

Shock Me The Way: Directional Electrotactile Feedback under the Smartwatch as a Navigation Aid for Cyclists

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Fig. 1. Left: A user in front of a junction wearing our directional navigation system under the smartwatch. He receives electrotactile feedback that informs him to take the left road. Right: The user feels the electrotactile sensation on the upper left part of the watch (electrodes 1 & 8), which indicates taking the left road. The electrode grid is attached to the back of the smartwatch.

Cycling navigation is a complex and stressful task as the cyclist needs to focus simultaneously on the navigation, the road, and other road users. We propose directional electrotactile feedback at the wrist to reduce the auditory and visual load during navigation-aided cycling. We designed a custom electrotactile grid with 9 electrodes that is clipped under a smartwatch. In a preliminary study we identified suitable calibration settings and gained first insights about a suitable electrode layout. In a subsequent laboratory study we showed that a direction can be encoded with a mean error of 19.28° ($\sigma = 42.77^\circ$) by combining 2 adjacent electrodes. Additionally, by interpolating with 3 electrodes a direction can be conveyed with a similar mean error of 22.54° ($\sigma = 43.57^\circ$). We evaluated our concept of directional electrotactile feedback for cyclists in an outdoor study, in which 98.8% of all junctions were taken correctly by eight study participants. Only one participant deviated substantially from the optimal path, but was successfully navigated back to the original route by our system.

CCS Concepts: • **Human-centered computing** → **Ubiquitous and mobile devices**; *Interaction design*; Interaction devices.

Additional Key Words and Phrases: electrotactile feedback, navigation, bicycle, electrode grid, smartwatch, cycling

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1 Introduction

Riding a bicycle while getting navigation information can be troublesome. While cycling in urban areas, the visual and the auditory systems are heavily in use to see and hear other road users, notice moving obstacles, observe the road conditions, and follow traffic signs and lights. Cycling navigation is more complex and stressful than pedestrian navigation due to higher speeds and rapid switching between different road conditions. Sometimes a part of the route is only shared with other cyclists and sometimes pedestrians or cars share the same infrastructure. Furthermore, the driving surface (asphalted roads, gravel, dirt, pave stones, etc.) as well as the location (parks, main streets, shortcuts, etc.) can be very diverse in their appearance. In many cities the trend towards micro-mobility is increasing, as witnessed by the growing number of rental bikes and electric scooters. The larger variety of vehicles requires additional attention by cyclists and generates a need for low-distraction navigation techniques.

Typically, a cyclist receives navigation information on the auditory channel via headphones, on the visual channel via a smartphone attached to the handlebars, or on a smartwatch. However, using these, already occupied, channels for navigation requires temporarily taking the auditory or visual attention away from the environment and from other road users. Recent research shows that vibration feedback that is integrated in the handlebars of a bicycle is a viable alternative [4, 37, 40]. Other options are equipping the user with additional wearables for providing navigation cues [41, 46] or accessories like a navigation helmet [52]. However, these options require carrying additional accessories or a modified vehicle, which is problematic if the user spontaneously wants to have a short ride with a rented bike. A potential solution to these issues is the use of electrotactile feedback on smartwatches. Multi-electrode electrotactile feedback allows providing directional tactile navigation cues, whose strength can be adjusted over a wide range. Since the smartwatch is always with the user, there is no need for a special helmet with navigation features or special rental bikes with a vibration handle.

We propose directional electrotactile feedback under a smartwatch, as shown in Figure 1. During navigation, the direction to the next waypoint is displayed via a coarse-grained electrotactile grid on the wrist. If the target lies in front of the user, a signal is routed through the upper two electrodes (1 and 2 in Figure 1). The signal generates tactile sensations on the skin beneath the electrodes. If the user approaches a three-way junction and has to turn left, the signal will be redirected through electrodes 1 and 8. Thus, the tactile sensation shifts its position on the skin and indicates to the user to turn left. The system conveys the different directions by activating eight different electrode pairs. Navigation output will be played at waypoints, such as junctions, as well as between two waypoints. For example, if the current section of the route is s-shaped, directional feedback is provided to keep the user on the way.

Based on its ability to evoke a range of tactile sensations with specific signal parameters [9], electrotactile feedback can go beyond navigation and additionally represent route properties or give information about points of interest. The system may use strong feedback to warn the user when approaching a dangerous waypoint or an accident. Electrotactile feedback is well suited for being integrated into smartwatches, because it can be miniaturized and requires only little energy. It may even interoperate with sensing functionality on already existing electrodes, as discussed by Duentel et al. [9]. Several smartwatches, like the Samsung Galaxy Watch 4, have two electrodes to measure the electrocardiogram (ECG) or skin resistance. Unfortunately, these electrodes are currently not used for other applications, like electrotactile feedback.

In this work, we propose enhancing smartwatches to provide an electrode grid on the backside and use it for electrotactile feedback in navigation scenarios. Therefore, we created a custom electrode clip with nine electrodes that can be placed under a Samsung Galaxy Watch 4 and analyzed it in three studies. In a first preliminary lab study, we evaluated the grid regarding which electrode combinations should be used to present directional cues and how to do calibration. A second lab study shows that with a circular arrangement of the electrodes, our participants were able to recognize a direction with a mean error of 19.28° when two adjacent electrodes are activated (native). Further, we show by rapidly switching back and forth between two adjacent electrode pairs that share one electrode additional directions can be created. With these interpolated configurations, our participants were able to perceive a direction with an error of 22.54° . However, due to a mean standard deviation of the perceived angles of 42.77° for the native configurations and of 43.57° for the interpolated configurations, we decided to use only the native electrode pairs for our third study and to omit the interpolated configurations. The third study is informed by the findings from the first two studies. Its goal was to assess the navigation performance of the proposed approach by guiding eight participants on a bicycle through a park. The results show that electrotactile feedback under the smartwatch is a suitable navigation method for cycling that does not occupy the visual or auditory channels.

Our main contributions are:

- (1) We present a novel electrode grid design for the back of smartwatches that enables direction-based navigation for cyclists using electrotactile feedback without augmenting the bicycle, the helmet, or the user with special devices.
- (2) We answer the questions of which electrodes to use, how to calibrate, and how accurate the system is, in a preliminary and a laboratory study with our prototype.
- (3) We provide insights on the suitability of our electrode design during cycling in an outdoor navigation study.

2 Related Work

Visual, auditory, tactile, and haptic navigation cues have been investigated for guiding users. We propose the use of electrotactile feedback for tactile navigation cues. To put this into perspective, we first give an overview of electrotactile feedback. Then we present related work on tactile feedback on smartwatches and similar devices followed by navigation systems with a focus on tactile and haptic approaches that are primarily intended for pedestrian navigation. Finally, we present related work for (motor) cyclists, as not all systems that are suitable for pedestrians are also suitable for cyclists.

2.1 Electrotactile Feedback

Electrotactile stimulation is a valuable technique in HCI with a long history. In earlier research, electrotactile feedback is often associated with electrotactile displays, which consist of 2D electrode arrays that can produce fine-granular electrotactile output on the user's skin [48]. [Strong and Troxel](#) show that an electrotactile display can generate a texture effect that is similar to the sensation when moving the finger across a textured surface. Moreover, [Kaczmarek et al.](#) [18] show how electrotactile displays can be used for sensory substitution to render audio signals to the skin. [Kajimoto et al.](#) [20] present an approach to control the strength of the electrotactile stimulation by measuring the touch force to create a more realistic sensation.

Currently, electrotactile feedback gains a lot of attention in HCI. It is particularly suitable as a feedback technology in virtual reality experiences to bring physical properties to virtual objects [23, 51]. For a wearable mobile context, in *TactileWear* [45] electrotactile feedback is directly

compared to vibrotactile feedback around the wrist and the finger, respectively. The main result is that electrotactile feedback could be a viable alternative to vibrotactile feedback, as it enables slightly better pattern recognition and is judged as more comfortable. The stimulus is also felt as more localized compared to vibrotactile feedback. Due to the small form factor of electrotactile feedback, it can be integrated in small wearables, like ear clips, to provide notifications to the user [44]. Duentel et al. [9] explore the concept of *colorful electrotactile feedback*. The term is meant metaphorically to express that electrotactile feedback is not restricted to create tingling sensations but is also able to evoke several distinct sensations (vibrating, pulling, jabbing, tickling, itching [39], etc.). The different sensations are evoked by combining 39 different pairs of frequencies and pulse widths of a biphasic rectangular stimulation signal.

