Around-the-Head Tactile System for Supporting Micro Navigation of People with Visual Impairments

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Tactile patterns are a means to convey navigation instructions to pedestrians and are especially helpful for people with visual impairments. This paper presents a concept to provide precise micro-navigation instructions through a tactile around-the-head display. Our system presents four tactile patterns for fundamental navigation instructions in conjunction with continuous directional guidance. We followed an iterative, user-centric approach to design the patterns for the fundamental navigation instructions, combined them with a continuous directional guidance stimulus, and tested our system with 13 sighted (blindfolded) and two blind participants in an obstacle course, including stairs. We optimized the patterns and validated the final prototype with another five blind participants in a follow-up study. The system steered our participants successfully with a 5.7 cm average absolute deviation from the optimal path. Our guidance is only a little less precise than the usual shoulder wobbling during normal walking and an order of magnitude more precise than previous tactile navigation systems. Our system allows various new use cases of micro-navigation for people with visual impairments, e.g., preventing collisions on a sidewalk or as an anti-veering tool. It also has applications in other areas, such as personnel working in low-vision environments (e.g., firefighters).

CCS Concepts: • **Human-centered computing → Accessibility technologies**; *Empirical studies in accessibility*; *Ubiquitous and mobile devices*; *Haptic devices.*

Additional Key Words and Phrases: visually impaired, tactile navigation, tactile guidance, tactile patterns, obstacle avoidance

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1 INTRODUCTION

Blind and visually impaired people (VIPs) face major challenges when navigating in unknown spaces or searching for objects, even in their own homes. Historically, only a few tools for exploring unknown spaces were available such as guide dogs or white canes. Only a low percentage of VIPs even utilize these aids (less than 10 % white cane users [60, 61] and about 2 % guide dog users [18] in the USA). One likely reason for this is the stigma of using a white cane or a guide dog, which shows the user to be visually impaired. There are also issues with adapting to white cane usage, safety concerns [19], and the high cost for a guide dog and the need to care for it [18]. A possible solution to these stigma issues are hidden auditory or tactile guidance systems.

Navigation involves two main components: mobility and orientation as defined by Loomis et al. [33]. Mobility or *micro-navigation* involves sensing the near-field environment and working out a way around static or dynamic

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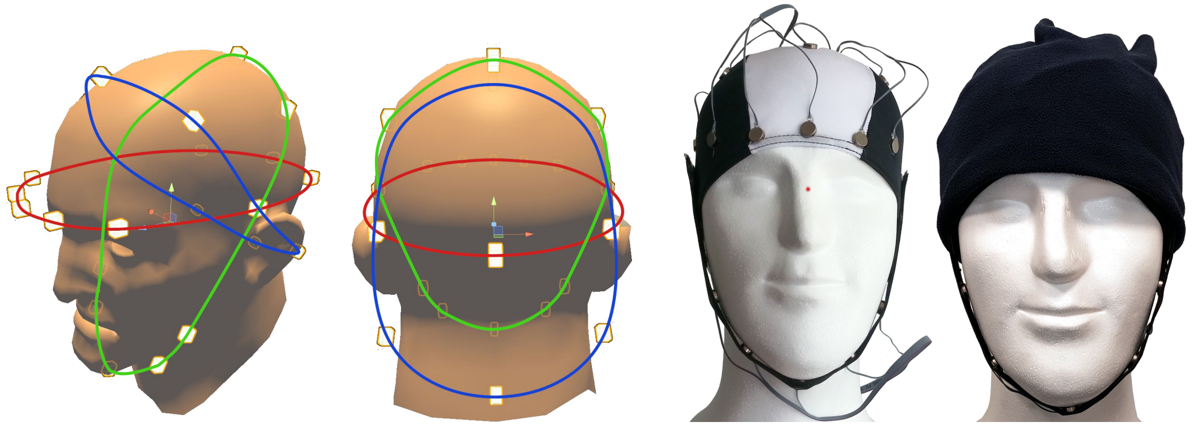


Fig. 1. HapticHead prototype with 24 actuators around the head and high-density areas on the forehead and chin. Left: the prototype modeled with all 24 actuator positions. Notice that all actuators are part of one of three rings around the head. Notice the higher density areas on the forehead and chin. Right: raw prototype and prototype integrated into a beanie. Previously published in [28].

obstacles. Orientation or *macro-navigation* involves being oriented (e.g., by detecting landmarks), path-planning on a broader scale, and detecting when a destination has been reached [25]. A navigation system for VIPs typically includes the following three components: *a set of position and orientation sensors* (e.g., magnetometer + GPS, DGPS, or Bluetooth beacons), *a geographic information system* for path-planning (e.g., pre-computed maps), and *a user interface* (e.g., auditory feedback or a tactile belt in conjunction with a white cane).

Examples for the first two components can be found in recent work on detecting open areas in front of a walking person [51], a social distancing assistant for VIPs with real-time semantic segmentation on RGB-D video [36]. One recent work even attempts to use technology intended for autonomous cars to sense the environment around VIPs [35]. Some systems merge the first two components into a single entity, such as simultaneous localization and mapping approaches with LiDARs, or modern self-localization frameworks such as Google ARCore [17] and Apple ARKit [2].

Occupying the sense of hearing for a navigation system's user interface is a safety concern as walking on the street requires unobstructed hearing, even for sighted people. A solution for this are tactile user interfaces that do not occupy the sense of hearing. Most existing tactile user interfaces for VIP navigation focus on the macro-navigation aspect. These systems aim to roughly guide VIPs through cities by providing turn-by-turn directions towards a destination, using either GPS as a position and orientation component or a remote operator (e.g., [44, 52, 59]). Due to the relatively low accuracy of their position and orientation components, these systems do not attempt to provide micro-navigation instructions but instead require the user to apply other micro-navigation tools (e.g., guide dogs or white canes). There is one work by Flores et al. [16], who presented an 8-actuator tactile belt system for micro-navigation of VIPs using a dynamic stimulus *vibrotactile pattern*. However, an average deviation from the optimal path of 49 cm prevents usage for a variety of micro-navigation cases requiring high precision, such as walking on a sidewalk while safely moving around obstacles and other people or walking to the counter in a crowded bar.

(Vibro-)tactile Patterns are essentially a set of carefully designed commands for one or multiple actuators over time. Predefined or dynamic tactile patterns can be played back on (vibro-)tactile displays. A simple example of a tactile pattern is a tactile phone notification pattern that turns an actuator on and off rapidly.

The human head presents itself as a mostly spherical surface for tactile feedback, which increases the design space of possible tactile patterns and is also intuitively the center of attention for humans, which has various advantages for tactile feedback on the head. For example, a strong tactile stimulus on the back of the head can intuitively be recognized as "something is behind me, might be dangerous" [29]. We define *intuitive* tactile patterns as mostly "self-explanatory" and requiring minimal training, like a single presentation of the available tactile patterns, to feel comfortable with the system and to operate it with minimal interpretation errors.

In prior work, we presented *HapticHead* [27, 28], a vibrotactile display around the head consisting of a bathing cap with a chin strap and a total of 24 vibrotactile actuators (see Fig. 1). We showed that our system can be used in 3D guidance and localization scenarios in virtual (VR) and augmented reality (AR) with relatively high precision and low task completion times. We also investigated characteristics of tactile patterns on the head in our prior work [28, 29]. The results gave us insights into important aspects of intuitive tactile patterns.

These prior works initially inspired us to think about other exciting use cases for precise guidance, such as micro-navigating VIPs. Our initial research question was: "Can we extend the HapticHead system to provide VIPs with precise micro-navigation instructions?" This first notion naturally led to more research questions: "What kind of instructions should we provide to VIPs and how should we represent them?" and finally: "How accurately can our system guide VIPs?" Our primary goal for this work was to achieve a higher micro-navigation precision for VIPs than the prior state-of-the-art system [16]. Due to our experiences with the blindfolded 3D guidance experiment in [28], and HapticHead's ability to steer users to an invisible target on a 3D sphere around them at a high median precision of 2.3° to the target [28], we assumed the HapticHead prototype to be able to steer VIPs alongside an optimal path at a higher precision than reported in [16].

1.1 Approach

After reviewing related work (section 2), we started with the elicitation of fundamental VIP navigation instructions through an informal interview (section 4.1). We then proceeded to design tactile patterns for these navigation instructions through a user-centric design approach, which included two user studies (sections 4.2 and 4.3). This approach produced four intuitive tactile patterns, which we combined with a continuous guidance stimulus from our prior work [28] and an additional ATTENTION pattern to form a highly precise micro-navigation guidance system (section 5).

To test the precision of our guidance system, we invited a total of 13 participants with normal vision who were blindfolded and two blind participants for the *Obstacle Course Experiment* (section 6). We found that our system was already significantly more precise than related work [16] and that we should further reduce the presentation time of our static patterns as participants sometimes went off-track because the long presentation time of our static patterns overshadowed the directional continuous guidance stimulus.

Consequently, we shortened and refined our static patterns (section 7) and finally validated the improved micro-navigation system with another five VIPs in the *Improved System Validation Experiment* (section 8).

1.2 Contributions

In advancing the fields of tactile micro-navigation and assistive technologies for VIPs, we make the following contributions: (1) a set of fundamental navigation instructions and associated *intuitive* vibrotactile patterns on the head, optimized in three consecutive studies for micro-navigation, and (2) a system using these optimized tactile patterns for essential navigation instructions combined with a continuous tactile guidance stimulus to provide precise micro-navigation instructions. The system supports navigation around obstacles and on stairs. The precision of our system is substantially better (5.7 cm mean deviation from the optimal path) than related work (49 cm mean deviation from optimal path [16]).

Compared to prior work, our system's substantially higher precision opens up a whole new set of use cases, like steering VIPs around obstacles on a sidewalk or steering VIPs in a mall without running into others. While the system was developed and optimized with an emphasis on high precision for micro-navigation, it can also be used in (combined) macro-navigation use cases and thus presents itself as a complete output solution to micro and macro-navigation for VIPs, given a suitable and precise tracking and obstacle detection system. Even though our system is primarily intended for VIPs, we imagine it to be also applicable in other scenarios where precise tactile guidance is necessary. For example, it could be used in guidance scenarios for firefighters or other personnel operating in low vision environments, jet or drone pilots, or VR/AR scenarios where the visual and auditory channels should not be overtaxed to show navigation instructions or guidance to specific targets.

2 RELATED WORK

Jones and Sarter [23] review and give general guidelines on the design of tactile displays. They conclude that different levels of vibrotactile intensity and frequency are hard to distinguish and even interfere with each other. Simultaneously, stimulus location and duration are easier to identify and can thus achieve a higher bandwidth of communicated information. These results were later confirmed for tactile patterns on the head alongside other head-based tactile feedback properties in [29], which influences the design rationale of tactile patterns in the current work.

