A head-based vibrotactile compass for cyclists

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Figure 1: The system supports cyclists in orientation with a headband (right) for vibrotactile feedback, which is activated by a push button mounted to the bicycle handlebars (left). The accompanying mobile app is not shown in the image.

ABSTRACT

Cycling stimulates the human mind and body in manifold ways. However, even on a leisure ride, certain waypoints or destinations must be reached. Therefore, orientation is a crucial task for every cyclist. Vibrotactile systems for cyclists do not clog up the visual and auditory senses needed to experience the immediate environment. However, our literature survey shows that previous work focuses on turn-by-turn navigation systems and does not leverage the potential of vibrotactile feedback on the head. Since the head is not in direct contact with the bike, we argue that vibrations occurring naturally are less confounding. Moreover, head movements are already crucial for wayfinding. We present an unobtrusive orientation system for cyclists with head-based vibrotactile feedback – a vibrotactile compass. In a user study, we show the feasibility of our system.

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CCS CONCEPTS

• **Human-centered computing → Haptic devices**; *User studies*; *Interface design prototyping*; User centered design; Activity centered design.

KEYWORDS

human-computer-interaction, interaction design, head, wearable, vibrotactile, navigation support, cyclist, user study

1 INTRODUCTION

The purpose of many (digital) tools and processes is to enable people to perform their tasks more efficiently. In contrast, most leisure activities are generally free and playful without the need to fulfill specific tasks as fast as possible. In this contribution, we focus on cycling as such a leisure activity. Although cycling is also used to reach a certain location, its value is often perceived to be the activity itself for purposes of recreation, sports, or group experiences. However, orientation is needed for a cyclist to determine their current location in the environment. Most navigation systems follow a turn-by-turn approach to reach a certain location as efficiently as possible by following a determined path. In contrast, we attempt to respect the autonomy of the user even more and not distract cyclists from their environment with unsolicited instructions. Hence, our goal is to support basic orientation in an unobtrusive way as shown in our user study. During a bicycle ride, cyclists are exposed to numerous environmental factors that already stress their visual and auditory senses, such as traffic or sightings in nature. Our approach is based on a vibrotactile interface in order to keep visual and auditory channels free for the actual cycling. The interface is located at the cyclists' head, since other parts of the human body are in closer contact with the bike and could thus be more susceptible to natural vibrations caused by cycling. The head is also the natural center for orientation and has a high sensibility for recognizing vibrations [16].

We present our contributions in this paper as follows: First, we review related work in the area of vibrotactile interfaces with a focus on navigation support for cyclists. Second, we describe the concept for our head-based vibrotactile system. In section 3, we also outline the technical realization of this system in a working prototype. This prototype was validated in a user study (section 4). Finally, we discuss the viability of our approach to support orientation for cyclists (section 4.4) and comment on future work (section 5).

2 RELATED WORK

Previous research shows how the tactile sense can be leveraged to convey information via so-called Tactons, generated using vibrotactile displays. Those "structured, abstract messages [...] can be used to communicate [...] non-visually" [3]. In the context of navigation, they can convey the direction or the distance to the destination. The system *Tacticycle* supports tourists in exploring their environment on a bike [17, 18]. The system combines vibrotactile feedback with a visual display in a multi-modal way. Potential traveling destinations and points of interests are highlighted on a visual display mounted on the handlebar. Both handles contain one vibration motor (tactor) each. Similar to our system, the immediate direction to the destination or point of interest is conveyed by vibrating. However, different intensities are used and only a 180-degree spectrum of directions ahead of the cyclist is covered. The system was tested in different settings following a requirements analysis. In contrast, *Vibrobelt* is a turn-by-turn navigation system for urban areas [19]. Eight tactors around the hips direct the cyclist towards the desired destination. Two distance levels are distinguished by the duration and repetition of the vibrations. Escobar Alarcón and Ferrise present vibrotactile wristbands for a navigation system [1]. Each wristband contains a single tactor. Consequently, the direction to the destination is conveyed by vibrations on either the left or right wrist. Similar to *Vibrobelt*, two distance levels are distinguished by the duration and repetition of the feedback. Matviienko et al. evaluated different modalities (visual, auditory, and tactile) for navigational cues tailored towards child cyclists [14]. Therefore, they present a navigation system *NaviBike* similar to *Tacticycle*, with a single tactor in each handle of the handlebar. Thus, conveying the direction to the next waypoint and signaling distance in the same way as with *Vibrobelt* and *Tacticycle*. Since hands, feet, and bottom are in direct contact with the bike they can convey outside vibrations to the body while cycling on uneven trails. Hence, in contrast to previous systems, we propose to investigate the head as location for vibrotactile feedback during cycling. Furthermore, the head is also the natural center for orientation and therefore we adapted the hardware setup of *Vibrobelt* to a headband. Due to the promising research results of using vibrotactile ring displays on the head [4, 5, 11–13, 15, 16], we aim to leverage this potential to support orientation for cyclists in a novel, head-based vibrotactile system.