We believe that coarse-grained electrotactile feedback could be an excellent feedback technology on smartwatches in terms of enabling new possibilities for interaction. Contrary to the presented work, we focus more on the spatial aspect, like *TactileWear* [45], but concentrate on the location of the back of the smartwatch. Because the two-point discrimination distance on the wrist is significantly larger than on the finger, we created a coarse-grained electrotactile grid. Koo et al. [27] report a two-point discrimination distance for the region 5 cm above the wrist of 13.9 mm ($\sigma = 7.1$ mm) for female participants and of 18.4 mm ($\sigma = 5.7$ mm) for male participants. Before we present our coarse-grained electrotactile grid that is placed on the back of the smartwatch, we present related work on mobile navigation techniques and systems for pedestrians and cyclists.

2.2 Tactile Feedback on Smartwatch Form Factor Devices

Tactile navigation on a smartwatch requires the production of navigational cues. Current smartwatch designs offer only one vibration motor. Therefore, distinguishable rhythms or temporal patterns of vibration have to be designed, learned, and memorized. These patterns get longer the larger the number of different cues becomes, which makes them more difficult to learn and recognize for the user.

A way to overcome this is to add more actuators to such devices. Panëels et al. and Matscheko et al. investigated the use of multiple vibration motors [30, 33] on the dorsal side of the wrist. Panëels et al. arranged 6 actuators on a circle and found that static patterns perform worse compared to spatio-temporal patterns. Matscheko et al. found that placing multiple vibration motors all around the wrist increases the recognition rates of vibration patterns, compared to actuators only on the dorsal side. A comparison between 8 and 4 vibration motors around the wrist done by Hong et al. [15] shows that a setup of 4 vibration motors provides better results in terms of accuracy, time, and preference than a setup of 8 motors. Lee et al. [28] evaluated a watch-back tactile display with 9 actuators in a 3×3 grid layout (4 cm \times 4 cm, 15 mm distance between the centers of two actuators). The results show that 4 spatial temporal pattern performs better with poke type actuators (accuracy: 87.0 %) than vibration feedback (accuracy: 78.9 %), and repeating stimuli 3 times for a factor increases the accuracy further to 89.1 %. By reducing the set of used actuators the accuracy was further increased to 92.4 %. *EdgeVib* [29] and *Heterogenous Stroke* [25] use a 2×2 grid on the back of a smartwatch (4 cm \times 4 cm, distance between the center of actuators 3 cm). In their studies Kim et al. showed that their approach could achieve 93.8 % accuracy for 26 alphabets and 92.4 % for 10 digits. These results were achieved by assigning different unique characteristics to each vibration motor, in particular by using different vibration frequencies and differently modulated current wave forms, to create a rougher vibration compared to the standard vibration.

A major drawback of all of these vibration motor setups is that they are bulky, due to the actuator and its decoupling with dampening material from the case or the wristband of the smartwatch. Besides increasing the output channel by placing multiple vibration motors also other actuators have been tried. For example, Shim et al. propose the use of air flow combined with vibrotactile

feedback to present multimodal feedback on the back of a smartwatch [43]. *Jetto* [13] provides haptic feedback for smartwatches by applying lateral forces through air pressure. *Squeezeback* [38] provides compression feedback. The presented systems using air are hard to miniaturize and finally to integrate based on the need to have fans [43], a pump [38], or a container [13] to store compressed air. The *SkinDrag* [17] prototype is able to draw tactile pictures to the skin under a watch, which could also indicate directions, but the approach needs several mechanical components in the casing of the smartwatch. Brushing was evaluated in *BrushTouch* [47] for notifications on the wrist. The prototype needs brushes as well as motors to drive them. Another option is to integrate thermal feedback in a smartwatch wristband as done in *ThermalBracelet* [34]. The results show that vibration and thermal feedback do not differ in their detection time and thermal feedback was better localized by the participants. A drawback is that thermal feedback is power intensive.

2.3 Tactile and Haptic Navigation

It is widely recognized in the literature that navigation and way finding tasks can put a high cognitive load on users and distract from the environment. Reducing cognitive load and distractions are prime concerns of pedestrian and cycling navigation systems [14, 32, 36]. To achieve this, we motivate to use the tactile channel by applying electrotactile feedback. Thus, the visual and auditory channels can fully attend to the physical surroundings. In the following we present tactile and haptic approaches that have been successfully investigated for navigation tasks.

Navigational cues can be presented in 3D haptically by pulling the ears [26] and in a tactile way by vibration feedback around the head on three ellipses [24]. On the upper extremities, there are investigations on the wrist with two [22] or one [6] vibration wristbands, on the hand by pointing in that direction [50], via electrical muscle stimulation (EMS), or by holding a device that haptically encodes the directions by moving weights [1, 16]. On the torso, approaches with multiple vibration motors encode different directions on a vest [11] or a belt [10, 14, 53]. On the lower extremities, the walking direction can be manipulated via EMS on the legs [35] without producing cognitive load. Further, the walking direction can be indicated by vibration feedback on the ankle [42] or on the feet [12, 49].

2.4 Cycling Navigation

Cycling navigation is typically guided by visual systems that are mounted on the handlebars [31]. These systems need visual attention during cycling, letting the cyclist lose his or her focus on the surroundings. Auditory guidance has the advantage that the visual channel is not blocked, but is affected by noisy environments, like streets. If closed headphones are worn, the auditory channel may be blocked from important traffic noises. Therefore, as for pedestrian, tactile and haptic navigation systems are a topic of interest in cycling navigation.

A point of consideration is that systems that are designed for pedestrian navigation do not always easily transfer to cycling. For example, systems that create hand gestures via EMS [50] or that require additional handhelds [16] for getting navigation instructions are not suitable, while concepts like vibration belts also work for cyclists. *Vibrobelt* [46] provides directional tactile cues for navigation when cycling. The system indicates the direction and distance to the next waypoint (supporting eight different directions) and gives endpoint information. Navigational clothing in the form of a vest with three vibrational factors was presented in *HaptiMoto* [41] to create tactile cues for motorcyclists. One factor is placed on each shoulder and one on the back to navigate the driver on intersections.

Alternatively, the bike itself can be used to output navigation cues. *Smart Flashlight* [5] is a system with a projector mounted to the front of a bicycle. It projects the map with visual navigation cues onto the street like a flashlight. The main disadvantage is that bright daylight negatively

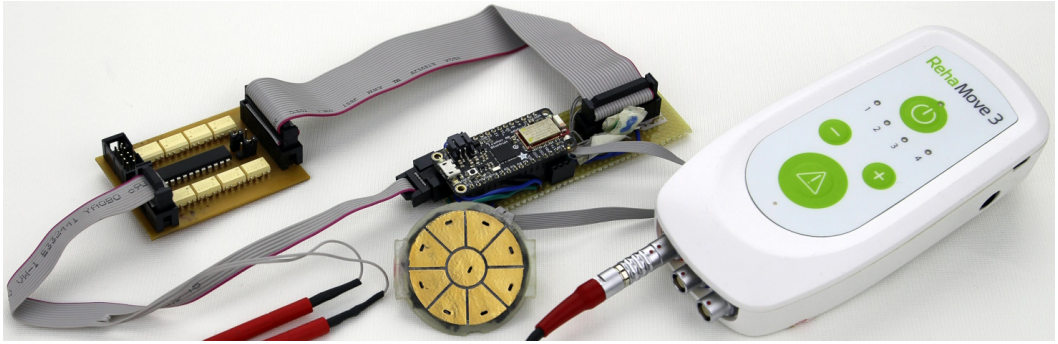


Fig. 2. The complete prototype. The gold plated electrode grid with 9 electrodes (middle) is connected over a PCB (top middle) with a switching board (top left). On the PCB an Adafruit Feather Bluefruit M0 with Bluetooth LE support is stacked. It controls the switching board and the Rehamove 3 device (right).

impacts the visibility of the projection. The augmentation of the handlebars is another approach to give directional feedback to the cyclist [37, 40] or electric scooter driver [4]. In *Tacticycle* [37, 40], the direction is encoded via the relative intensity of the vibration in the handlebars. A smartphone serves as an additional display that is mounted on the handlebars to support the navigation.