2.1 Vibrotactile Pattern Terminology, Characteristics, and the Funneling Illusion

Eccentric rotating mass (ERM) actuators such as those we use in this paper [48] can essentially only be turned on (~0.5 V < supply voltage < 3.6 V) and off (supply voltage < ~0.5 V). The input voltage can also be supplied by modulating a 5 V input signal with pulse-width modulation (PWM), which is the usual approach when working with ERMs. Certain actuator characteristics such as spin-on-time and full-stop-time determine what kind of stimuli can be created and how they feel.

When talking about modulating the input signal to create a vibrotactile pattern, we use the following terms:

- **intensity** – modulating the input signal at a frequency above 1 kHz. This is usually the PWM frequency and leads to decreased perceived intensity and amplitude when decreasing the PWM signal's on-off-ratio.
- **roughness** – modulating the input signal between 12 and 50 Hz. This leads to the stimulus feeling "rough" and uneven, especially when using square waveforms.
- **rhythm** – modulating the input signal at a frequency of less than 12 Hz. This can create special rhythms such as 500 ms on, 500 ms off, repeatedly for a defined instruction or meaning.

It is possible to chain multiple actuators together and thus modify the **location** of the stimulus. This chaining can result in a *static pattern with a static stimulus location* – e.g., three motors vibrate together on the left side of the head. It may also result in a *static pattern with a dynamic stimulus location* where multiple actuators work together to create a moving tactile stimulus – e.g., through smoothly interpolating between four actuators from the backside of the head over the top to the forehead using an algorithm such as Tactile Brush [22]. For simplicity, we will refer to both of these kinds of patterns as *static patterns* as they do not change based on the environment. Modifying the location of a tactile stimulus on the head has a significantly higher positive impact on recognition performance than modifying the rhythm or intensity/roughness of standard ERM actuators [29].

Finally, it is also possible to create dynamic stimulus location patterns that change and react to, e.g., a target in 3D space around the user, indicating the user's target location. An example of this is the target acquisition task in [28]. We will refer to these patterns as *dynamic* or *continuous patterns*, as they change based on the environment.

Tactile Brush [22] is an interpolation scheme for multiple tactile actuators arranged in a grid in order to purposefully generate a moving tactile funneling illusion, which simulates the feeling of a continuous motion with a single localization point, even though multiple actuators are active at a time. The continuous guidance algorithm we use in this work is related to the original Tactile Brush algorithm as summarized in [28]. Our work on the funneling illusion on the head [30] shows that actuators' spacing should be 5 cm or less on the forehead for the funneling illusion to occur for most users. HapticHead uses a spacing of around 4 cm on the forehead, which is crucial for navigation. Experiencing the funneling illusion should increase comfort, as the switch between nearby actuators feels like one continuous stimulus instead of two separate stimuli.

More advanced vibrotactile actuators such as a Tacton C2 (a voice coil) used by Brown et al. [6] can create more complex stimuli by outputting audio waveforms like a bone-conduction speaker. These actuators allow adjusting frequency and intensity separately, which is not the case for ERM actuators. Brown et al. investigated the effectiveness of specialized vibrotactile patterns (Tactons) using a C2 Tactor on the fingertip. They found that their pattern rhythm was easily identified with an average success rate of 93 % for three different possibilities, while the roughness of the pattern (another three possibilities) was less easy to identify with an average success rate of 80 %. Our experiments in this paper build upon this work and introduce another factor besides rhythm and roughness: spatial location around the head. The addition of spatial location dramatically increases the total distinguishable number of patterns available to the user [29].

2.2 Head-Worn Vibrotactile Perception and Displays

In a series of experiments, Myles et al. [39–42] investigated the vibrotactile sensitivity of different head regions and hair densities and use a headband with seven C2 Tactors to provide vibrotactile stimuli to soldiers. They found that soldiers preferred a tactile to a visual or auditory display for directional cueing and that the forehead, frontal, parietal, and temple regions were most sensitive to tactile stimuli.

The literature lists several vibrotactile displays on the head. *Haptic Radar* [8] is a ring around the head, consisting of multiple infrared sensors and vibrotactile actuators to give users a "spider-sense" of approaching objects. A similar concept is *Proximity Hat* [5], which uses pressure instead of vibrotactile actuators, thus stimulating other receptors (*Merkel disks*). *VibrationCap* [14] is a concept similar to HapticHead [26, 28] but miniaturized into a beanie and without the chin strap. They evaluated tactile sensitivities of stimuli on the head, confirming the conclusions of Myles et al. [39–42]. Diener et al. [14] also did an initial evaluation of tactile localization accuracy, which was later examined in more detail together with an investigation on the funneling illusion on the head [30]. Our prior work [30] shows that the forehead achieves the highest accuracy in the localization of vibrotactile stimuli (0.7 cm mean absolute deviation), followed by the frontal top of the head (0.9 cm deviation), the chin (1.2 cm deviation), and the bottom back of the head (1.2 cm deviation). The rear top (1.4 cm deviation) and sides of the head (1.5 cm deviation) relatively scored the worst in localization performance. These results and the ones presented in [42] suggest that the forehead is a great candidate for tactile patterns in high-precision guidance applications. Our continuous guidance stimulus in this work resides mostly on the forehead.

2.3 Indicating Direction with Vibrotactile Output

Several recent works have focused on indicating direction via a variety of vibrotactile outputs. The most promising systems use vibrotactile feedback on the feet, wrist, waist, neck, or forehead, and usually focus on macro-navigation instructions (e.g. "turn left at the next intersection"), while we focus on precise micro-navigation.

Wrist. Paneels et al. [46] investigate tactile patterns on a bracelet for indicating directions in macro-navigation. They found that static patterns with a static stimulus location are not well recognized due to the actuators being too close and being recognized as one impulse instead of multiple impulses (funneling illusion). In contrast, static patterns with a dynamic stimulus location are recognized with higher accuracy. We use mostly static patterns with a dynamic stimulus location or fully dynamic patterns in this work. Paneels et al. also conducted a vibrotactile pattern discrimination test for their wristband and found detection accuracies for four directions (and three other meanings) after training to be 66 % (and 73 % in a second iteration after further training).

Waist. *ActiveBelt* is a vibrotactile belt for directional macro-navigation [55]. This belt was proposed for various use cases such as macro-navigation in a city or notifications of valuables left behind. In a study, participants had to discriminate between the 8 actuators on the belt. Five of the six study participants answered that they could easily discriminate between the actuators. They also report that participants often failed to recognize vibration with a pulse length of less than 500 ms when walking. One of the patterns we use in this work has a pulse length of only 75 ms and is still recognized with near-perfect accuracy, which indicates that vibrations on the head are perceived much more strongly and are more "present" to the user than vibrations on the waist.

Van Erp [57] suggested using spatial vibrotactile cues for navigation directions and tested spatial accuracy with a vibrotactile display mounted on different locations around the torso. He found that the spatial accuracy of vibrotactile stimuli is best in the front-sagittal region with a standard deviation of 4-8° while it is much worse in the other regions with standard deviations around 10-18°. Heuten et al. [20] presented a 6-actuator vibrotactile belt with smooth in-between actuator interpolation to indicate high-resolution walking directions. They found a total average deviation to the indicated angle of 15°, which is comparable to [57]. Using GPS, they performed a continuous macro-navigation task and found their users to deviate 6.6 m from the optimal path on average. The large deviations can be attributed to the inaccuracies caused by GPS and to the relatively simple navigation algorithm. Ouyang et al. [45] did a follow-up study on [57] and [20] with a 12-actuator tactile belt, utilizing the tactile funneling illusion. They reported a detection rate of 91 % for a resolution of 7.5°, which is better than both predecessors. The 1D detection accuracies in [20, 45, 57] can be compared to the results of the invisible target finding task in [28] (mean 2D sphere deviation to the target of 2.3°, SD=1.8°).

Neck. A vibrotactile collar around the neck for macro-navigation is presented by Schaak et al. [50]. Their experiment showed that the concept worked well for simple turn instructions (e.g., right, front-left). Matsuda et al. [37] developed a vibrotactile collar around the t-shirt seam and showed its ability for 3D spherical guidance by reproducing a study from [28]. While the guidance performance in [50] was significantly weaker than the guidance performance of HapticHead [28], a vibrotactile collar is a less complex system and can more easily be hidden under a shirt or jacket for social acceptability.

Head. In an experiment comparing simple visual to tactile cues, Nukarinen et al. [44] presented a set of tactile glasses, which can indicate simple left or right tactile navigation commands for macro-navigation. A tactile helmet developed by Kerdegari et al. [31] uses twelve ultrasound sensors and seven vibrotactile actuators on the forehead for micro-navigation in terms of following a wall in a low-vision scenario involving firefighters. Their experiment shows a slightly lower route deviation for the vibrotactile modality compared to auditory feedback, highlighting the advantages of using vibrotactile over auditory feedback for micro-navigation. However, this scenario is not directly comparable to our micro-navigation experiments as participants in [31] were following a wall while potentially touching it, which may increase precision. The paper neither reports whether the wall was touched nor the distance of the optimal path from the wall. The starting positions suggest that the optimal path was very close to the wall (see Fig. 5a in [31]).

2.4 Assistive Technologies for VIPs

Csapó et al. [10] summarize developments of assistive technologies for VIPs based on audio and tactile feedback. Scene sonification is an exciting research direction, which allows VIPs to perceive a scene via auditory cues [21]. Hu et al. [21] investigated three different kinds of scene sonification (depth image sonification, obstacle sonification, and path sonification) in a comparative study and found that preference for specific sonification approaches was highly individual and that sonification of high-level scene information (e.g., the direction of a pathway) is generally easier to learn than sonification of low-level scene information (e.g., raw depth images).

In terms of obstacle detection, Poggi et al. [47] proposed a mobile system that detects objects through deep learning to give speech-based warnings of obstacles to VIPs. Using a tactile 3×3 grid on the abdomen, Van Erp et al. [58] presented a system to indicate obstacle information around the user, including direction (3 levels), distance (4 levels), height (3 levels), and type (4 levels). They found that users had difficulties distinguishing the large number of tactile patterns needed to identify the obstacle information with detection rates between 42 to 76 % for direction and height and 12.8 to 47 % for object distance after training. These results highlight the importance of well-designed patterns that ensure correct identification, especially in critical situations (e.g., crossing a street). Van Erp et al. went for a multimodal pattern presentation approach (tactile+auditory) in their follow-up experiments [58].

Recently, there have been attempts to allow VIPs to experience virtual reality and allow easy white cane training through enhanced white canes, which are tracked, actively braked by virtual obstacles, and that even provide vibrotactile feedback about ground properties [54, 62].

2.5 VIP Guidance via Tactile Feedback

There are two main kinds of assistive tactile technologies in navigation scenarios:

(a) Vision substitution systems that map a depth-image from an RGB-D camera to a high-density tactile grid placed on the tongue [4], back [3, 7], forehead [24], or abdomen [53].
(b) Tactile feedback systems that directly map orientation information onto a low-density actuator arrangement (usually a ring or grid configuration) and mostly placed on the wrist [46, 52], head [11, 44], neck [37, 50], feet [59], or waist [9, 16, 20, 55].