3 CONCEPT AND IMPLEMENTATION

The metaphor for our approach is a compass, which offers support for orientation by indicating the direction to north. In our case, a single reference point serves as the final destination or an arbitrary orientation point selected by the cyclist. Moreover, we extended the metaphor by giving feedback when a destination is reached.

3.1 Requirements

In order to support orientation for cyclists in an unobtrusive and comfortable way, basic system requirements must be met, following the standards from ISO 9241 (11, 110, 210) [8–10]. Simplicity is a fundamental requirement of the technical system (R1–simplicity). During the bicycle ride, the outputs should be immediately interpretable and usable for route planning. The frequency of interaction with the system should be as low as possible (R2–interaction). Furthermore, it should be possible to use the system on longer tours. An important prerequisite of this is a high level of wearing comfort in terms of pressure, weight, and vibration (R3–comfort). In addition, the use of the head-based vibrotactile output system and its activation should provide high usability (R4–usability).

3.2 Design and Implementation

As shown by systems like *Tacticycle* [17, 18] and *Vibrobelt* [19], two-dimensional directional information seems sufficient for the context of cycling. Therefore, we conceived a circular vibrotactile display, integrated into a headband, that signals the direction to a destination in relation to the user's head orientation.

The hardware to realize this system consists of three parts: a headband, a push button unit, and a smartphone. Since Dobrzynski et al. showed that twelve tactors are well perceived around the head [5], we followed this suggestion and constructed a vibrotactile headband with twelve eccentric rotating mass (ERM) tactors. Each of these are 2 mm thick and 10 mm in diameter and were mounted orthogonally in relation to the head, in order to utilize their vibration direction. This was achieved by inserting them into soft plastic foam glued onto the headband (see Figure 1 and Figure 2 (2)). Twelve holes were cut into the outer layer of the headband to route the tactor cables to the *WeMos Lolin32* single-board microcontroller at the back of the band. The processing unit and a lithium-polymer battery pack were wrapped by foam rubber and fixed by reusable velcro ties onto the headband. The headband is made of elastic material, which fits a wide range of head sizes. This preliminary design for the headband is inferior to a version integrated into an actual helmet, which is our plan for the future. In total, the headband weighs 125 g. To trigger the vibration in a safe manner, we placed a push button unit consisting of a push button, an indicator LED, an *Arduino HUZZAH32* single-board microcontroller and a lithium-polymer battery pack on the bicycle's handlebars. A custom application running on a smartphone (Google Pixel 2) is used to set the destination on a map and provides the necessary location