Apart from augmenting the bicycle, typical cycling accessories, like the helmet, can be augmented. *LEaD* [52] is a guidance system, that can be attached to a helmet. It is implemented as an LED stripe with six different light movement patterns to indicate turns and absolute direction cues. Further, *Matviienko et al.* [31] evaluated different unimodal navigation cues during cycling for children.

Our approach differs from the ones presented above in that we do not augment the bicycle, the user, or the helmet with additional hardware. The system is usable without a helmet and is thus suited for spontaneous navigation tasks on arbitrary bicycles, like rental bikes or e-scooters. It also does not require that the vehicle is equipped with a navigation interface or navigation hardware. Instead, directional tactile navigation cues are provided on the backside of a smartwatch.

3 Prototype

Our prototype consists of an electrode grid (diameter of 40 mm) with nine custom gold plated electrodes. They are placed in a circular layout on a 3D-printed case that can be clipped on the back of a Samsung Galaxy Watch 4 to ensure that the electrodes have direct contact to the skin. The diameter of the clip was chosen based on the smartwatch size. To follow the round design of the smartwatch and to fully utilize the existing area under the watch, the electrodes were arranged in a circular layout on the 3D-printed case.

As shown in *Figure 1* right, one electrode (electrode 9) has a circular shape and is located in the middle of the surface of the case. The other eight electrodes (electrodes 1 - 8) are pie-shaped circle sectors and surround the central electrode (electrode 9). The idea of dividing the area under the smartwatch into 8 parts was inspired by *Vibrobelt* [46], which also supports 8 different directions for cyclist navigation. The additional electrode in the middle of our prototype should offer the opportunity to not only encode the 8 different directions, but also to stimulate additional areas under the watch for further applications. The electrodes were applied to the surface of the 3D print by a combination of spraying copper lacquer and galvanization as described in *A Touch of Gold* [8]. Based on the manufacturing process also grids with 12 or 16 electrodes could be created with slightly increased complexity.

The electrodes are connected over a switching board to a Rehamove 3, a medically approved device for functional electrical stimulation (cf. Figure 2). The switching board is similar to the one presented in *Zap++* [7]. Electrotactile feedback is activated, if two adjacent electrodes are connected to the stimulation channel of the Rehamove 3 and an electrical signal is routed through them. The diameter of the central electrode has been chosen such that all electrodes have the same surface area. This ensures that the current densities of the gold plated electrodes are equal when the current flows through the skin from one electrode to the next electrode.

The switching board can activate any two adjacent electrodes on the ring (electrodes 1 - 8) or the central electrode (electrode 9) and one electrode on the ring. This results in eight stimulation areas on the ring and eight additional stimulation areas between the central and an outer electrode. Using the numbering scheme in Figure 1 right, the following 16 electrode activations are possible: (1, 2), (2, 3), (3, 4), (4, 5), (5, 6), (6, 7), (7, 8), (8, 1), (9, 1), (9, 2), (9, 3), (9, 4), (9, 5), (9, 6), (9, 7) and (9, 8). The switching board technically also allows combinations of more than two electrodes, such as ((1,3), 2), but because these combinations result in different current densities, they are not recommended and have not been explored yet. By adding further connections to the 8 outer electrodes of the switching board (as for the center electrode) arbitrary electrode combination could be created, such as ((1, 2, 3, 4), (5, 6, 7, 8)).

4 Preliminary Study

Before we analyzed the accuracy of specific fine-grained perceived angles, we tested our prototype in a preliminary laboratory study to get first insights on the suitability of using an electrode grid under the smartwatch. We evaluate the usage of the central electrode in two coarse-grained directional patterns. The design allows us to create dynamically moving electrotactile feedback in two directions: clockwise and counterclockwise. This coarse-grained feedback can be created by only using the outer electrodes (e.g. creating the sensation of movement in a big circle) or with a combination of an outer and the inner electrode (e.g. creating the sensation of movement in a small circle). In this first study, we test if such a coarse-grained pattern can be recognized and what the user experience of such directional electrotactile feedback under a smartwatch is like. The study complied with our ethical review process.

4.1 Participants

We recruited 15 participants (7 female, 8 male) with a mean age of 27.5 years ($\sigma = 7.35$ years). Thirteen of them were right-handed and two left-handed. More than half of the participants (8 participants) regularly wear a watch or a smartwatch. Seven of the regular (smart)watch users were right-handed and wear it usually on the the left wrist. One regular user was left-handed and wears it on the right wrist. Further, we asked the regular users for what reasons they wear their watch. Multiple mentions were possible. 7 of them used the watch for time management, 7 for fitness measurements, 6 for getting notifications, 3 for health tracking, 1 for listening to music, and 1 for navigation purposes. Regarding the feedback modality, only 2 participants had experience with electrotactile feedback from prior studies.

4.2 Procedure

At first, the participants filled out a consent form and a demographic questionnaire. The consent form informed the participants about the study and, especially, about their right to end the study at any time without giving any reason. Also, the form presented a list of health-related points to them under which they were not allowed to participate. The participants could indicate whether any of the points applied to them, without explicitly naming them. In this case the participant would have been excluded from the experiment. However, none of the participants had to be excluded from the

study. After their consent, the electrode grid and skin were sanitized and the participant put on the smartwatch prototype on the wrist on which they preferred to wear a wristwatch. For each participant, the current amplitude of the biphasic signal for each of the 16 possible combinations consisting of two neighboring electrodes was calibrated. The current was increased in steps of 1 mA until the stimulus was strong but still comfortable and not hurting. We used a biphasic signal with a frequency of 85 Hz and a pulse width of 50 μ s, which creates a gentle prickling sensation [9].

After the calibration, we played a clockwise electro-tactile pattern with our prototype. The pattern consisted of the following sequence of electrode activations, each of which had a duration of 1000 ms: (1, 2), (2, 3), ..., and (8, 1). The pattern was played once. We then asked the participants whether they could sense the feedback well on a 5-point Likert scale (ranging from 1 “strongly disagree” to 5 “strongly agree”). Further, we asked them how they would describe the direction in which the feedback was experienced. The answer could be given as a single choice from three options: (1) clockwise, (2) counterclockwise, and (3) free-form description entered by the participant.

We then presented a second pattern. This time the inner electrode (9) was used as follows: (9, 1), (9, 2), ..., and (9, 8). Like the first pattern this is a clockwise pattern and again each activation was maintained for 1000 ms. Like for the first pattern, the participants were asked to describe the direction. Additionally, we asked them for which of the two patterns it was easier to identify the direction. A closing questionnaire followed and finally each participant received a bar of chocolate as a sign of gratitude for participating. The study took about 20 minutes per participant.

4.3 Results and Discussion

The calibrated mean amplitude for all participants was 6.53 mA ($\sigma = 4.18$ mA). A Friedman test shows significant differences ($p < 0.01$) for the calibrated amplitudes between different participants. Regarding the chosen current amplitudes based on the different electrode pairs a Friedman test did not show significant differences. Based on these results, for electro-tactile feedback with our electrode design under the smartwatch, it is sufficient to only calibrate a single amplitude for each participant for all electrode-pair combinations. The equal areas of the electrodes facilitate a single calibration. Moreover, the spatial distance between the electrodes is small, so that the skin sensitivity should be relatively uniform as long as the impedance does not change due to, for example, lifting of the electrodes. However, this could be prevented by a continuous impedance measurement under the skin [19] which is currently not implemented in our prototype. Overall, this speeds up the calibration process considerably and reduces the effort for users.

For the first electro-tactile pattern, which was played on the outer electrodes in clockwise direction, all 15 participants indeed experienced it as a clockwise movement. For the second pattern, which was played as a combination of outer electrodes and the central electrode in clockwise direction, only 5 of the participants recognized the pattern as a clockwise movement. Five participants misidentified it as counterclockwise and the remaining 5 participants provided other descriptions, which did not fit to the clockwise playback. One participant only felt the stimuli “*in the middle*”, one described it feels “*like a ribbon*”, one as “*interrupted*”, one as “*back and forth*” and one answered having only felt “*two signals*”. Twelve participants stated that they could identify the first pattern more easily. In contrast, 3 participants said that it was easier to identify the direction of the second pattern. For both patterns the majority of the participants stated that they felt the feedback clearly (compare Figure 3 statement 1 & 2). At the end of the study, the participants filled out a questionnaire with 5-point Likert scale items regarding whether they found the electro-tactile output tiring, if they got used to it after some time, and if they could imagine to use electro-tactile output on a smartwatch regularly. As shown in Figure 3, the majority of the users did not find the electro-tactile feedback tiring or exhausting and got used to it after a few sensations. The last statement about a regular use of electro-tactile feedback was judged slightly negatively by the participants.