Not all of the systems mentioned above are targeted explicitly at VIPs but could conceivably be used in assistive scenarios as well. Specifically for VIPs, Scheggi et al. [52] performed a macro-navigation task using two vibrotactile wristbands and a remote operator for providing simple left or right navigation instructions to the VIP. Micro-navigation was still performed by the user using a white cane. Velazquez et al. [59] presented vibrotactile shoes to indicate four directions for macro-navigation (forward, backward, left, and right) and achieved a detection accuracy of > 89 % in their pattern discrimination study. While they also performed a macro-navigation study in a city, participants performed micro-navigation using their white cane.

Finally, Flores et al. [16] tested a vibrotactile belt with eight actuators in a micro-navigation scenario comparable to our work but without obstacles and stairs. They further compared vibrotactile to auditory guidance and found an average absolute distance to the optimal path of 49 cm using the tactile belt, compared to 61 cm using auditory guidance. Their tracking system has an accuracy of < 10 cm (ours < 1 cm). These deviations can be directly compared to the average absolute distance to our final system's optimal path, which is an order of magnitude (8.6 times) smaller at 5.7 cm.

The hardware system used in this work (presented in [28]) is most closely related to the waist-belts mentioned above, as it basically takes three actuator ring-configurations and puts them on the head in different orientations to provide 3D guidance instead of the 2D guidance of other systems. While 3D guidance is not always necessary, the increased actuator count compared to the usual waist belts and their spatial distribution around the head allows for more detailed vibrotactile patterns that feel more "present" to the user and are easier to interpret due to the given spatial relations [29]. Therefore, we expect less of a chance to misinterpret a tactile pattern in a stressful or dangerous situation, such as when approaching a down-leading staircase at a train station.

3 HARDWARE PROTOTYPE FROM PRIOR WORK

Our prototype consists of a bathing cap with 19 vibration actuators (Precision Microdrives 312-101 [48], 12 mm coin type, 3 V, 75 mA, 12500 rpm, 2.6 g maximum amplitude) attached on the outside and distributed on the whole surface. The non-stretchable chinstrap hosts an additional five vibration actuators on the inside and can be adjusted to different head sizes using a Velcro fastener (see Fig. 1). This prototype may optionally be integrated into a beanie due to the questionable aesthetics of the naked prototype. Software PWM signals control the vibration actuators at a frequency of 40 kHz using the pigpio library [1] on a Raspberry Pi 3 [49] connected to a custom actuator driver board. This prototype was first presented in [28], in which its concept is explained in greater detail, and the performance for 3D guidance is evaluated.

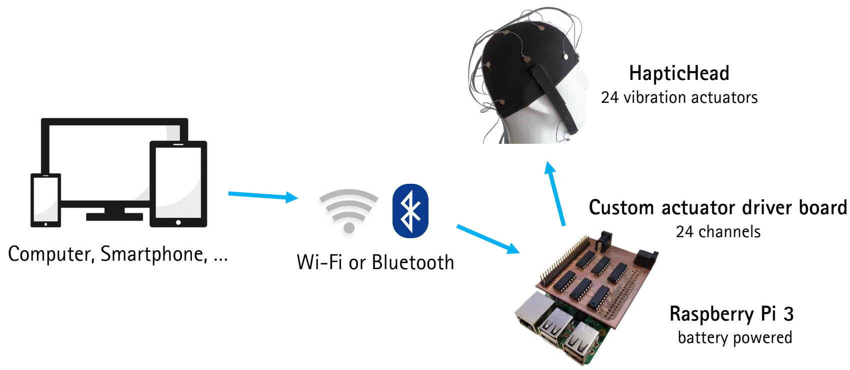


Fig. 2. System overview of the components of HapticHead as in [28]: A PC or smartphone wirelessly connects to the actuator driver board, which in turn connects to 24 vibration actuators.

On the software side, a Lenovo Phab 2 Pro phone running an Android control application (Elicitation Study and Pattern Recognition Performance Study), a Galaxy S8 (Static Patterns Refinement Study), or a PC running a Unity application (Obstacle Course Experiment and Improved System Validation Experiment) take care of playing vibrotactile patterns by sending actuator commands wirelessly to the Raspberry Pi 3 through Bluetooth (Elicitation Study, Pattern Recognition Performance Study, and Static Patterns Refinement Study) or Wi-Fi (Obstacle Course Experiment and Improved System Validation Experiment) at a variable update rate of up to 90 Hz. Fig. 2 depicts the system components and their interactions.

4 INITIAL DESIGN OF TACTILE PATTERNS FOR SPECIAL NAVIGATION INSTRUCTIONS

This section introduces our steps to elicit four fundamental navigation instructions through an informal interview with VIP navigation experts. Two subsequent user studies allow us to select suitable static tactile patterns from a large set and finally to optimize and validate the selected patterns for intuitiveness and practical use.

4.1 Informal Interview at an Educational Center for VIPs

Early on in our research, we made an appointment at an educational center for VIPs in Hanover, Germany, which teaches blind children and teenagers usage of the white cane and additional skills and navigation tools. We were greeted by a teacher, who is herself fully blind, and a caretaker. Because of their jobs in the educational center for VIPs and personal experience, both the teacher and the caretaker can be considered experts in VIP navigation and tools for supporting bling navigation. We presented them an early version of our continuous guidance stimulus (see section 5.1), implemented on a Google project Tango device (Lenovo Phab 2 Pro). This version of the guidance system had the advantage of being mobile, but the tracking system was very slow (5 fps), and it did not yet include any static patterns (e.g., stairs down). Despite the advantage of offering fully mobile guidance, this prototype system was not published, as we deemed it was not safe enough due to the somewhat inaccurate and slow obstacle tracking provided by the Lenovo Phab 2 Pro.

We demonstrated the system to the blind teacher by navigating her successfully around a corridor and through doors while the caretaker supervised the experiment. We then conducted an informal interview with both the teacher and the caretaker and asked how they would improve the system and what other information VIPs would need to navigate, potentially without a white cane. Through our conversation, we came up with the four navigational instructions that were deemed necessary by the teacher and the caretaker. Apart from the general direction, the following four navigation instructions: GO / START, STOP, UP, and DOWN. The START instruction indicates that the user should start following navigation instructions. The general directional guidance may then be used to navigate around obstacles on a safe path. Elevation changes (e.g., single sidewalk steps or stairs) can be indicated by the UP and DOWN instructions, and the STOP instruction may be used in potentially dangerous situations, if the user diverges too far from the safe path, or has to wait for other reasons (e.g., at a streetlight). Thus, these four identified navigation instructions can be used in all kinds of micro-navigation scenarios alongside general directional guidance.

4.2 Elicitation Study: Designing the Initial Tactile Patterns

In a pre-experiment, two of the authors iteratively designed a total of 16 spatial vibrotactile patterns for the head. The design rationale for these tactile patterns was defined by our experiences in prior work [29], where we conducted experiments exploring tactile patterns for general use cases on the head. We found that (a) stimulus location was significantly more straightforward to identify than pattern rhythm or intensity and (b) static patterns with a static stimulus location were easier to identify yet more uncomfortable than static patterns with dynamic stimulus locations. Thus, we chose strong static patterns with static stimulus locations for the navigational instruction STOP as we wanted these patterns to be clearly recognizable and feel very strong and uncomfortable. For the other navigational instructions, we chose static patterns with dynamic stimulus locations as we wanted these to feel comfortable yet intuitive and recognizable through their movement over extended areas of the head (e.g., a movement from the chin over the sides of the head to the top for the UP navigational instruction).

We created many more patterns than needed to represent the required instructions and then discarded those that we could not identify correctly. Through this pre-experiment, we singled out four patterns for each of the instructions above (START, STOP, UP, and DOWN), which we assumed to intuitively represent those instructions (4 instructions $\times$ 4 patterns per instruction = 16 patterns). To find the best four possible patterns, we conducted a short study with 11 participants (9 male, 2 female, mean age 28.2, standard deviation 10.2 years). Even though all participants had normal vision, this is no confound as it did not help them solve the task.

For this short user study on the patterns' intuitive meaning, we implemented a simple Android application running on a Lenovo Phab 2 Pro device. This application can play predefined spatial tactile patterns around the head by sending actuator control commands to the Raspberry Pi 3. For this study, we implemented a mode to play a random pattern (no repetition allowed) and then asked the participant for that pattern's meaning. The participant could answer by pressing one of four buttons (START, STOP, UP, and DOWN). The choice was forced as there was no neutral button. During the study, participants did not receive any feedback about whether their intuition for the pattern meaning was correct. Each of the 16 possible patterns was repeated 10 times. The patterns were randomly shuffled (seeded by participant id) to counterbalance possible learning effects. There was no training phase. Participants were unaware of which specific patterns were in the set of possible patterns and also unaware of how many different patterns there were in total. The whole study, including filling out questionnaires, took around 45 minutes per participant.

As a result of this first user study, every pattern, except for one, scored more than 50 % accuracy, so our initial iterative design approach for finding intuitive patterns did yield acceptable results. The best patterns scored accuracy scores of 69 % for START, 84 % for STOP, 94 % for UP, and 83 % for DOWN. After the study, we optimized the winning patterns by adding a 100 ms directional stimulus after the initial patterns (for all but STOP), based on user feedback and our experiences. The optimized patterns are defined below (see also Fig. 3):

- START – starting at the back of the head, simultaneously moving across both sides and ending at the forehead. Signal 800 ms + pause 300 ms + signal 800 ms + pause 100 ms + direction signal 100 ms.

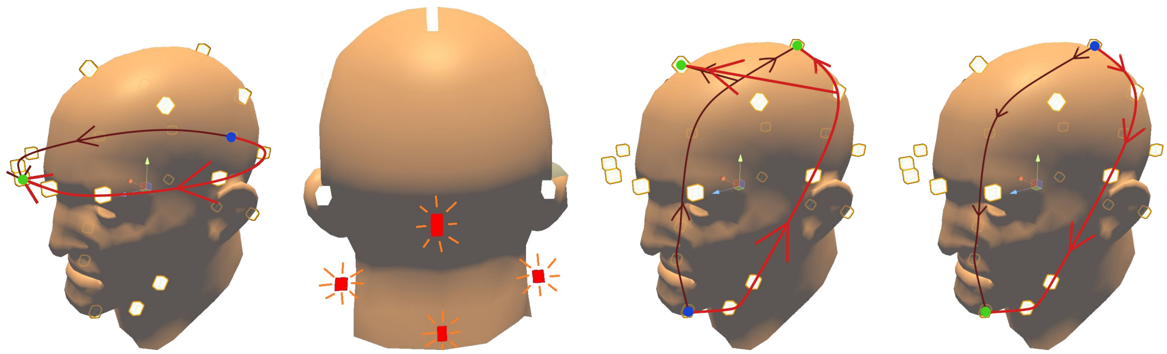


Fig. 3. Visualization of patterns. Blue: start of pattern; green: end of pattern. The UP pattern uses two actuators as end points, because the top of the head is less sensitive to tactile stimuli [30, 40] and needs a stronger tactile impulse to emphasize the direction at the end of the pattern.