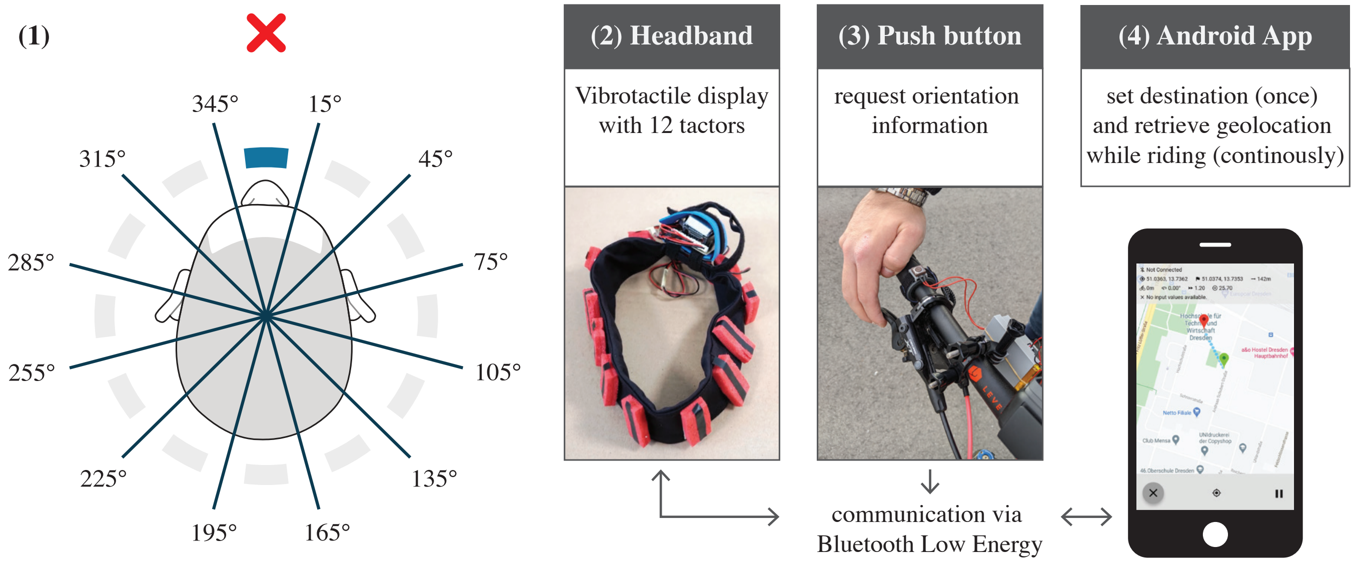

Figure 2: The vibrotactile compass consists of three main components: the headband as vibrotactile display (2), a push button to trigger the feedback (3), and a mobile app (4). The headband displays the direction towards the destination with a resolution of 30 degree (i.e. twelve directions in total) with respect to the user's head orientation (1).

data while riding. All three hardware components communicate via Bluetooth Low Energy.

For the directional output, we use simple and concise tactons by encoding the direction to the destination via the position of a single activated tactor (see Figure 2 (1)). All tactons used for displaying directions to the user appear in a repeating sequence of 300 *ms* vibration followed by a 300 *ms* pause. The duration of the output is determined by the user, who can request the vibrotactile feedback in a self-determined manner by pressing the push button (see Figure 2 (3)). The feedback that the destination has been reached must be clearly distinguishable from the directional tactons described above. For this purpose, a tacton with a transformation is used. Alternately, every other tactor is activated for 500 *ms* each. To ensure that the tacton is perceived by the user, it is repeated again after a 500 *ms* pause. We purposely omitted other distance information to keep the system as simple as possible (see R1).

We decided to use a fixed vibration frequency for all outputs. As the manufacturer does not provide a characteristic curve, the employed frequency can only be estimated by utilizing curves from similar tactors. By measuring the voltage and using the curve of *NFP 310-118*, we estimated the vibration frequency to be around 200 *Hz* and thus slightly higher than recommended by [4, 15] to make sure that vibrations are perceived impeccably in the conditions of cycling. Since the frequency and the intensity of the vibration is coupled for ERMs the intensity remains the same across the tactons as well.

4 USER STUDY

We validated the requirements defined in section 3.1 for our concept to test its feasibility for the use case of cycling as a leisure activity.