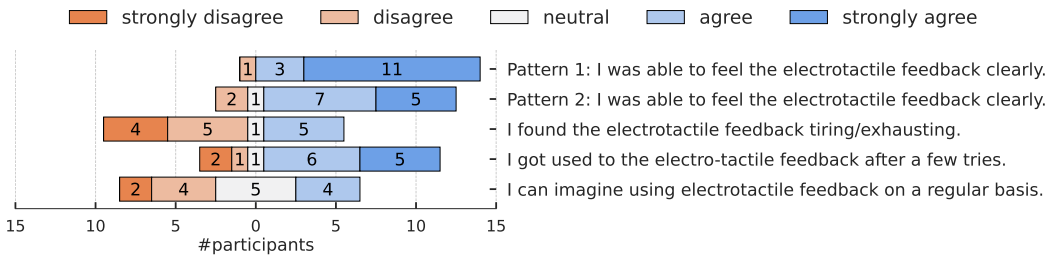


Fig. 3. Qualitative feedback of the participants.

The results of this preliminary study suggest that the second pattern, which uses the central electrode, should not be used as a direction indicator. The majority of the participants was not able to reliably recognize the inner clockwise pattern. The low recognition rate of the inner pattern might be related to the small distance of the stimulation points and hence the small area between the electrodes relative to the receptive fields on the wrist. The distance for the outer electrodes is about 10 mm. The distance for combinations of the inner and an outer electrode is about 5 mm. [Koo et al. \[27\]](#) report a two-point discrimination threshold for the region 5 cm above the wrist of 13.9 mm ($\sigma = 7.1$ mm) for female participants and of 18.4 mm ($\sigma = 5.7$ mm) for male participants. This might be a reason for the different recognition accuracies of both patterns.

5 Study 1 – Accuracy of Perceived Angle

As our aim was to analyze the perceived locations for navigation purposes, we did not use combinations involving the center electrode (9) based on the results of the preliminary study. Instead, we focused our analysis on the different outer electrode combinations (1, 2), ..., (8, 1). This leads to 8 native electrode combinations that represent 8 directions (see [Figure 1](#)). Further, we analyzed whether it is possible to create interpolated directions, that lie in the middle of two native directions by quickly switching between two adjacent combinations sharing one electrode. To create this sensation, we alternately activated two combinations at a stimulation frequency of 100 Hz: at first, we activated one combination (e.g., electrodes 1 and 2) for 10 ms, then switched to a combination that shares one electrode with the first combination (e.g. electrodes 2 and 3) for 10 ms, and then switched back to the first combination (e.g., electrodes 1 and 2). This was repeated for the complete stimulus duration of 1000 ms until the trial was completed.

In a pre-experiment with 3 participants we determined 10 ms as a suitable value. At 10 ms, the stimulation was perceived as a single event at a single location and not as two separate events. In this pre-experiment, we analyzed different switching times, beginning with 100 ms and decreasing to 50 ms, 20 ms, and finally to 10 ms. The reported illusion only occurred at a switching time of 10 ms. The resulting stimulation corresponds to a simultaneous stimulation of both areas at a frequency of 50 Hz. Because of the switching, the biphasic pulses are not presented at exactly the same time, but in such a short distance that the single-location perception occurs. Using this approach, 8 additional interpolated directions can be created, each in between of the native directions.

This leads us to 80 trials that each participant performed during this study: 8 native directions \times 5 repetitions + 8 interpolated directions \times 5 repetitions. We counterbalanced the order of the 16 electrode combinations with a balanced Latin square. To enter the perceived angle, the participants had to move a handle on the smartwatch touchscreen to the angle where they felt the sensation (see [Figure 4](#)). The starting angle for the handle was set randomly for each trial. The study complied with our ethical review process.



Fig. 4. A participant is rotating the handle on the smartwatch touchscreen with two fingers to match the handle's orientation with the presented electrotactile feedback.

5.1 Participants

For this study, we recruited 10 participants (2 female, 8 male, mean age = 28.7 years, $\sigma = 8.8$ years). None of them had participated in our preliminary study. Of the participants, 8 were right handed, 1 was left handed, and one participant was ambidextrous. Half of them (5 participants) used to wear a watch or a smartwatch. All of these 5 participants wear the smartwatch on the left wrist. We also asked them for what reasons they wear their watch (multiple answers were possible). From the 5 regular watch or smartwatch users, 4 used the watch for time management, 3 for fitness measurement, 2 for notifications, 2 for health tracking, 1 participant for music, and also 1 participant for navigation purposes. Regarding our feedback modality, 5 participants had experiences with electrical stimulation from prior studies.

5.2 Procedure

First, the participants filled out a consent form and a demographic questionnaire. The consent form informed the participants about the study and especially about their right to end the study at any time without giving any reason. Also the form presented a list of health-related points to them under which they were not allowed to participate. The participants could indicate whether any of the points applied to them without explicitly naming them. In this case the participant would have been excluded from the experiment. However, none of the participants had to be excluded from the study. The participants were instructed to wear the smartwatch with the electrotactile grid on the wrist on which they would wear a watch. For each participant based on the results of the preliminary study, one single current amplitude was calibrated that was used for all electrode pairs. We tested the current for its comfort over all outer electrode pairs to reduce the needed calibration time. Before the trials started, the participants performed a training phase in which they experienced each of the 16 different stimulations once.

Then the participants started with the five blocks of the experiment. An app on the smartwatch guided the participants through the study. They could start each stimulation with a button on the smartwatch screen. Then they got another view in which they could rotate a handle to indicate the direction of the experienced tactile feedback. With a further double tap on the middle they could start the next electrotactile signal. The participants had the opportunity to pause between two blocks. After finishing the 5 blocks, the systems was powered off, the participant put down the watch, and a closing questionnaire was completed. Finally, each participant received a bar of chocolate for participation. The study took about 30 minutes per participant.

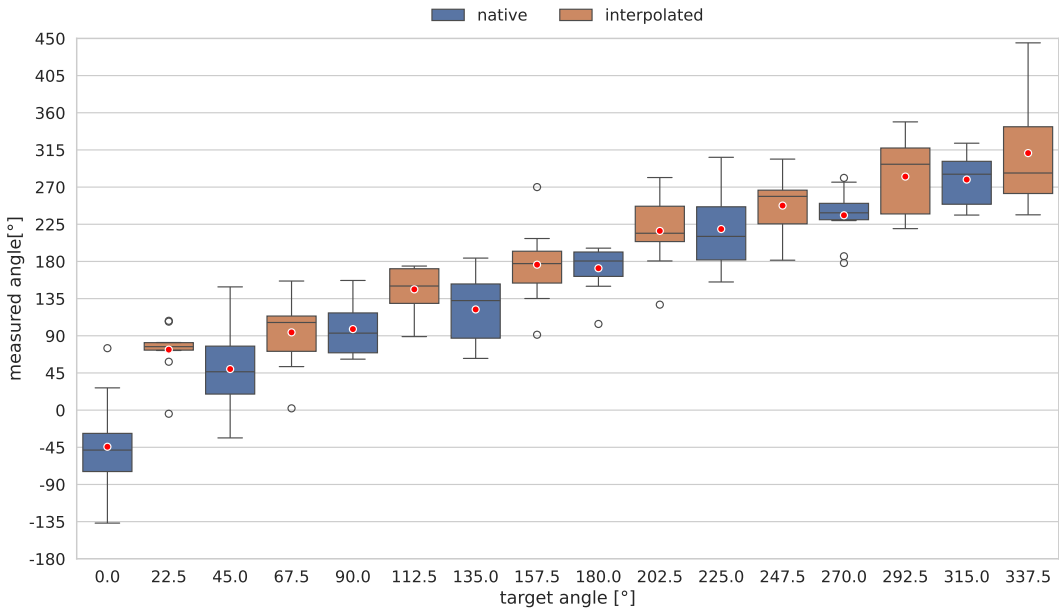


Fig. 5. The boxplots show the recognized angles of the played electro-tactile feedback for the different target angles. The red dots show the mean values.

5.3 Results and Discussion

The mean calibrated amplitude across all participants was 7.7 mA ($\sigma = 2.58$ mA). This is slightly higher than the calibration values in the preliminary study, which were at 6.53 mA ($\sigma = 4.18$ mA).