- STOP – all actuators at the back of the head at the same time. Signal 100 ms + pause 150 ms + signal 100 ms + pause 150 ms + signal 100 ms.
- UP – starting at the chin, simultaneously moving up on both sides and ending at the top of the head. Signal 800 ms + pause 300 ms + signal 800 ms + pause 100 ms + direction signal 100 ms.
- DOWN – like UP but starting at the top of the head and ending at the chin.

We hypothesized that if people receive minimal training on these four patterns, a recognition rate of close to 100 % can be achieved. This hypothesis was tested in a second short user study.

4.3 Pattern Recognition Performance Study

For the pattern recognition performance follow-up study, we invited 10 participants (9 male, 1 female, mean age 24.3, standard deviation 2.8 years) with normal or corrected to normal vision, which again did not help them solve the task. Compared to the prior study, we introduced a 5 minute training phase with visual feedback on correctness before the study's test part began, which was identical to the first study (no feedback on correctness). We logged recognition rates for both the training and the test part.

The results showed a nearly perfect recognition of the optimized patterns. Overall, 391 of 400 trials or 97.8 % in the training part and 397 of 400 trials or 99.3 % in the test part were successful. One participant had some difficulties understanding the experimental task due to language barriers and scored a little lower than the other participants. This participant failed 8 trials (20 %) at the beginning of the training part before we intervened and explained the task again, and another two (5 %) in the study part.

Fig. 4 shows the subjective results of the post-questionnaire. Participants strongly agreed that they could easily and intuitively recognize the four tactile patterns and had no trouble memorizing them. Furthermore, most of them did not feel the feedback to be disruptive and would even trust their ability to recognize the meanings of those patterns in low-visibility situations correctly.

The recognition results of the pattern recognition performance study are close to perfect, just like we expected. We did not expect the results in the initial training part to be that good, however. These results lead to the conclusion that these four new, slightly modified patterns were more intuitive than the winning patterns in the prior study. Only a single participant (P8) failed more than one trial due to language barriers. Together with the

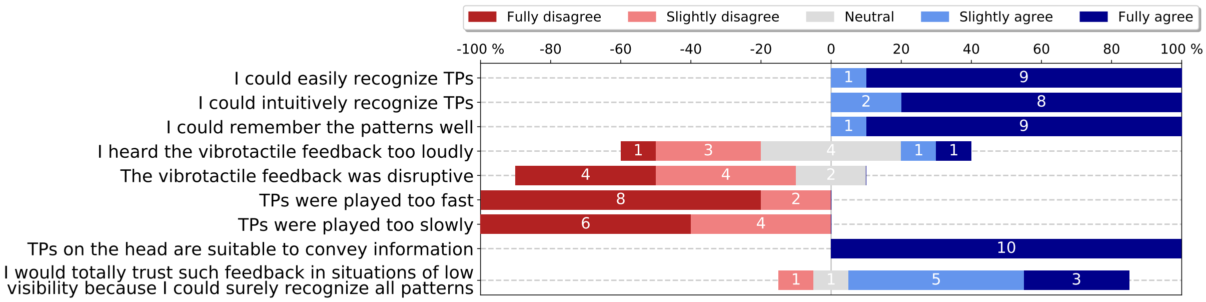


Fig. 4. Results of the post-questionnaire of the Pattern Recognition Performance Study about the suitability of the chosen four tactile patterns (TPs) for conveying the four instructions (N = 10).

encouraging subjective results – participants stated that they could easily recognize these patterns – we believe these patterns may be used in mission-critical applications, such as VIP guidance near traffic lights or stairs after a brief familiarization step.

These results provide the basis for the implementation of our micro-navigation system. We use the developed patterns in conjunction with a continuous tactile navigation pattern for VIP guidance in the implemented system. This combination poses the particular challenge of how to interleave the continuous directional tactile guidance signal and the specific command patterns.

5 IMPLEMENTING THE MICRO-NAVIGATION SYSTEM

When we first started experimenting with micro-navigation, we noticed that playing a STOP pattern every time the user diverges a little too far from the optimal path is disturbing, as the pattern is very strong and meant to convey immediate danger. We felt the need for an instruction to focus back on the navigation task once the user diverges too much, but non-critically, from the optimal path. A friendly reminder to focus is needed, as users in our preliminary tests were often distracted by random thoughts, noises, or talking while navigating.

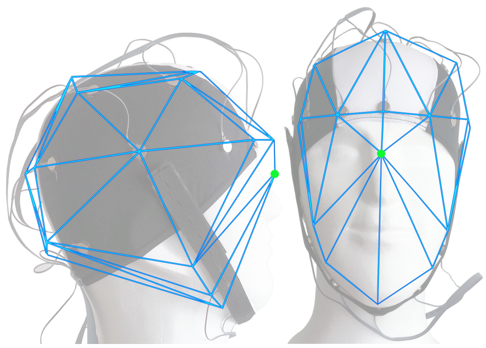
In addition to the four patterns that resulted from the previous studies, we introduced an additional ATTENTION pattern as a reminder for the user to focus. It is identical to the STOP pattern but without repetitions. The ATTENTION pattern is used when a participant deviates too far from the route or gets close to an obstacle (other than the stairs). On the other hand, the STOP pattern is used when the participant deviates too much from the path and needs to realign while stopping. Moreover, the STOP pattern is used before playing the UP or DOWN patterns, so the participant stops and recognizes the pattern before climbing stairs.

We combined our patterns with a continuous tactile navigation stimulus that indicates the next waypoint's direction while no other pattern is active. The following patterns were implemented in the first version of our micro-navigation system in addition to the patterns validated in the Pattern Recognition Performance Study, also visualized in Fig. 3:

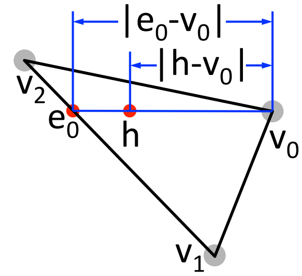
- ATTENTION – same as the STOP pattern in the Pattern Recognition Performance Study but without repetitions.
- CONTINUOUS-GUIDANCE – while no other pattern is active, actuate the three actuators closest to the next waypoint to guide towards the next waypoint. Details are given in the next subsection.

Because related work has shown that the number of simultaneously active actuators should low to avoid confusion [15], we decided only to present one pattern at a time, while prioritizing some patterns over others in case the system needed to playback multiple patterns at the same time (e.g., in front of the stairs if the participant was moving fast). The STOP pattern had the highest priority and could thus overwrite (and push back) any other pattern, followed by the UP/DOWN and the ATTENTION patterns. The CONTINUOUS-GUIDANCE pattern had the lowest priority and was only active while no other pattern was being played back at the time.

5.1 Continuous Guidance Stimulus



(a) Side and front view of modeled actuator positions. Does not fit perfectly due to the size and asymmetries of the Styrofoam head. The guidance algorithm uses triangles between actuators, including a virtual point zero (green) between the eyes.



(b) Actuator intensity calculation for tactile stimulus interpolation.

Fig. 5. Continuous guidance tactile stimulus: Actuator positions and intensity interpolation algorithm.

This section gives an overview of the continuous guidance stimulus and interpolation approach of [28]. For the guidance algorithm, we defined a virtual point zero (VPZ) precisely between the eyes of the user (see Fig. 5a). We then tessellated the actuator space by placing triangles between each triple of adjacent actuators (including the VPZ) without overlaps, as shown in Fig. 5a. A ray between the center of the head and the guidance target (the next waypoint) intersects exactly one triangle t of the tessellation in a hit point h. Triangle t is defined by its adjacent actuators (v_0, v_1, v_2). Let point e_i be the intersection of a line through v_i and h and a line through $v_{(i+1)mod3}$ and $v_{(i+2)mod3}$, the other two actuator positions (mod is the modulo operation). The intensities (0 to 1) of the three actuators are then calculated as:

$$intensity(v_i) = 1 - \frac{|h - v_i|}{|e_i - v_i|}$$

Special case: If the VPZ is part of the intersected triangle, the intensity of the remaining two actuators is amplified to give the user a sense of direction on the ring around his face, meaning the actuators on the forehead and chin. The user is then drawn slightly more in the indicated direction by actuating only the two actuators closest to the target. Practically, users should try to keep the vibration stimulus on the forehead between the eyes as precisely as possible, as this means that they stay on the optimal path. In case the signal travels, e.g., to the right, this means that the participant has to turn a bit towards the right. In case the signal travels to the chin, this usually means that the participant needs to re-adjust his head to keep it straight.

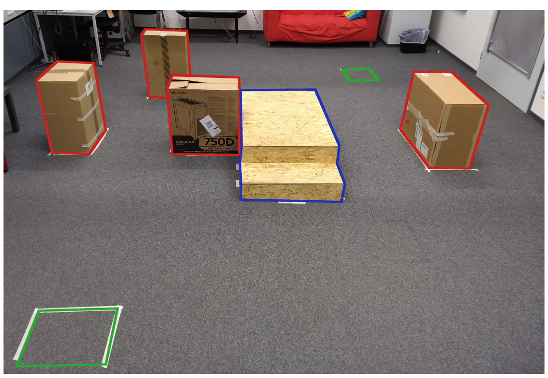
We used this interpolation approach because prior work [28] has shown it to be fast and accurate for precisely locating targets around the user's head and, therefore, orienting the head and body in space.

6 OBSTACLE COURSE EXPERIMENT

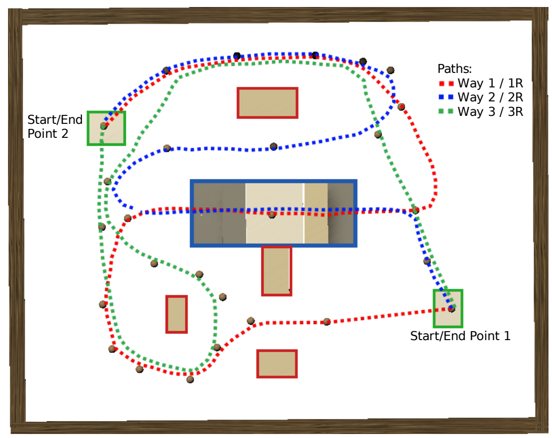
To test the designed micro-navigation system in a realistic environment, we designed an obstacle course and invited 15 participants (11 male, 4 female, mean age 28.3, standard deviation 9.7 years; range 19-57 years) for the experiment. Of those 15 participants, 2 had a severe limitation of sight with 0 % and 2 % vision, respectively. To ensure that these two participants did not use their remaining sight, they also wore blindfolds. The two VIP participants were a couple who were in the experiment room together, doing the experiment one at a time. The other participants did the experiment alone. This is a confound in the experiment as the two VIP participants kept talking to each other and the experimenters and thus were less concentrated on the task at hand. We felt that it would have been inappropriate to separate them for the experiment as they would likely have felt uneasy about being alone. Another confound is that the two VIP participants were older (45 and 57 years) than the other participants.