4.1 Preliminary Test

We tested the output of directions via the headband in a laboratory setting with 12 participants and in a restricted parking area where five given destinations had to be reached using feedback from the headband. All participants reacted or stated that they perceived the vibrations. In total, 144 directional outputs were displayed in the lab and participants aligned themselves to the correct direction 140 times. In 82% of these tasks, the recognition time between presentation of the direction and final alignment of the participant was equal or below 10 seconds. In the parking area, 9 of 12 participants used head rotation for orientation before steering their bicycles in the appropriate direction. When moving to the target, 11 of 12 participants had to repeatedly correct their route. Due to the limited dimension of the test field, circular movements were used to move closer to the target area. However, 10 of 12 participants rode directly to the target and only made fine adjustments on the spot. Hence, we could prove that our headband provides perceivable and interpretable feedback.

4.2 Study Design

The main study was conducted with six participants (three female, three male) with an average age of 30,5 (SD=13,05) in a large park area (1900 $m \times 950$ m) in the center of Dresden. The objective was to reach a given destination in a natural navigation scenario. To make this situation even more realistic, we allowed participants to use their own bicycles. A common starting point and a destination unknown to the participants were selected. They were free to find their own route without further restrictions (e.g. time limit) and there was only one test run per participant. An experimenter entered the target into the mobile app before starting the test. After that, the participant was free to activate the system for orientation

Table 1: Results of the NASA RTLX (0 Very Low - 100 Very High).

Dimension	Mean	Median	SD	Min.	Max.
Mental Demand	30	22.5	23.24	5	65
Physical Demand	13.33	17.5	8.76	0	20
Temporal Demand	12.5	15	8.22	0	20
Performance	25.83	22.5	29.40	0	80
Effort	11.67	10	11.25	0	25
Frustration	15	17.5	12.65	0	30

at any time by pressing the push button. Each participant was accompanied by two experimenters in approximately 5 to 10 meters distance in order to observe their general behavior. After the navigation task, the participants were asked to fill in some questionnaires to gain qualitative data for the evaluation of R1 (simplicity), R3 (comfort), and R4 (usability).

4.3 Results

First of all, all participants were able to find and reach the destination.

Simplicity was investigated using the NASA RTLX test [6, 7]. A total value of 18 (scale 0 - 100, where 0 means easy to use) was obtained, which means that the system can be used with little cognitive effort. A detailed list of the results can be found in Table 1. In addition, the participants were asked to recall landmarks or occurrences seen during their rides (see Figure 3). In particular, they were requested to state the number of cyclists and families with children, as well as recalling points of interest (POIs). The majority of participants were able to indicate the correct number of cyclists seen (4 of 6) as well as families (5 of 6). Participants who failed to indicate the correct numbers stated that they had paid more attention to animals during the ride. All participants were able to name the correct POIs, even in chronological order. During the study, participants exhibited relaxed behavior. They were able to perceive the environment at their leisure and even talk to the accompanying investigators. The overall results suggest that the use of the technical setup is pleasant and effortless (R1–simplicity).

In addition, 4 of 6 participants actively looked around by turning their head. This behavior shows that using our system is in line with natural head movements of the user for orientation. For better traceability, the duration and location were saved as soon as the push button on the handlebar was pressed. The analysis of these log files showed that the system was only used selectively and not continuously. The average duration for displaying the signal was $1.12\,s$. In addition, all participants used the system ahead of intersections, while 3 of 6 also used the system on straight stretches of road to make sure where the destination was located. The study suggests that the system is mainly used at intersections, but can also serve as confirmation on straight stretches of track. The rare interaction with the system met the requirement R2 (interaction).

The requirement for comfort (R3) referred to the wearability of the headband in general. In a post questionnaire the comfort was rated as pleasant, with median values of 5 for pressure, 5 for vibration, and 4.5 for weight (1=unpleasant, 5=pleasant). Overall, the majority of the participants mentioned that the pressure, vibration and weight of the headband didn't bother them at all during the ride. Furthermore, they stated to not feel restricted in their movements by the system. In summary, R3 has been met. Usability (R4) was investigated in the natural setting with a System Usability Scale (SUS) questionnaire. The average result of 87 points indicates that the system is "excellent" to "best possible" [2]. In the qualitative evaluation, the participants also stated that they liked the system because it affords freedom of movement and ease of use. In addition, they were able to concentrate completely on the track, being in control of frequency and duration of the feedback without being distracted by a navigation display. This consistently positive feedback shows that R4 (usability) was met in our validation.