Figure 5 and Table 1 summarize the results of this study. The figure shows the distribution of the differences between the target angle and the angles selected by the participants. The table presents the mean angular distance and its standard deviation for the different target angles. The target angles either belong to the native group or the interpolated group. A native target angle is created by a single pair of adjacent electrodes, e.g. (1, 2) for target angle of 0° (compare Figure 1). An interpolated target angle is created by quickly switching between two pairs as described above, e.g. (1, 2) and (2, 3) for the target angle of 22.5° with a frequency of 100 Hz. The table also shows a distance value in mm that is derived from the absolute mean angular difference. It is calculated with the cosine theorem based on an isosceles triangle. The distance is the third leg of the triangle, for which 2 equal legs are the radii (20 mm) of our circular grid. The angle between these two legs is the absolute of the presented mean angular difference.

The results show that the mean absolute differences for both groups are very similar (native: 19.28° vs. interpolated: 22.54°) and also that their standard deviations are very similar (native: 42.77° vs. interpolated: 43.57°). A Wilcoxon signed rank test does not show a significant difference between the absolute mean angular differences of the native and the interpolated groups ($Z = 14.0$, $p = 0.64$).

The mean angular differences and their standard deviations vary a lot for the different electrode combinations. This is also depicted in Figure 5. Given the current feedback design and these results, it becomes obvious that 16 different directions cannot be reliably distinguished. Thus we analyzed if it is possible to distinguish 8 different directions. We performed Wilcoxon signed-rank tests with Bonferroni correction for the 8 neighboring native directions, i.e. for the pairs of target angles: 0°

Table 1. Quantitative results for the direction estimations on the smartwatch.

	Activated Electrodes	Target Angle [°]	Mean Angular Difference [°]	Standard Deviation [°]	Distance on Outer Circle [mm]
Native	(1, 2)	0.0	-44.35	61.98	15.10
	(2, 3)	45.0	4.72	61.21	1.65
	(3, 4)	90.0	8.10	33.59	2.83
	(4, 5)	135.0	-13.11	42.39	4.57
	(5, 6)	180.0	-8.22	28.25	2.87
	(6, 7)	225.0	-5.77	48.82	2.01
	(7, 8)	270.0	-34.09	33.10	11.72
	(8, 1)	315.0	-35.87	32.83	12.32
Absolute Mean			19.28	42.77	6.63
Interpolated	(1, 2), (2, 3)	22.5	50.73	31.23	17.14
	(2, 3), (3, 4)	67.5	26.64	44.11	9.22
	(3, 4), (4, 5)	112.5	33.69	28.79	11.59
	(4, 5), (5, 6)	157.5	18.58	47.16	6.46
	(5, 6), (6, 7)	202.5	14.45	43.63	5.03
	(6, 7), (7, 8)	247.5	0.13	34.82	0.05
	(7, 8), (8, 1)	292.5	-9.75	46.34	3.40
	(8, 1), (1, 2)	337.5	-26.33	72.50	9.11
Absolute Mean			22.54	43.57	7.75

& 45°, 45° & 90°, ..., 315° & 0°. Of these, only 0° & 45° differ significantly ($p < 0.05$). Wilcoxon signed-rank tests for the 8 interpolated target angles (22.5°, 67.5°, ..., 337.5°) show that only 67.5° & 112.5° and 202.5° & 247.5° are significantly different ($p < 0.05$). This means that our prototype cannot create 8 distinguishable directions with our current stimulation protocol. Therefore, we analyzed whether it is possible to display 4 different directions. Wilcoxon signed-rank tests with Bonferroni correction for pairs 0° & 90°, 90° & 180°, 180° & 270°, and 270° & 0° show that all neighboring distributions differ significantly ($p < 0.05$). The same ($p < 0.05$) holds for the target angle pairs 45° & 135°, 135° & 225°, 225° & 315°, and 315° & 45°. This also holds ($p < 0.05$) for the interpolated target angles, for both groups (22.5°, 112.5°, 202.5°, 292.5°) or (67.5°, 157.5°, 247.5°, 337.5°).

Across the 10 participants we observed very individual, but consistent distributions of the angular distance to the target angle. Also the mean angle difference for some target directions is quite small, e.g. a deviation of 4.72° for a target angle of 45°. For other target angles, like 0°, it is relatively high at 44.35°. This seems like a systematic effect, that could be based on the fact that three different nerve strands run through the wrist area that is covered by the grid (lateral cutaneous, medial cutaneous, and posterior cutaneous). Depending on which nerve strand meets which region of the grid, the accuracy of the perceived direction may change distinctly between two adjacent electrodes. This effect could possibly be compensated for by an individual calibration of different electrode combinations, as done in the preliminary study, or by a calibration of the system based on where a user perceives the stimulation.

Figure 6 shows the answers of our participants to five 5-point Likert scale statements regarding the experienced electro-tactile feedback. Half of the 10 participants found the electro-tactile feedback on the wrist pleasant. 4 stayed neutral and one (P1) disagreed strongly with the statement. This

participant is also the only one who felt the electrotactile feedback as tiring/exhausting and who strongly disagreed to the next two statements. The majority of the participants (7 of 10) found the electrotactile feedback not tiring or exhausting and also stated to get used to it after some tries. Only 4 participants could imagine to use electrotactile feedback on a regular basis. Only 3 participants found it easy to recognize the direction of the electrotactile signal. The majority (6 of 10) did not find it easy. Contrary to these results, 7 of the 10 participants can imagine to use such a system in everyday life. The 7 participants mentioned different daily use cases for the system (multiple mentions were possible): navigation (4 mentions), presentation of notifications (4 mentions), and presentation of processes (1 mention). We got also some additional comments from our participants: “Interesting and novel experiences, I can well imagine that this could be used in practice.” - P4. Participant P1 reported a poor user experience and commented: “Difficult placement of the prototype at the wrist ankle. Watch is not worn at the usual position.” This could have led to a bad connection of the electrodes to the skin and also could have resulted in a suboptimal experience of the electrotactile feedback.

The presented results show that the localization of the electrotactile feedback on the one hand is sometimes very precise and on the other hand is very diffuse for different electrode combinations. In terms of absolute distance, the localization results are sufficient for coarse-grained direction estimation. For the native and for the interpolated target angles the mean absolute distance is less than 8 mm. However, for a directional navigation system the high standard deviations for most of the target angles is concerning. The standard deviation of over 40° is higher than the angle between two targets, which is 22.5° . So for an electrotactile navigation system on the wrist a fine directional granularity is not beneficial, if the directions cannot be reliably distinguished. Therefore, we continue in the following with only 8 different native target angles. The results might be improvable with a different encoding of the directions, as done by Panëels et al. [33] who evaluated spatial temporal patterns to increase accuracy. This would on the other hand introduce a necessary learning phase for the patterns. The advantage of the encoding we propose in this work is that the directions are encoded directly and not via patterns, which could introduce additional cognitive load and the need to recognize, memorize, and recall the patterns.

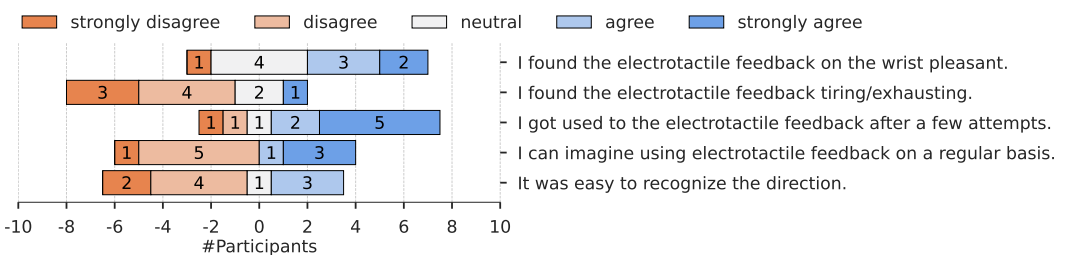


Fig. 6. Qualitative feedback of the participants.

6 Outdoor Navigation Study

In order to evaluate our prototype in an outdoor scenario, we implemented an electrotactile navigation system for cycling. As shown in Figure 7 left, we used a standard step-through 28" bicycle with 7 gears. The bike was not augmented or modified for this study in any way. The prototype offers 8 different locations to create the directional stimuli. Therefore, we divided the angles into 45° intervals. Table 2 shows the mapping of the target angles to electrode combinations.