In the sections below, the participants with normal vision are called "sighted participants" while the VIP participants are called "blind participants." All of the participants wore blindfolds.

6.1 Obstacle Course Experiment – Design and Implementation



(a) The actual obstacle course with highlighted obstacles.



(b) The obstacle course modeled in Unity including the different paths. Spheres represent the waypoints.

Fig. 6. Photo and model of obstacle course. Color coding: green – start/end zones; red – obstacle; blue – stairs.

To test our navigation approach, an obstacle course (see Fig. 6) was created with cardboard boxes and a specially constructed wooden platform. The platform consisted of plywood and was planned and built in accordance with the German DIN 18065 [13]. The norm limits the ascent to 14-20 cm, the tread to 23-37 cm, and the platform's width to at least 80 cm. These limits are mandatory for essential stairs in residential buildings. The platform consists of a step on each side (ascent: 17 cm; tread: 29 cm) and an 80 cm wide level on top (Fig. 7).

Specifically for this study, we also implemented a simple path-finding system where paths through the obstacle course were hard-coded as a set of waypoints. The next waypoint in a path was selected once the participant was within a 10 cm range of the current waypoint. The participant's orientation was determined by an OptiTrack [43] head tracker. Simultaneously, the body position was determined by the average position of two shoulder-trackers instead of the head position as the head may move around too much, which may cause the signal to change rapidly, causing confusion. OptiTrack reported an accuracy of better than 1 mm.

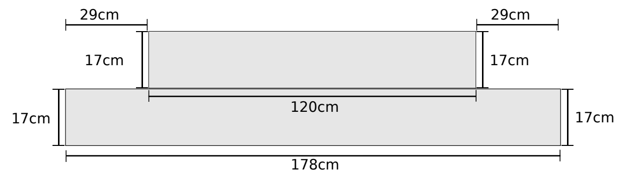


Fig. 7. Model of the staircase with measurements. Top view in center of Fig. 6b. The stairs are 80 cm wide.

6.2 Obstacle Course Experiment – Procedure

Fig. 8. Participant climbing the stairs while being accompanied by one of the experimenters for safety reasons.

After a short greeting, the participants were asked to fill out an introductory questionnaire, a mandatory informed consent form, and optionally a photographic release form. Then they were introduced to the HapticHead prototype. After that, the HapticHead was adjusted to fit over the balaclava that participants wore for hygienic purposes. A vest with additional shoulder trackers was fitted, and two more trackers were attached to the participant's shoes with painter's tape. Lastly, the participants were blindfolded.

The blindfolded participant was then guided into the experiment room with the obstacle course. At the first starting position (see Fig. 6b), the five static patterns were played once and explained to the participants. Following the pattern introduction, the OptiTrack tracking markers for the HapticHead were attached and roughly calibrated into the correct orientation by asking the participant to turn around until they felt a stimulus precisely between the eyes.

After testing whether the participants remember the static patterns correctly, the patterns were either explained again, or the experiment was started. In 24 runs, the participants were guided on all six routes (three paths, in both directions, Fig. 6b) four times in random order (participant number as seed). If the starting point of the following path was different from the endpoint of the last path, the participants were guided on a randomly chosen route through the obstacle course by the experimenter. At least one attendant was walking next to the participants at all times to prevent any injuries from possible falls (see Fig. 8).

In case the tracking system failed (lost tracking for more than 1 s), we repeated a trial. This happened a total of 12 times. A post-study questionnaire gathered further subjective data on the performance of the prototype. The whole study, including setup and questionnaires, took about one hour per participant.

6.3 Obstacle Course Experiment – Results

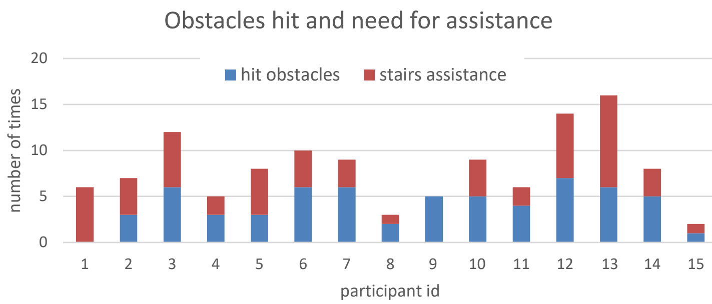


Fig. 9. Number of times participants needed assistance when on the stairs and number of obstacles hit (including participants just brushing the obstacles with their clothes). Participants 12 and 13 are VIPs, the others are sighted, but all of them were blindfolded. There were 24 runs per participant, and there could be multiple hits or needs for assistance in a single run.

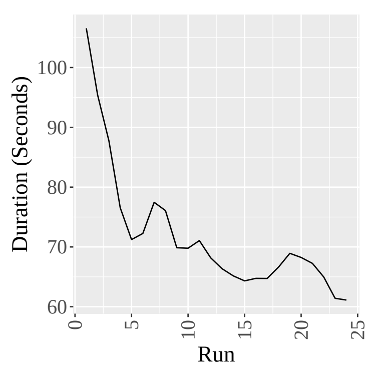


Fig. 10. Mean time needed per run (across all participants). The means are smoothed by a weighted moving average with a window size of 3. The weights are 0.25, 0.50, and 0.25.

For all runs, we counted every time a participant touched an obstacle or needed assistance. We were conservative in counting obstacle hits. Even just brushing the side of an obstacle with their clothing was counted as an obstacle hit. Being too close to the staircase's borders (shoe rim on or over the side-ledge of the staircase) was counted as needing assistance on the stairs as we did not want to risk participants falling.

The results are shown in Fig. 9, where they are graphically presented for sighted and blind participants in addition to the overall data. In 33.6 % of all runs, an obstacle was hit, or assistance was needed. Of those, 17.4 % were obstacle hits, and 16.2 % were assistance needed while using the stairs.

Our blind participants hit an obstacle on 27.7% of their runs while needing assistance on the stairs or re-positioning in 36.2 % of all runs. In contrast, the sighted participants hit an obstacle on 15.8 % of all runs on

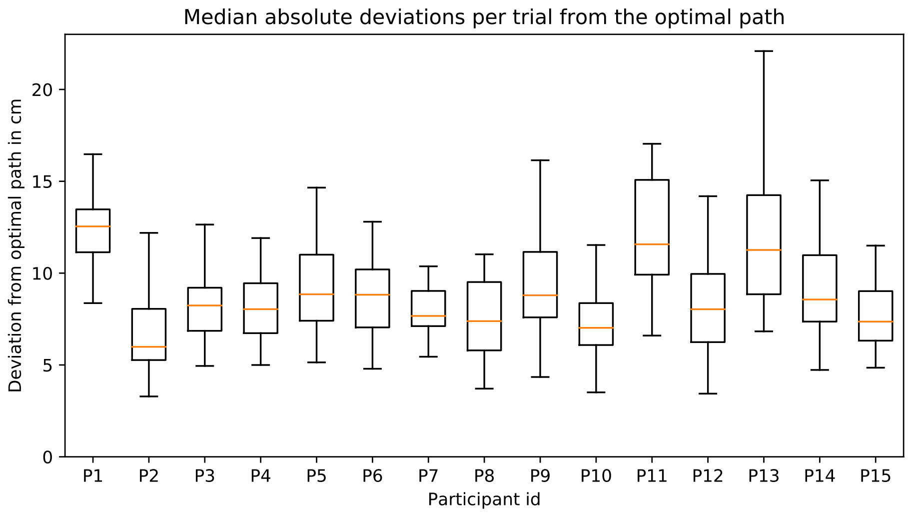


Fig. 11. Boxplots showing the median absolute deviations of each participant from the optimal path for all trials. Participants 12 and 13 are VIPs.

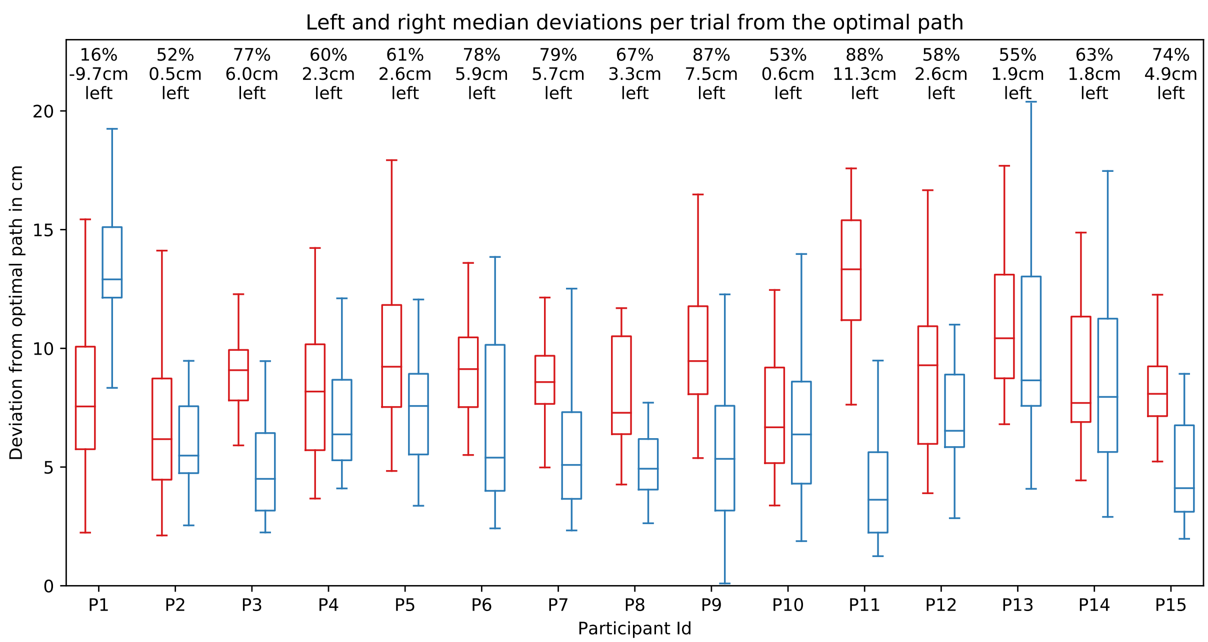


Fig. 12. The median (left=red, right=blue) deviation per trial for all participants (N=15). The numbers above the boxplots show the percentage of time a participant spent on the left of the optimal path and the average deviation to the left. Ideally, these numbers should be 50% and 0 cm; deviations from them indicate a systematic error. Participants 12 and 13 are VIPs.

average while needing assistance with the stairs in 13.2 % of the cases, totaling 29 %. Of course, these results cannot be generalized to the blind population as we only had two blind participants in our experiment.

An additional measurement was the duration of every run. Fig. 10 shows that the average duration in each case reduces with the number of runs, indicating a learning effect. Across all participants, the average run duration starts at 103 s for the first run and reduces to 61 s for the last run, which amounts to a decrease of 41 %.

