual navigation system. The left picture shows the participant looking on the street, the right picture shows the distraction that occurs when looking to the navigation system.

5.7 Discussion

The results of the study indicate that vibrotactile navigation on a motorcycle in the real-world is possible. This supports also the findings of Haptimoto [PTGH14]. Participants reported that they felt more distracted using the visual navigation system compared to the vibration navigation system. The same effect applies for navigating a car [EV04] and is in accordance with the multiple resource theory [Wic02]. These findings support the initial hypotheses $H2$.

Participants made fewer errors using the vibration system compared to the visual system. Thus, we can accept $H1$. This is contrary to the findings of other studies. Steltenpohl and Bouwer [SB13] compared a vibrotactile navigation system to a visual navigation system while riding a bicycle. Whereas Pielot and Boll [PB10] compared a vibrotactile navigation system to a visual navigation system for pedestrians. Both used a vibrotactile belt and reported more errors using the vibration navigation system. The reason for the differences could be the different context of navigation. The two studies were executed in an urban environment that might lead to ambiguous turn instructions. On the other hand, our study was executed on typical motorcycling roads, that try to avoid urban areas but prefer rural streets. On rural streets, turns are less frequent and less complex than in urban areas.

Ten participants were able to navigate without any errors using either system. However, six participants made at least one error with the visual system and one participant made an error with the vibration system. The usual turn error with the visual navigation system was a missed turn. Participants stated that they focused on the driving task and therefore forgot to check the display for turn instructions. All participants that own a visual motorcycle navigation device stated that this happens frequently in their everyday motorcycle navigation. However, no participant uses more than one modality for motorcycle navigation. Participants stated that one modality is enough distraction, especially since the second modality would be audio in most cases. The participants that use audio as the only modality stated that they don't like it because it is distracting and uncomfortable, but they use it from time to time if they need to navigate to an unknown location. In the car twelve participants use a multi-modal approach to navigation (combination of audio and visual), only four participants use only visual. This leads to the theory that drivers like multiple modalities for navigation if they are not interfering with the actual driving task. Multi-modal approaches are known to reduce the workload of an activity [Wic02]. This effect was also shown for car navigation [EV04]. So this might be true for motorcycle navigation, as well.

6 Conclusion and Future Work

In this thesis, we evaluated the suitability of vibrotactile feedback for motorcycle navigation in the real-world. We measured the distribution of vibration, induced by the motorcycle, with different motorcycles and riders, and could find that the best location for providing vibrotactile feedback is the waist. We designed a prototype that is integrated into a kidney belt, that creates vibrotactile feedback that is perceivable and understandable during high cognitive loads occurring while riding the motorcycle. We evaluated its usability in a real-world driving study, that compared the vibrotactile approach to a traditional visual approach. We found that the vibrotactile system outperforms the visual system in terms of errors made and induced distraction.

In order to measure vibration while riding the motorcycle, we created a measurement prototype that distributed ten accelerometers symmetrically at crucial spots of the human body (five on each side). We measured the vibration with five different participants, each using their own motorcycle. Most vibration occurred at the wrists, followed by the arms and calves. Least vibration occurred at the back of the shoulders and the waist. We decided to use the waist as position to apply the vibration to for three reasons: (1) there was slightly less vibration at the waist, (2) Hapitmoto [PTGH14] reported skin contact issues at the back of the shoulders, (3) and the integration to a kidney belt can be done easily without adding another garment since most motorcyclists wear a kidney belt while driving.

When designing the vibrotactile belt we paid special attention to integrating it unobtrusive, but perceivable into the motorcycling environment. We started with a pair of parallel wired vibration motors per side, using vibration patterns that were proposed by related work for the use in car navigation [AB10]. After several test rides, we figured that differentiating between the patterns is difficult in high workload situations. Therefore, we added two pairs of vibration motors per side, to allow the vibration patterns to perform a horizontal movement, for example, a swipe movement. This change made it easier to differentiate the different patterns, but it was not possible every time. Therefore, we created a 3x2 vibrator matrix on each side that allows the vibration patterns not only to move horizontally but also vertically.

We evaluated the system in a real-world driving situation, using a route that uses typical motorcycle roads. The route consisted of two parts, each approximately 35km long. One part was done with the vibrotactile navigation system, the other part was done with a traditional visual navigation system. We evaluated the errors that a participant made with each system, as well as the subjective feedback that was collected in an interview after riding the route. We found that using the vibrotactile navigation system statistically significant fewer errors were made and that all participants felt less distracted using the vibrotactile navigation system. Therefore, vibrotactile stimulus proved to be a viable mean for motorcycle navigation.

6.1 Future Work

6.1.1 Multi-Modal Approach

This thesis shows that vibrotactile feedback is capable of navigating motorcyclists along regular roads used by motorcyclists. Nevertheless, the amount of information that can be transferred with vibrotactile feedback is limited. In particular, there are two situations that might be complicated to solve exclusively with vibration. On the one hand, two (or more) very close crossings are complicated to communicate with vibration. The driver is moving, the GPS has limited accuracy, and the human perception, including the estimation of distances, is limited. If there are two turns that are close to each other, it is very difficult to differentiate between these two turns using only vibrotactile feedback, this issue was also reported by Haptimoto [PTGH14]. On the other hand, there might be two turns at the same crossing, one is slight, the other is sharp. The current implementation does not provide different patterns for the different sharpness of turns. Adding more patterns, in this case, seems not appropriate since they might be hard to differentiate and, thus, challenging for the motorcyclist. For both scenarios, adding a visual navigation aid, that can be checked if a rider feels unsure, can be beneficial. However, we have to make sure that we do not induce additional distraction. The combination of visual and vibration was also requested by several participants during the interview. It would be interesting to research the implications of a multi-modal approach for motorcycle navigation and to see if it further reduces distraction, or might even increase distraction, as the visual aid might be focused too frequently.

Figure 6.1: A different vibration motor placement, proposed by a participant.

6.1.2 Research Different Patterns

In Chapter 4, we provided an informal evaluation of different vibration patterns and prototypes. In chapter 5, we evaluated selected patterns in a user study. In general, we received positive feedback regarding the understandability and differentiability of the patterns. However, one participant stated to have some issues differentiating the patterns. Other participants stated to like the pattern but proposed a different placement of the vibration motors. Therefore, we want to create a user study evaluating different patterns and placements of the vibration motors. A proposal that was made by three participants, was to place four vibration motors in a circular shape. One proposed to additionally add another vibrator horizontally alignment (see Figure 6.1). Using this placement, we could save two vibration motors but still create a circular, horizontal, and vertical movement. Two participants proposed to distribute the vibration motors around the torso, instead of placing them on the back, similar to the approach by Boll et al. [BAH11]. Initially, we rejected this approach due to three reasons: (1) vibration motors on the back integrate very well into the currently existing motorcycle environment, for example, they could be also integrated into a back protector, (2) the placement of the vibration motors has to be adjusted individually according to the users waist size, and (3) most motorcycle suites align tightly in the back, which results in increased pressure on the vibration motors in the back. However, this approach allows creating even more differentiating vibration patterns. Therefore, it would be interesting to compare these different approaches.

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I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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