For example, if the target is in front of the participant (the target angle is in the interval 337.5° to 22.49°), then electrodes 1 and 2 are activated for 500 ms to indicate this direction.

The target angle was calculated every second based on the actual and last GPS position of the user and the GPS position of the next waypoint. To calculate the angle that is presented by the electrotactile grid, we used the bearing relative to the north pole. “A bearing is the direction [the user] is facing, measured clockwise as an angle from true north on a compass.”¹ First, the bearing between the current GPS position and the next waypoint was calculated. This returned the direction in which the user has to move to reach the next waypoint. Afterwards, the bearing between the last and current GPS position was computed, resulting in the driving direction of the user. To match the calculated angles (bearings) to the layout of the prototype we subtracted the bearing of the direction of the user from the bearing between the current GPS position and the next waypoint.

In that way the system informs the participants every 5 s about the target direction to the next waypoint. The time interval was chosen to prevent fatigue or habituation effects of the participants, which can lead to a reduced perceptual accuracy [2, 54].

Table 2. Mapping of navigation direction, defined by target angle range, to active electrodes (cf. Figure 1).

Target Angle [°]	Navigation Direction	Active Electrodes
337.5 – 22.49	straight	(1, 2)
22.5 – 67.49	straight right	(2, 3)
67.5 – 112.49	right	(3, 4)
112.5 – 157.49	backward right	(4, 5)
157.5 – 202.49	backward	(5, 6)
202.5 – 247.49	backward left	(6, 7)
247.5 – 292.49	left	(7, 8)
292.5 – 337.49	straight left	(8, 1)

To enable a mobile waypoint-based navigation, we implemented an Android application using the Mapbox SDK², which runs on an Android smartphone. This application sends the navigation cues to the prototype via a Bluetooth low-energy connection. Further, the application records the coordinates and speed of the participants during the study. For the navigation task, the smartwatch was powered off and was only worn to fix the electrode grid onto the wrist.

To evaluate the functionality of the system while cycling, we defined a specific outdoor route. The goal was to quantify the reliability and accuracy of bicycle navigation using our wearable electrotactile feedback system. The study complied with our ethical review process.

6.1 Route Design

Figure 8 shows the defined route that leads the participants through a park with different ground properties (gravel, asphalt, dirt). The park is well frequented by cyclists and pedestrians. For cyclists the park is a part of their journey from the outer town areas to the inner city. One of the 13 main velo routes of the city is routed through this park. The route has 21 junctions of different types with different angles. The decision for the park has also been made for safety reasons for our participants, as only cyclists and pedestrians are on the park trails, but no cars. The individual blue markers in Figure 8 show the manually set waypoints for navigation. The placements were chosen so that a waypoint is always set shortly after a junction. This means that the navigation signal

¹<https://docs.mapbox.com/help/glossary/bearing/>

²<https://www.mapbox.com>



Fig. 7. Left: The bicycle used in the study. Right: A participant on the bicycle wearing the electrode grid under the smartwatch on the left wrist. The Rehamove 3 and other components are located in the waist bag.

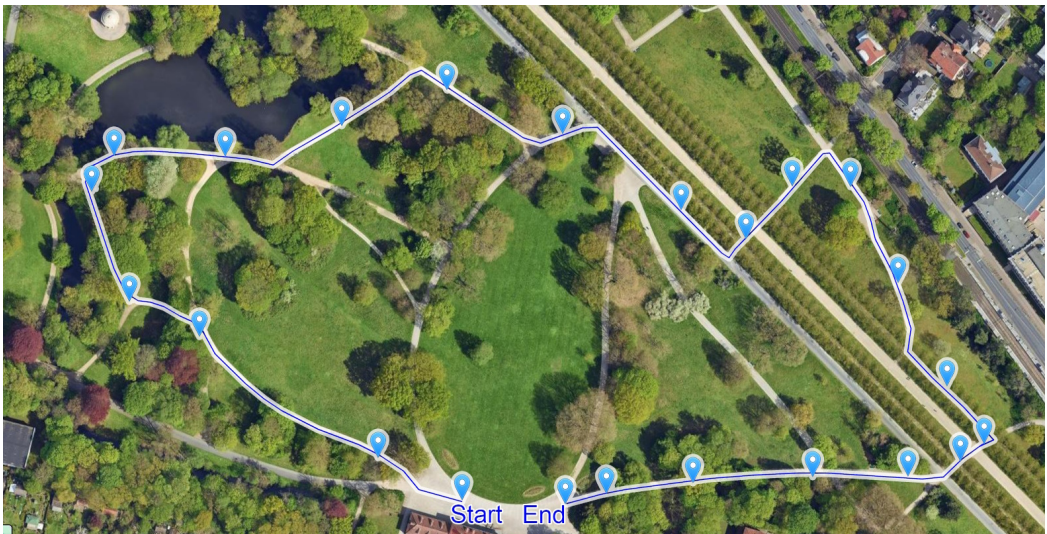


Fig. 8. The route on a map. Map from Google Maps with ©2023 GeoBasis-DE/BKG, GeoContent, Maxar Technologies. Kartendaten ©2023.

should always be oriented in the direction of the next junction. For longer routes in one direction, several points were placed in between to support slight curves in the park trail. The route had a total length of approx. 1.3 km and was created with *My Maps* from Google³. The waypoints on the route had an average distance of 56.5 m ($\sigma = 25.1$ m). In general, the route was chosen in such a way that the participants pass intersections with varying types of branches.

6.2 Participants

A total of eight people (4 female, 4 male, age 22-60, $M = 39.4$ years, $\sigma = 17.2$ years) took part in the study. All participants had no prior experience with electro-tactile feedback. However, each participant was familiar with the use of audio-visual navigation by smartphones. One participant also regularly uses the car's navigation system. Google Maps is most commonly used for general navigation, e.g. each of our participants uses it regularly for bicycle navigation. Further, one

³<https://www.google.com/maps/d/>

participant also uses the apps Komoot⁴ or AmiGo⁵ for navigation. We asked our participants about their cycling regularity in terms of how often they cycle per week. Three participants do not cycle regularly, three participants use their bike up to five times a week and one person cycles seven times a week. One of the participants also stated to ride a bike 20 times a week. This was the highest value that could be selected in the questionnaire. The regularly cycling participants use navigation between one and four times a week while riding. Three of them use a cell phone holder for bike navigation.

6.3 Procedure

At the beginning, the participants filled out a consent form and an initial questionnaire. The form included a list of health-related points under which they were not allowed to participate. The participants could indicate whether any of the points applied to them without explicitly naming them. In this case, the participant would have been excluded from the experiment. Further, the participants were informed about their right to end the study at any time without naming any reason.

After the questionnaire, we presented the prototype and explained the purpose and components of the study. The system was switched on and connected to the navigation app. As shown in Figure 7, right, the participants put on the smartwatch with the electrotactile grid clip. The system's hardware was stored in a belt bag that was worn around the upper body. The intensity of the electrotactile impulses was calibrated before the study started, so that they were strong but not hurtful. After the calibration, a small training phase was conducted. Therefore, we played the directions in a random order. After each electrotactile output, the participant to guessed intended direction. We revealed the correct direction after the guess. We repeated this process until the participant was familiar with the signals, had experienced each direction at least once, and had no further questions about the system. The entire calibration procedure took approximately 5–10 minutes per participant. The height of the bike's saddle was then adjusted to suit the participant.

The participants were instructed to pass all waypoints in order to complete the route. We told them that the route does not leave the park but they did not know, which park ways belong to the route. This was intended to prevent the participants from driving onto streets that are used by cars, where they may get into a dangerous situation. After that, the navigation was started and the users had to confirm that they perceived the navigation signals, then they could drive off. The experimenter accompanied each participant on a second bicycle. In order to record momentary impressions of the participants during navigation, the experimenter asked questions about perception of the feedback. The duration of the study was approximately 45 minutes per participant. After the destination of the route was reached, the system was switched off and the participant removed the belt bag and smartwatch. The participant then filled out the final questionnaire that asked for the participants' experiences and feelings while using the system. For taking part in the study, each participant received a bar of chocolate.