Furthermore, the deviation from the predefined optimal path was measured overall and for left and right deviations (see Figures 11 and 12). We found an overall average absolute deviation to the optimal path of 9.3 cm (SD=2.0 cm) across all participants. The group of blindfolded participants with normal vision scored an average deviation to the optimal path of 9.0 cm (SD=1.8 cm), while the group of the two blind participants scored a marginally higher average deviation to the optimal path of 11.1 cm (SD=2.5 cm).

6.4 Obstacle Course Experiment – Subjective Results

During the study, we asked the participants whether they had a sense of where they were in the obstacle course and how many paths they thought there were during trials while they were not at risk of bumping into an obstacle. We were interested in whether participants were able to create a mental map of the obstacle course. While they figured out that there was only one staircase with two steps after around half the study was done, not even the VIP participants could tell how many paths or obstacles there were.

The evaluation of the post-study questionnaire is shown in Fig. 13. All 15 participants were pleased with the navigation method they had experienced. Furthermore, 12 of all 15 felt safe while being navigated through the obstacle course. Fourteen of the fifteen participants stated that the way of navigating was intuitive. Even stair recognition was deemed easy by 13 participants, while 10 participants stated that climbing stairs with the given tactile support was easier than climbing stairs without support. Lastly, all participants judged the vibration feedback placement as appropriate and the patterns themselves as not disruptive. Overall, 93 % of the participants stated that they would use this tactile navigation method in everyday life if integrated into a beanie.

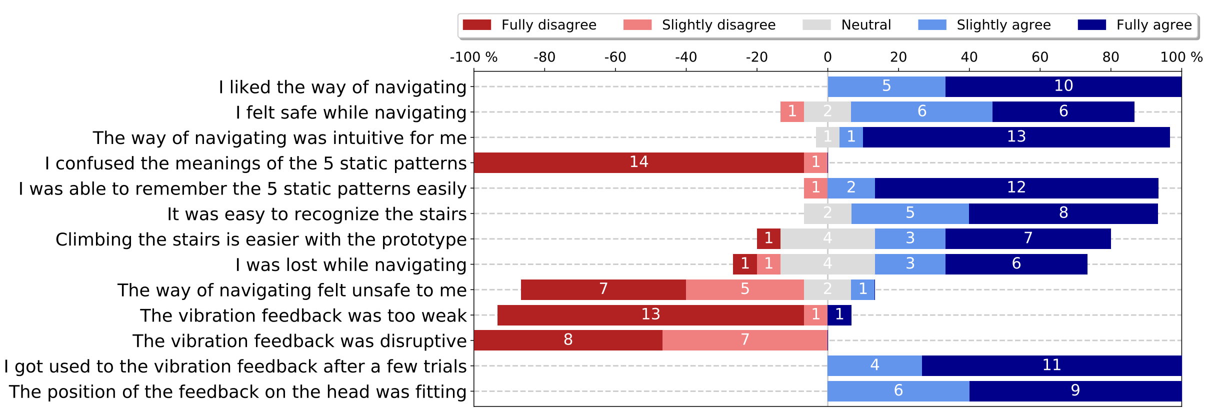


Fig. 13. Subjective results of the post-study questionnaire.

Sighted participants. All 13 of our sighted participants liked the way of navigating, with 10 of those feeling safe while doing so. For 12 participants, the navigation was intuitive and the patterns easy to remember, while all 13 stated that they did not confuse the meaning of the five static patterns. 11 of 13 participants stated that it was easy to recognize the stairs, with only eight claiming ease of use for stair climbing. Nevertheless, 12 of 13 participants (92.3%) expressed an interest in using a system like HapticHead if integrated into a beanie.

Blind participants. For the blind participants taking part in the study, the ratings were predominantly positive. The way of navigating was experienced as pleasing, the navigation was perceived as safe, and the usage seemed intuitive. The stair recognition and climbing were judged as easy. Additionally, the blind participants got used to the vibration feedback after a few trials, and the vibration motors did not feel disruptive to them. Both blind participants stated that they would use a system like HapticHead integrated into a beanie and were quite excited about the prospect.

6.5 Obstacle Course Experiment – Discussion

The above results suggest that our system worked rather well as a guidance method in unknown environments. While the users felt safe and were pleased with navigating, the vibration feedback was not too strong or disruptive. It was rated as unobtrusive, which surprised us, especially since both our blind participants specifically stated that the vibration noise on the head did not bother them at all. We expected them to complain about the noise, as their sense of hearing is usually one of their primary senses to navigate an unknown environment. We were also surprised at how safe our users rated the system, given the number of times obstacles were hit. This is likely because we were rather inclusive on what to count as an obstacle hit. Furthermore, the obstacles were quite close together (smallest gap: 71 cm), so a slight deviation from the path already led to an obstacle hit.

We did not have any incident of a participant falling, and the most dangerous situations arose when participants got too fast and hit the lower part of the stairs with their feet before reacting to the STOP pattern. This aspect could be improved by implementing the system to consider the current movement speed and play the vibration patterns earlier if users get too fast.

The graphs in Fig. 10 imply a learning effect: On average, the run's duration decreases with practice. This was not a result of learning a path, as almost all participants stated that they felt completely lost and did not know where they were or even how many paths there were.

While blind participant 1 (P12) walked unhurried, blind participant 2 (P13) nearly jogged through the obstacle course. Except for the unhurried pace, blind participant 1 was not as careful while walking and hit seven obstacles. Most obstacle hits of blind participant 1 occurred because of talking while moving. We suppose that the attention faded from the navigation task. Blind participant 2 only hit six obstacles but needed regular assistance on the stairs because of the walking curve's large radius. With the increased walking speed in the small obstacle course, sharp turns would have been necessary to stay on the optimal path but were rarely done. Therefore, the participant often walked into different directions and diverged from the path, not responding fast enough to the tactile guidance signal changes. The measurements clearly show this increased deviation: See P13 in Fig. 11.

The increased curve radius is an effect that was observable for most participants after getting used to the prototype, feeling safe, and starting to walk faster. With the reduced run-duration, the effect of increased walking speed dominates, meaning that users with more training will take bigger steps and widen their curves. Consequently, problems occurred with our prototype's software at specific bottlenecks of the path, like the stairs' starting point. The participants often stood on the very edge of the first step on the stairs because their wide curve from the last navigation point led them outwards. While climbing the stairs, sometimes no directional feedback was offered due to the relatively long durations of the static patterns and to keep the number of currently active signals to one, both for static or dynamic patterns. On top of the platform, the continuous guidance pattern was activated again, and the participants corrected their alignment back into the middle of the path. We improve this aspect of the prototype in the Improved System Validation Experiment by reducing the static patterns' playback time to give continuous guidance feedback in between the other patterns while climbing the stairs.

Fig. 12 shows the median left and right deviations from the optimal path for all participants. Ideally, the participants should diverge as much to the left as to the right while wobbling around the optimal path with each step. However, we did expect a systematic error here consisting of (a) tracker placement errors on the HapticHead,

(b) HapticHead placement errors on the participant's forehead, and (c) the individual participant's feeling of where the frontal vibration direction actually is as this does not necessarily have to be exactly between the eyes on the forehead. Since we are aware of and can quantify the systematic error in this experiment, we can consider it in the conclusions drawn. Almost all of the participants experienced a systematic error to the left except for P1. While we do not have an explanation for this phenomenon, the average absolute systematic error for this experiment is still rather low at an average of 4.4 cm (SD=3.2 cm) across all participants. This systematic error could be reduced by performing a more sophisticated per-participant calibration in future experiments. On the other hand, reducing this systematic error would also mean that the experiment would be less realistic as users in the real world would likely not want to perform a calibration step each time they put on their navigation aid.

Fig. 11 shows the median absolute deviations of each participant from the optimal path for all trials. Our participants tended to deviate an average of 9.3 cm from the optimal path. In light of the systematic directional error discussed above, which also influences the absolute deviation, the absolute deviation from the optimal path still seems relatively low. It may be further lowered by improving the guidance algorithm, e.g., by taking into account the current participant speed rather than directing to the next waypoint once within 10 cm of the current waypoint. Compared to related work by Flores et al. [16], our average deviation from the optimal path was already significantly lower in this experiment (9.3 cm vs. 49 cm).

Our OptiTrack tracking system turned out to be not as resilient as expected. The foot tracking precision was significantly reduced in the corners of the course, primarily due to limitations of the OptiTrack [43] camera perspective and masking by obstacles. This limited the obstacle detection in front of the feet because the feet' virtual representation may point in a different direction shortly before an obstacle was hit. Furthermore, the trackers were sometimes confused with each other even though we made sure they were configured correctly.

7 STATIC PATTERNS REFINEMENT STUDY

This study is concerned with evaluating further improvements of the static patterns. While the static patterns were generated in an iterative process, we still felt the need to optimize these further as the total playtime, especially for the START, UP, and DOWN patterns was too long and sometimes led to the system playing just static patterns (e.g., on the stairs) without letting the participant know the correct direction by playing the dynamic guidance pattern. Furthermore, we saw room for improving the guidance algorithm in terms of collision prevention performance (e.g., steer users depending on current speed, steer towards the inside of a curve).

In order to optimize the static patterns, we took the following measures:

- We decided to omit the START pattern altogether as it is pretty obvious the system is guiding the user while the dynamic guidance pattern or any of the static patterns is currently on.
- We decided that the two repetitions of the UP and DOWN patterns took too much time, and thus we only play the pattern once instead of twice now.
- As related work shows that the localization precision and perceived stimulation strength is worse on the top of the head compared to the center of the chin [30, 40], we included two more actuators to represent the "top of the head" for both, UP and DOWN patterns and let that part of the pattern run for 20 % longer for the UP pattern.
- We further worked on the UP and DOWN patterns so that the feeling of something moving up or down the head feels smoother than before.
- We worked on distinguishing the STOP and ATTENTION patterns more clearly by adding another seven full intensity actuators to the STOP pattern so that the resulting actuation is perceived as much stronger than the ATTENTION pattern.

7.1 Static Patterns Refinement Study – Implementation

We implemented the four static patterns as follows:

- ATTENTION – 4 actuators at the back of the head at the same time. Signal 100 ms.
- STOP – 11 total actuators (7 in the front and 4 in the back of the head) at the same time. Signal 100 ms + pause 50 ms + signal 100 ms + pause 50 ms + signal 100 ms (total 400 ms).
- UP – starting at the chin, simultaneously moving up on both sides and ending at the top of the head. Signal 800 ms + pause 100 ms + direction signal (four actuators on the top of the head) 250 ms (total 1150 ms).
- DOWN – starting at the top of the head, simultaneously moving down on both sides and ending at the chin. Signal 800 ms + pause 100 ms + direction signal (single center actuator on the chin) 250 ms (total 1150 ms).