4.4 Discussion and Limitations

The aim of the user study was to verify the feasibility of the technical system. The results showed that the tactons displayed via the headband are perceptible and distinguishable. With the help of the tactons, the participants were able to orient themselves in a large area (approx. $2\,km^2$) and to navigate self-determinedly. The headband proved to be usable, easy to use, and comfortable. Explicitly, the high freedom of movement and the immediate interpretation of the results should be emphasized. In addition, there are individual differences and requirements of the cyclist and the chosen route. Orientation becomes more challenging in unknown environments. Since most of the participants in the study already knew the test area, we cannot fully validate the supporting effect of our system in unknown environments. We need to investigate this in the future. The evaluation of comfort showed a high level of satisfaction. However, the duration of use in the study was shorter than we intended for a typical bicycle tour that could last more than an hour. In addition, the headband could only be worn in place of a helmet. Integrating the system into a helmet could make a significant difference in safety, perception, and comfort.

5 CONCLUSION AND FUTURE WORK

In this work we presented a vibrotactile feedback system for cyclists that encodes directional information in order to support orientation. We conceived and implemented a technical setup that keeps the user self-determined and conducted a user study to test its feasibility. The results show that the headband meets our requirements for simplicity (R1), interaction (R2), comfort (R3), and usability (R4).

For the further development of the system, it is planned to examine the headband in an in-situ study. This requires investigating longer and more intensive use during bike tours. Additionally, we should consider comparing our system to similar (compass-like) navigation systems. Moreover, we can investigate the level of distraction and cognitive effort of using visual and vibrotactile navigation systems individually or in a combined setup. So far, the system only provides directional information to the user and there are various options to extend the corresponding tactons. To increase the degrees of freedom when designing tactons we have to switch to another type of tactors – namely linear resonant actuator (LRA). These enable separate control of the vibration's amplitude

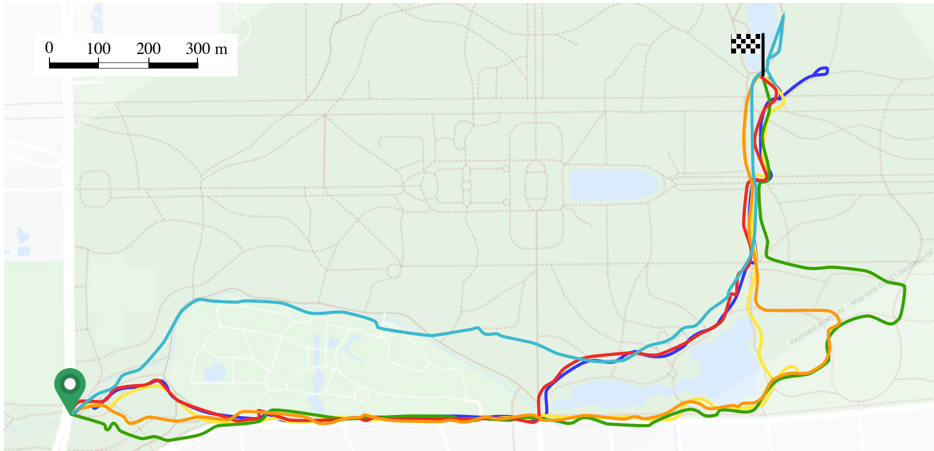

Figure 3: The routes chosen by the participants in the restricted area.

and frequency. This also allows us to better accommodate the characteristics of vibrotactile perception. Additionally, users can adapt the vibration's intensity according to their individual preferences. From the conceptual perspective, it might be useful to provide more information such as the distance to the destination. We plan to publish the schematics and circuit layout as well as the source code (i.e. firmware and app) under open source licences. This should encourage others to reproduce the system or even file pull requests for enhancements or new features.

We are convinced that the suggested setup is not limited to the context of cycling. Hence, we will consider a transfer to other helmet systems and user groups, e.g. firefighters, visually impaired people, or industrial workers.

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