6.4 Results

All eight participants reached the destination using the electrotactile navigation system without any accidents. Only 2 of the 168 junctions (8 participants \times 21 junctions) were taken falsely. This corresponds to an accuracy of 98.8%. Six of the eight participants traveled the route without any major deviations from the original route (cf. Figure 9 left). Figure 9 middle shows the route of participant 8 that differs considerably, because the participant took the wrong turn at the second

⁴<https://www.komoot.com/>

⁵<https://www.tomtom.com/navigation/mobile-apps/amigo/>



Fig. 9. Left: Aggregated speed profile for all participants who followed the correct route without errors. Middle and right: The trajectories of the only two participants (7 & 8) who took a wrong turn in the study. Middle: The participant took a wrong junction the very at the beginning, but after some time was guided back to the original route and continued with the next waypoint. Right: The participant took a path parallel to the correct one, recognized the error quickly, and turned around to follow the correct route.

junction. A small deviation can also be seen in Figure 9, right, in which participant 7 took a path parallel to the correct one. Because of the reversed electro tactile feedback, participant 7 then turned around and returned to the right way. Both participants successfully completed their journey despite the deviations from the original route. Notably, the experimenter did not intervene to redirect the participants back onto the intended path.

The participants had an average speed of 8.53 km/h ($\sigma = 2.05$ km/h) during the study. Figure 9 shows the average speed on the route aggregated over all participants.

Figure 9, left, shows the aggregated speed profile of all participants that followed the route correctly. While the speeds on straight parts of the route are relatively constant (9.0–14.3 km/h), it is particularly noticeable that the speed was reduced before every intersection to 5.4–8.9 km/h. Shortly before the end of the route, the speed was the highest at about 18 km/h, which is in the typical speed range of average cyclists. The final part of the route was long and straight section without branches.

Figure 9 middle shows the speed profile of participant 8, who took the wrong turn at the second intersection (circled in blue). The wrong turn was not communicated to the participant during the entire trip. Over the entire route the speed was significantly higher as the average speed the participants who drove the intended route (Figure 9, left). On the straight sections of the route the speed was 16.2–19.7 km/h. At the junction at which the participant got lost the speed was almost twice as high with 12.6–14.3 km/h as that of the participants who took the correct junction. After the trip, the participant stated that he did not reduce his speed because he was certain to have felt the signal in the direction in which he turned. He then felt an ambiguous signal on the right side of the prototype. This hints at a connection between speed and accuracy of navigation.

Figure 9, right, shows the trajectory of participant 7 that deviated from the regular route too. As described above, the participant chose a path that was parallel to the intended path, at a junction at the end of the route (circled in blue). What is particularly noticeable here is that the speed over the entire maneuver was only 7.2 km/h–8.9 km/h. Furthermore the speeds over the entire route were similar to those of the participant who drove the original route correctly. The speed was also reduced at the junctions. In comparison to participant 8, this participant directly noticed the deviation from the original route and was able to correct it.

6.5 Qualitative Feedback

Figure 10 left shows the qualitative results of 5-point Likert scales about the presentation of the electro tactile navigation feedback at the wrist. All participants agreed that the wrist is an appropriate location to present tactile navigational feedback. 6 of 8 participants could imagine using electro tactile feedback as an alternative to conventional types of navigation. The remaining

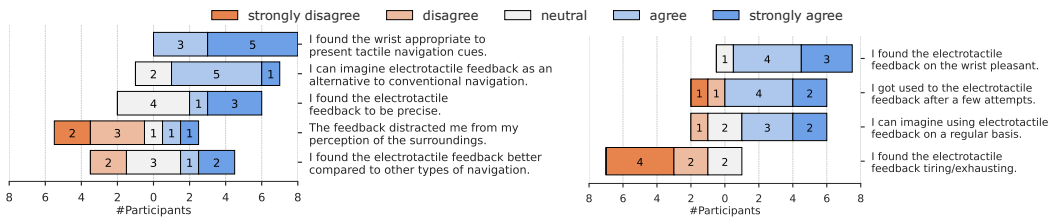


Fig. 10. Left: Feedback for our navigation approach. Right: Feedback for general statements about electro-tactile feedback.

two indicated a neutral attitude towards this statement. Also positively, the feedback was judged as being sufficiently precise by the half of the participants. The other half had a neutral opinion to this point. The majority (5 of 8) found the electro-tactile feedback not distracting during navigation, while one person had a neutral opinion and two participants found it distracting. Regarding the question if navigation based on electro-tactile feedback is preferable to other types of navigation, the answers were mixed. Two participants indicated that they disagree with this statement. Three had a neutral opinion. The remaining three found the electro-tactile navigation system better than conventional types of navigation, e.g. audio-visual navigation.

To gather further insights regarding preferences for different navigation modalities, we asked the participants to indicate, as free text, which features they judged as well supported in visual, auditory, and tactile navigation. One participant preferred audio-visual navigation because of the easier direction presentation, while another participant preferred it out of habit. These participants disagreed to Figure 10, left, statement “I found the electro-tactile feedback better compared to other types of navigation”. Of the three users that remained neutral to this statement, one said that the level of concentration on the correct interpretation of the electro-tactile signal was higher compared to audio-visual navigation. Another participant of that group described the electro-tactile navigation as “clear directions on branched roads, paths, etc.”. The three participants who found electro-tactile feedback better compared to other navigation modalities, described electro-tactile navigation as less distracting and less restricting. There is no need to focus on a display or on the audio output as “[...] the stimulation quickly made it clear where the route led”. This enables “conversations with a possible companion [...] without missing relevant announcements”.

We asked the participants whether they found the frequency at which the navigation signals were sent (every 5 s) to be appropriate. The majority (7 of 8) found the frequency appropriate, only one participant stated that he would prefer a higher update rate.

Figure 10 right shows the general feedback of the participants to electro-tactile feedback on a 5-point Likert scale. The first statement shows an overall agreement on the pleasantness of the electro-tactile feedback on the wrist (7 of 8), one remaining neutral. The majority of the participants (6 of 8) agreed that they got used to the electro-tactile feedback after a few trials. The other two participants disagreed with that statement. The majority of the participants (5 of 8) could imagine to use electro-tactile feedback on a regular basis. Two other participants were neutral and one participant disagreed with that statement. The majority of the participants (6 of 8) disagreed with the last statement that the electro-tactile feedback was perceived as tiring or strenuous. The remaining two stayed neutral.

Additionally, the participants had the option to give feedback as free text about how they experienced the electro-tactile feedback. From the 6 participants who gave additional feedback, 4 described the feedback as pleasant. Participant 3 described the feedback as innovative, while participant 6 felt it intuitive and non-distracting. Participant 2 mentioned to have felt the different

directions with varying intensities and participant 4 described the feedback as practical but not always clear. Overall, the majority of the participants perceived the electrotactile feedback positively, as pleasant, not tiring, and appropriate for regular use.

At the end, in a free-text section of the survey, we asked whether the participants could imagine using the system in everyday life and in which situations a user would benefit from the system. Seven out of 8 participants responded positively, with one responding negatively regarding the inquiry whether they could imagine using the system in everyday life.

Six participants mentioned navigation as use cases for such a system. The participants deemed the proposed navigation method as suitable for both cities and rural areas. One participant mentioned that the system could also be used for hiking. Another suggestion referred to the usage of the system in a group setting as electrotactile navigation does not cause audio-visual distractions and thus does not interfere with interactions among the group members. Two participants also stated that people with disabilities could benefit from the system, as the perceived signals directly encode the direction without the need for further interpretation. One participant imagined that the system could be used as a navigation aid for people with visual impairments. Another participant found the system particularly advantageous for people with right-left weakness.

In summary, the majority of the participants was positively impressed by the system and could imagine using it in various scenarios as an alternative to conventional navigation.