With these improvements implemented, we had to re-validate these patterns for their intuitiveness and recognition accuracy. We also decided to test different pattern playback durations in the same study as we still felt the patterns were too long. Even without UP and DOWN's repetitions, we wanted to test how fast we could play these patterns without loosing intuitiveness and recognition accuracy. Thus, we defined five different duration factor conditions: 0.4, 0.5, 0.6, 0.75 and 1.0, where 1.0 represents patterns as defined above. We modified the Android app that was used in the Pattern Recognition Performance Study in the following ways:

- In addition to STOP, ATTENTION, UP, and DOWN, a fifth option was given so that participants could indicate that they were unsure.
- In the first half of the trials, we did not give participants feedback on whether their guess was correct, while in the second half of the trials, participants received visual feedback on the correctness of their guess. The visual feedback was implemented as an additional view indicating CORRECT or FALSE with the correct pattern after choosing. This design allows assessing the patterns' intuitiveness and how well participants can learn the patterns with feedback training in the second half of the study. However, we do not expect perfect accuracy in the second half, as the feedback was only provided *after* selecting an answer.
- Thus, the participants experienced (in randomized order within the feedback condition):
  4 patterns (ATTENTION, STOP, UP, DOWN)
  $\times$ 5 duration factors (0.4, 0.5, 0.6, 0.75, 1.0)
  $\times$ 5 repetitions per pattern
  $\times$ 2 feedback conditions (no feedback, visual feedback)
  = 200 trials per participant.

7.2 Static Patterns Refinement Study – Procedure

The procedure of this study is very similar to the Elicitation Study and the Pattern Recognition Performance Study. After a short greeting and filling out an introductory questionnaire, the participants were handed a Galaxy S8 with the aforementioned Android app and started the trials. Each trial consisted of the participant feeling a particular pattern, then a choice between "attention," "stop," "up," "down," "not sure," and "repeat." After their choice and only in the second part of the study (trials 101-200), the participants got visual feedback on whether they were correct or not.

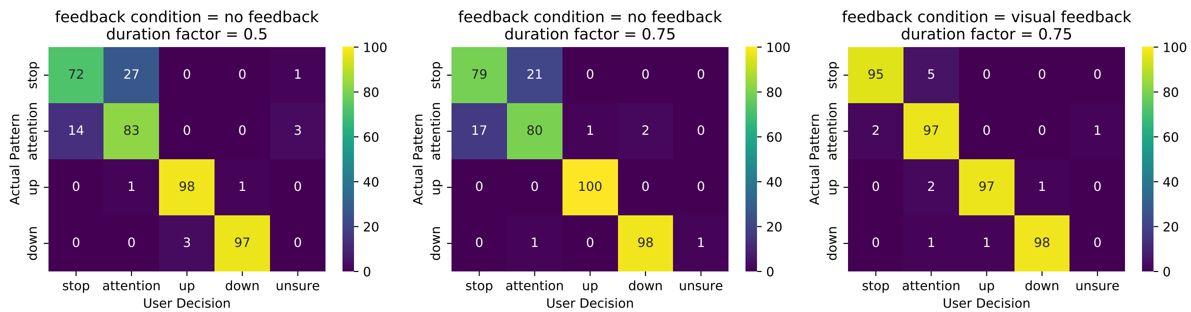
The repeat option was added as we planned to conduct the study in a crowded computer room with other students, so some distractions were inevitable and desired to create a more realistic environment and increase external validity. If a participant was distracted at a particular trial, they had the option to repeat the pattern.

Finally, the participants filled out another questionnaire on their experience and were compensated with a bar of chocolate. The entire study, including filling out questionnaires, took around 15 minutes per participant.

7.3 Static Patterns Refinement Study – Participants

We invited 20 participants (19 male, 1 female, mean age 21.5 y, SD = 3.4 y) for this study, which took around 15 minutes on average, including the questionnaires. None of the participants took part in the prior experiments.

7.4 Results



(a) No feedback, duration factor 0.5 (b) No feedback, duration factor 0.75 (c) Visual feedback, duration factor 0.75

Fig. 14. Confusion matrices of the most interesting results from the Static Patterns Refinement Study. Cell values are absolute with $N = 100$ per row.

The participants had the option of repeating a pattern before deciding on its meaning if they were distracted. Patterns were repeated in 9.1 % of the cases. In these repetition cases, a pattern was repeated 1.3 times on average.

We generated 10 confusion matrices out of the 2 feedback conditions and 5 duration factors. Fig. 14 shows confusion matrices for the best-scoring combinations of feedback conditions and duration factors. The numbers in the confusion matrices are absolute ($N = 100$ for each row of the matrix).

In terms of intuitiveness (no-feedback condition), the UP and DOWN patterns scored high accuracies of 98 % and 97 % at a duration factor of 0.5 and do not improve by much at duration factors higher than 0.5 (see Fig. 14a). Even at a duration factor of 0.4, UP and DOWN's accuracies are still rather high at 98 % and 91 %. HOWEVER, the STOP and ATTENTION patterns were mixed up quite often with intuitiveness accuracies of only 72 % and 83 % (Fig. 14a). This improves to 79 % and 80 % at a duration factor of 0.75 (Fig. 14b). In the feedback condition (while receiving visual feedback), the STOP and ATTENTION patterns improve to 95 % and 97 % at most with a duration factor of 0.75 (Fig. 14c).

7.5 Static Patterns Refinement Study – Discussion

The STOP and ATTENTION patterns received mixed intuitiveness results of around 80 % correctness. We estimate this is due to the feeling of urgency of, e.g., an ATTENTION pattern with a duration factor of 1.0, which can be similar to a STOP pattern with a duration factor of 0.4 as this translates into one 100 ms actuation vs. three short actuations of 40 ms each (total actuation time 120ms). The reader should keep in mind that with the five different duration factors, we were essentially testing 20 different patterns for four different meanings, leaving more room for error for the participants compared to the Elicitation Study (16 patterns, no training) and the Pattern Recognition Performance Study (4 patterns, training, and evaluation phase, close to perfect accuracies). Therefore, the patterns are not as counter-intuitive as they seem, but this is instead caused by this study's design with different duration factors. Thus, if we were to repeat this study with a set duration factor of 0.75, we would likely get much better results for STOP (total actuation time 225 ms) and ATTENTION (total actuation time 75 ms), as they would differ more clearly.

Even an intuitiveness result of around 80 % is sufficient, especially if participants receive a short training period *before* using these patterns (Fig. 14c, shows results *while* conducting training). With these results in mind, we set the final patterns to be used in the Improved System Validation Experiment as follows:

- ATTENTION – 4 actuators at the back of the head at the same time. Signal 75 ms.
- STOP – 11 total actuators (7 in the front and 4 in the back of the head) at the same time. Signal 75 ms + pause 37.5 ms + signal 75 ms + pause 37.5 ms + signal 75 ms (total 300 ms).
- UP – starting at the chin, simultaneously moving up on both sides and ending at the top of the head. Signal 400 ms + pause 50 ms + direction signal (four actuators on the top of the head) 125 ms (total 575 ms).
- DOWN – starting at the top of the head, simultaneously moving down on both sides and ending at the chin. Signal 400 ms + pause 50 ms + direction signal (single center actuator on the chin) 125 ms (total 575 ms).

In conclusion, these patterns are much shorter than those found in the Elicitation Study and used in the Obstacle Course Experiment while offering comparable recognition performance and are thus a better fit for real-time micro-navigation.

8 IMPROVED SYSTEM VALIDATION EXPERIMENT WITH VIPS

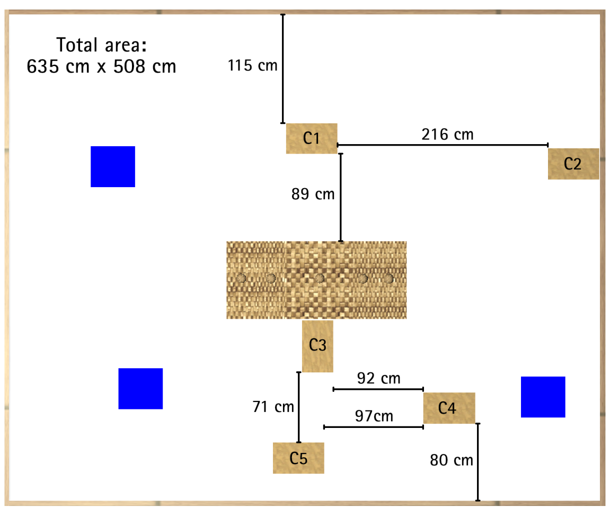
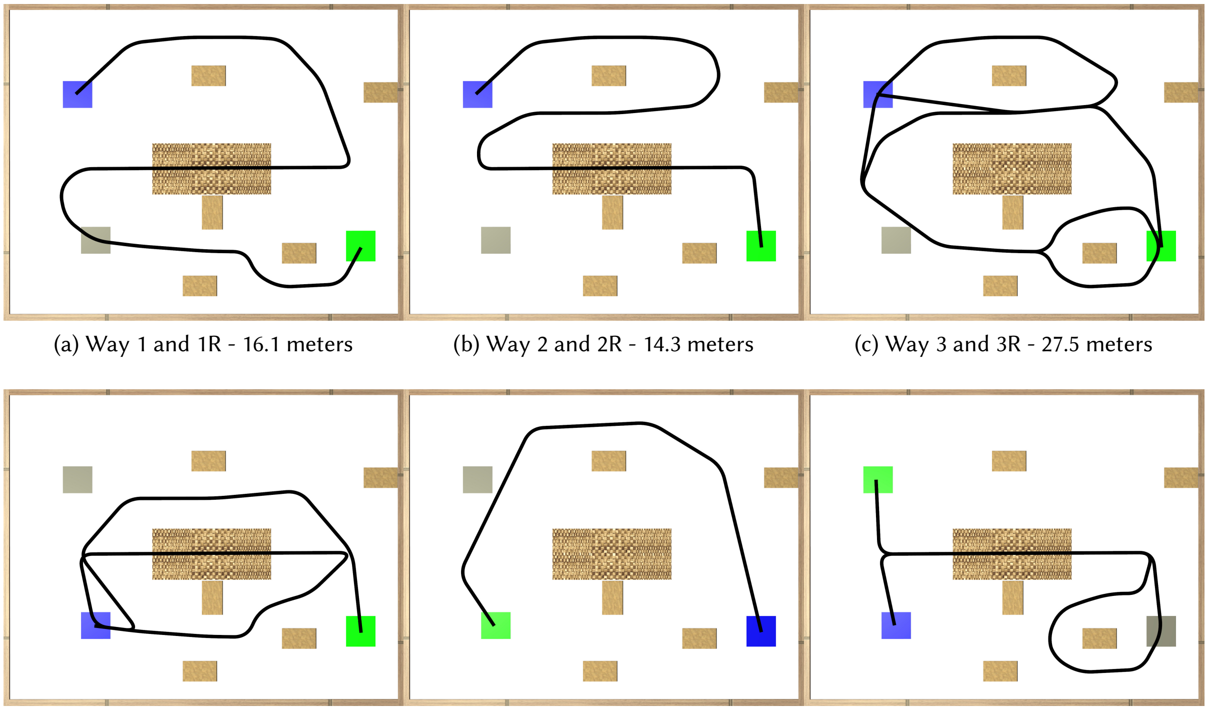


Fig. 15. Top view of the obstacle course for the Improved System Validation Experiment, including dimensions. Cardboard obstacle (C1-C5) dimensions are 53.5 cm×33 cm (height 61.5 cm). Starting and ending zones are marked in blue. The dimensions of the stairs are given in Fig. 7.