7 Discussion

In the outdoor study we noticed that all study participants rode the bike relatively slowly with a mean velocity of 8.5 km/h. In their comparative study [Steltenpohl and Bouwer \[46\]](#) report a mean speed of 9.8–10.8 km/h for vibrotactile feedback and of 11.3–12.2 km/h for visual feedback. Their first route had a length of 950 m with 4 branches. The second route was 900 m long with 7 branches. Our route had a length of 1300 m with 21 branches. Also their routes only contained 90° turns on roads in a quiet residential area of Amsterdam. We evaluated our prototype with various angles and branch types on mostly gravel paths. The course had different types of intersections: 9 intersections had 3 junctions, 11 had 4 junctions, and 1 intersection had 5 junctions. The angles of the turns vary in the range from about -90° to about +90° as shown in [Figure 8](#). The route required 5 left turns, 7 right turns, and 9 straight continuations at the junctions. So the routes and the speeds are not directly comparable, as a higher branch count is obviously related to a lower speed. However, it should be taken into account that both the route and the bicycle were unknown to the participants. Also the road properties and the high variance of different intersection types may have led to the lower speed of the participants. We additionally asked the participants why they cycled so slowly. All participants stated that they reduced their speed due to the unfamiliar nature of the navigation modality. Some also stated that they needed some time to be able to correctly interpret the results. A direct comparison of all routes shows that the accuracy of navigation decreased with increasing speed, given a fixed frequency of one navigation signal every 5 s. The five-second interval is appropriate on a straight route, but it might be beneficial to increase the feedback frequency when approaching a junction or if the cycling speed is high. A longitudinal study could determine if the average speed is higher with more practice.

An open question is whether the simple static tactile feedback design could be improved. A critical aspect is the relatively large receptive fields at the wrist, compared to the size of a smartwatch. A modified design could try to involve two opposite pairs of electrodes to maximize the distance between the activated areas. For example, to indicate the upper-left direction, instead of just activating the electrodes 1 & 8 (see [Figure 1](#)), the opposing electrodes 4 & 5 could be briefly activated, directly followed by 1 & 8. This may be experienced like a motion from the lower-right to the upper-left and further emphasize the sense of direction.

8 Limitations

The use of electrotactile feedback has some limitations. As done in the studies, a calibration is necessary to find a current that evokes sufficient tactile sensations and is still comfortable. In the preliminary study, all possible electrode pairs were calibrated separately. The results of the preliminary study showed that the calibrated values vary strongly between individuals, but for a single individual the values of the different electrodes pairs differ only slightly. This is likely due to the small spatial distance between the electrodes. So the calibration was simplified in the subsequent studies in that the calibration was only done for a single electrode pair and this current was tested with all other electrodes pairs. This substantially reduces the calibration time, but a short calibration phase is still necessary. A change of the frequency and pulse width parameters of the electrotactile signal also entails a recalibration, but this could be sped up by using a log-log correlation [9]. Duentel et al. showed that the combination of pulse width and frequency correlates with the calibrated amplitude.

The calibrated threshold further depends on the impedance of the electrodes and their connection to the skin. The impedance can change, for example, due to sweating or if the watch is mechanically stressed and an electrode lifts slightly up. Such cases are not handled by our prototype yet, but Kajimoto investigated real time impedance measurements to leverage such problems [19].

Another limitation is that electrotactile feedback is often experienced as less comfortable than vibration feedback [45]. Therefore, the calibration should be done carefully and the parameters that are chosen for the frequency and the pulse width also define how pleasant the signal is [9, 21].

Our prototype systems lacks a real integration of the stimulator and the switching unit in the smartwatch. Therefore, the system currently needs an additional bag worn around the waist and cables that connect it to the electrodes under the smartwatch. The components are at the moment bulky, but they can be miniaturized quite well. Pohl and Hornbæk present a small self-made stimulator that was used to provide electrically evoked itch feedback [39]. The board is of the size of an Adafruit Feather and demonstrates the miniaturization potential of the technology, even by a non industrial design and manufacturing process. The switching board could also be miniaturized if the stimulator is integrated. Not all of the provided 16 channels are used and the additional galvanic isolation of the switching board can be omitted by integrating it in the stimulation circuitry.

In comparison to other works, e.g. [46], we did not compare our system to visual navigation. Based on our premise that we do not want to augment the bicycle or other body parts, smartwatch-based visual navigation would be a conceivable baseline condition. But this would potentially also be more risky. In contrast to a smartphone holder, the gaze of the cyclist would not only have to be lowered but also move to the left or right to focus the small smartwatch screen. This could be dangerous. However, even without another modality as a baseline condition, the presented studies provide valuable insights in the suitability of a wearable electrotactile bicycle navigation system. The core question is whether such a system is successful in guiding cyclists. The results show that this is the case, with some limitations regarding the design of the electrotactile signals and the resulting cognitive load of the users. Still, the results are interpretable without direct reference to an additional baseline.

In our study, we evaluated our approach only with a single bicycle, which had straight handlebars. There is a wide variety of different types of handlebars that could have an impact on the presented navigation approach. While the direction of the lower arm pointing in the driving direction remains the same, the wrist orientation changes for some handlebars (cruiser bars, drop bars, bullhorn bars, etc.). As a result the angle presented on the plane defined by the smartwatch case may no longer coincide with the target angle. This could increase the cognitive load, which could in turn affect the navigation performance.

Lastly we tested our system only in a park environment and not on streets for safety reasons. We did so, because electro-tactile feedback is quite different from other modalities and likely unfamiliar for most people. The risk of performing the study on general streets or roads would have been too high for the participants.

9 Future Work

In the future, we plan to adapt the design of our prototype to current smartwatch designs, which have a heart rate sensor on their back, with electrodes placed in the center. One example is the Samsung Galaxy Watch 4. As the preliminary study showed, for providing directional feedback our center electrode could be omitted and a free space could be left to enable simultaneous usage of the prototype and the already integrated sensors.

Our proposed concept could be also transferred to other areas like skiing, snowboarding, or pedestrian navigation, and be further evaluated. The system is currently limited to show only the direction to the target, but it could also be used to inform the wearer about general notifications, the remaining distance to the target, the direction of points of interest and about obstacles behind the cyclist, skier, or snowboarder. Spatio-temporal patterns could be created to encode this additional information, or signals with different electro-tactile colors [9] could be used.

Furthermore, if studies were made for other types of mobility, e.g. pedestrian navigation, the effect of the orientation of the smartwatch could be investigated. For cycling navigation, future work could investigate the effect of different handlebar designs and resulting changes of the orientation of the wrist. Appropriate tactile feedback designs could be identified that are immune to or adapt to different orientations.

Also it appears promising to investigate if the funneling illusion effect could be created with electro-tactile feedback if two electrode pairs are simultaneously stimulating the skin. This could reduce the number of needed electrodes. Further it should be investigated if our effect of interpolated directions is similar to the funneling illusion effect [3]. Finally, a detailed comparison of vibrotactile feedback and electro-tactile feedback on the wrist (under a smartwatch) would be desirable, covering both performance differences in the lab and in an outdoor cycling setting.

10 Conclusion

We presented a circular electrode design on a wearable electro-tactile navigation system located on the wrist for encoding directional electro-tactile cues. We evaluated our approach and found that the inner electrode is ineffective for indicating directions, as stimulations of different pairs of outer electrodes and the inner electrode could not be distinguished well. Therefore, we focused on the outer electrode ring and evaluated in a laboratory setting how well participants can distinguish the indicated direction under a smartwatch for 16 different electrode combinations. The results show that the accuracy of the 8 native directions ($MAE = 19.28^\circ$, $\sigma = 42.77^\circ$) does not differ significantly from another set of 8 interpolated directions ($MAE = 22.54^\circ$, $\sigma = 43.57^\circ$). The interpolated directions are rotated 22.5° compared to the native directions. While the reported mean absolute angular differences seem large, a transformation of the angles to a distance in mm on the outer electrode ring shows that the absolute difference is actually relatively small. The mean distance is 6.63 mm for the native directions and 7.75 mm for the interpolated directions. As the standard deviations are large, we analyzed how many non-overlapping directions can be displayed with our prototype. Based on the laboratory results of Study 1 we conclude that the prototype is able to reliably display 4 directions that differ significantly and are easy to distinguish. Further, the additional interpolated directions might be of future interest for the encoding of dynamically moving patterns.

Based on the high variance when considering all 16 directions we decided to reduce the set of supported directions for an electro-tactile navigation system to 8 different directions, even if they

overlap, to increase the resolution of the feedback as well as to offer a larger number of design options for electrotactile feedback. Using these 8 directions we created a directional continuous tactile navigation system and evaluated it in an in-the-wild setting for cycling. The results show that the participants were successfully guided with the tactile system, without having to rely on the visual or auditory channel. The error rate for the test route remained low at about 1.2 % and the majority of the participants positively judged the system and could imagine using it as an alternative to conventional navigation.

As this tactile system is integrated in smartwatches, in the future it could not only be a viable alternative for navigation tasks, to tackle the increasing load of the visual and auditory system, but also be used for notification purposes or for presenting electrotactile patterns.

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