Since the Obstacle Course Experiment only included two VIPs, we still had to validate our system with a larger number of VIPs. Thus, this experiment has a very similar setup as the Obstacle Course Experiment. However, we improved the implementation in various regards, added more possible paths through the obstacle course, and slightly altered the obstacle course to include an additional obstacle and an additional starting point (see Fig. 15).



(a) Way 1 and 1R - 16.1 meters
(b) Way 2 and 2R - 14.3 meters
(c) Way 3 and 3R - 27.5 meters
(d) Way 4 and 4R - 18 meters
(e) Way 5 and 5R - 9.3 meters
(f) Way 6 and 6R - 16.5 meters

Fig. 16. The six possible ways (including reverses) for the Improved System Validation Experiment. Start and end zones are shown in green and blue. The black line shows the smoothed optimal way pre-calculated by our navigation algorithm.

8.1 Improved System Validation Experiment – Implementation

Compared to the Obstacle Course Experiment, we changed the following implementation-specific aspects in the improved version of the system:

(1) The users' average speed over the last second and reaction time is now taken into account for the guidance algorithm, leading to more adaptive guidance across participants.
(2) Instead of just taking defined waypoints for navigation, the guidance algorithm interpolates smoothly between defined waypoints using thousands of intermediate waypoints generated by a Gaussian moving average on the position (shown as the black line in Fig. 16). This avoids instant direction changes and an overall smoother feel of the directional guidance.
(3) We added an additional starting/ending position (three in total), moved one of the obstacles, added a fifth one, and doubled the path count to 12 (6 + 6 reverse) as shown in Fig. 16. Three of the paths include the stairs once, and one path includes it twice. This was done so that participants could not be sure of encountering another staircase after the first one. The paths were randomized with the participant ID as a seed.
(4) The static patterns used were exchanged with those resulting from the Static Patterns Refinement Study. The ATTENTION pattern is played once the user deviates more than 22 cm from the optimal path, and the STOP pattern is played at greater than 40 cm deviation from the optimal path. Both of these are repeated

once every second until the user returns to an acceptable distance to the optimal path. The STOP pattern is also played once before playing the UP pattern when the user approaches the stairs.

(5) We changed the tracking system from OptiTrack to an HTC Vive Tracker setup, using four HTC Vive base stations v2.0. These proved to be more reliable and precise than our OptiTrack setup consisting of 24 720p IR cameras (reported error < 1 mm), even though it should, in theory, be less precise as related work suggests an average tracking error of 7.5 mm for the Vive tracking system [34]. However, this related work used a setup of just two Vive base stations v1.0 compared to our four base stations v2.0.

We mounted two Vive trackers on each of the participants' shoes with Velcro straps, two on each of the shoulders (mounted on a vest) and another one on the head, attached to the HapticHead via Velcro as well. The foot tracking mostly servers for obstacle hit verification. The shoulder trackers' average position and the head tracker's orientation served as input for the directional guidance algorithm. We take the shoulders' average position instead of the head position because of possible head wobbling, just like in the Obstacle Course Experiment.

8.2 Improved System Validation Experiment – Procedure

The procedure of this experiment was like in the Obstacle Course Experiment except for the following changes:

- The number of trials was doubled to 48, but a limit of 2.5 hours, including pauses, was set to the study time. Not all participants completed all trials within this time frame. This is a limitation of this experiment as the trials were still randomized, and so not every participant conducted the same number of certain routes.
- We only blindfolded participants if they had no residual vision left (including sensing brightness) as it is otherwise not necessary.
- Our participants did not wear a balaclava below the prototype for this experiment because the balaclavas attenuate the vibration intensity, which may lead to feeling only a weak stimulus in certain positions. Instead, we treated the prototype with disinfectant after each participant. This change was implemented due to our own experimentation and observations with the prototype.

In case the tracking system lost tracking for more than 1 s, we repeated a trial. This happened a total of 3 times.

8.3 Improved System Validation Experiment – Participants

We talked to several associations for VIPs and recruited 5 participants (all male, mean age 55.4 y, SD = 14.5 y) through word of mouth, public news on websites, and announcements through a local radio station for VIPs. Ideally, the study would have been conducted with more participants, but this was not possible due to the COVID-19 outbreak in 2020, and the smaller experiment still provided a wealth of valuable insights. This study took around 1-2.5 hours per participant, including the questionnaires. None of the participants took part in the Obstacle Course Experiment, and all of them are regular white cane users. Participant details are given in Table 1.

8.4 Improved System Validation Experiment – Results

Table 1 shows the five participants' general performance and their demographics. Like in the Obstacle Course Experiment, we were quite conservative in counting obstacle hits and stairs assistance. If the edge of the shoe rim was on or over the side-ledge of the staircase, this event was counted as needing assistance, and obstacle hits were counted as soon as a participant brushed an obstacle with their clothing.

Unsurprisingly, almost all obstacle collisions happened between C3, C4, and C5 (see Fig. 15). Only a single collision happened at C1 when one of the participants was distracted by talking. No collisions happened at the stairs as the STOP pattern was played early enough so that the participants were careful, and they also got the UP pattern right on time to lift their foot to the first stair. The six times in total where we had to assist the participants on the stairs were usually because the participants accidentally got too close to the edges of the

Participant ID	Sex	Age [years]	Visual impairment diagnosis	Residual vision	Total trials completed	Median time per trial [s]	Average time per trial [s]	SD of time per trial [s]	Stairs assistance count	Obstacle hit count	Issues in % of conducted trials	Walking speed [m/s]
1	m	48	Glaucoma, fully blind since age 16	None	**48**	51.5	49.5	19.4	3	4	14.6	0.34
2	m	68	Glaucoma, fully blind since age 65	None	**14**	124.7	148	83	2	7	57.1	0.11
3	m	56	Retinal detachment, fully blind since age 20	None	**48**	63.7	68.1	32.4	0	1	2.1	0.25
4	m	70	Glaucoma, impairment since age 64	30 pct	**24**	187.2	191.9	101.2	0	1	4.2	0.09
5	m	35	Retinal detachment, fully blind since age 25	None	**48**	74.4	76	33.1	1	8	18.8	0.22
Average		**55.4**				**94.2**	**96.4**	**46.5**	**1.0**	**3.5**	**9.9**	**0.23**

Table 1. Improved System Validation Experiment – participants overview. Note that P2 was excluded from the average results due to broken cables of actuators (see text).

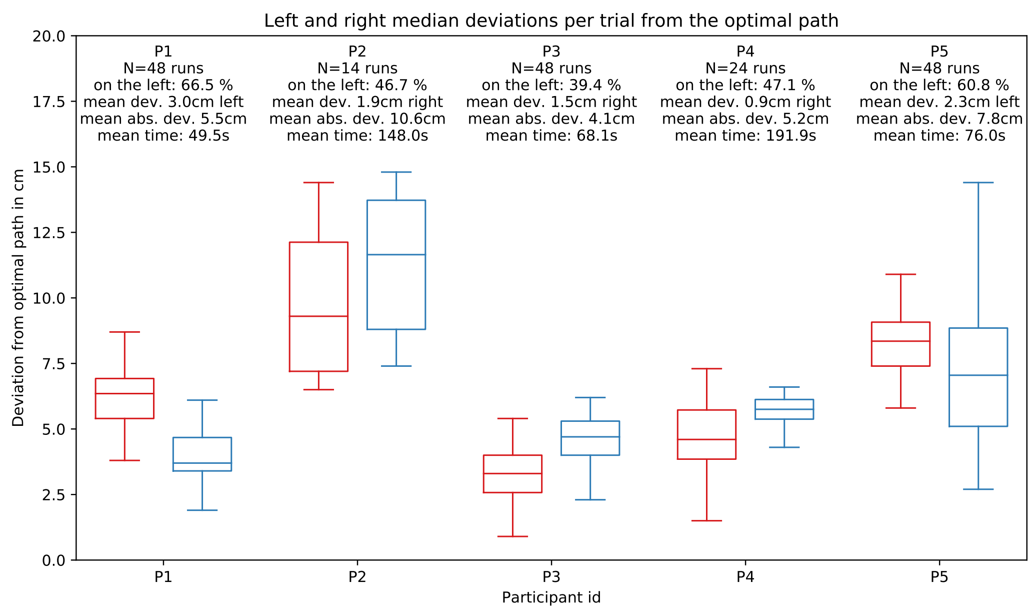


Fig. 17. Improved System Validation Experiment – mean left and right median deviations from the path. The red boxplot shows mean left deviations, the blue boxplot mean right deviations. Note that P2's results have to be viewed with caution due to broken cables of actuators (see text).

stairs or when their first step onto the lower stair was too close to the edge, and we wanted to make sure that they would not fall off with their next step.

When comparing the counts for obstacle hits and stairs assistance in Figures 9 and 1, the reader has to keep in mind the different number of trials of the Obstacle Course Experiment (24 trials per participant) and the Improved System Validation Experiment (varying number of trials, up to 48).

The results of participant P2 have to be viewed with caution. P2 was curious about the prototype on his head, kept touching it, and ended up breaking a total of three cables of actuators during the experiment, including one on the forehead, which is the most important one for navigation. Thus, P2 had significant disadvantages compared to the other participants regarding navigation, as some actuators stopped working during the experiment. This made P2 more likely to bump into obstacles and increased the deviation from the optimal path, as seen in Fig. 17. For this reason, we excluded P2 from all evaluations involving aggregated data (e.g., the averages in table 1).

Fig. 17 depicts the mean left (red) and right (blue) deviations from the optimal path for all trials conducted by the respective participant. We found an overall average absolute deviation to the optimal path of 5.7 cm (SD=1.4 cm) across all participants. We also report the percentage of time on the left side of the optimal path and the mean deviation towards the left or right here as a measure of a systematic error that the participants experienced. With the prototype perfectly fit to participants, they should ideally have a mean deviation of 0 cm, which would indicate a symmetric movement to the left as to the right side of the optimal path. However, even when the prototype was perfectly placed on the participants (e.g., central actuator on the forehead was perfectly above the nose), they might still experience a slight systematic error, as the center above the nose might not *feel* central to the participant (see discussion about this phenomenon in the discussion of the Obstacle Course Experiment). This is especially true for individuals who have been fully blind for a long time and develop a condition where they tend to tilt their head a bit off-center permanently (e.g., to compensate for hearing loss in one of the ears) [38].

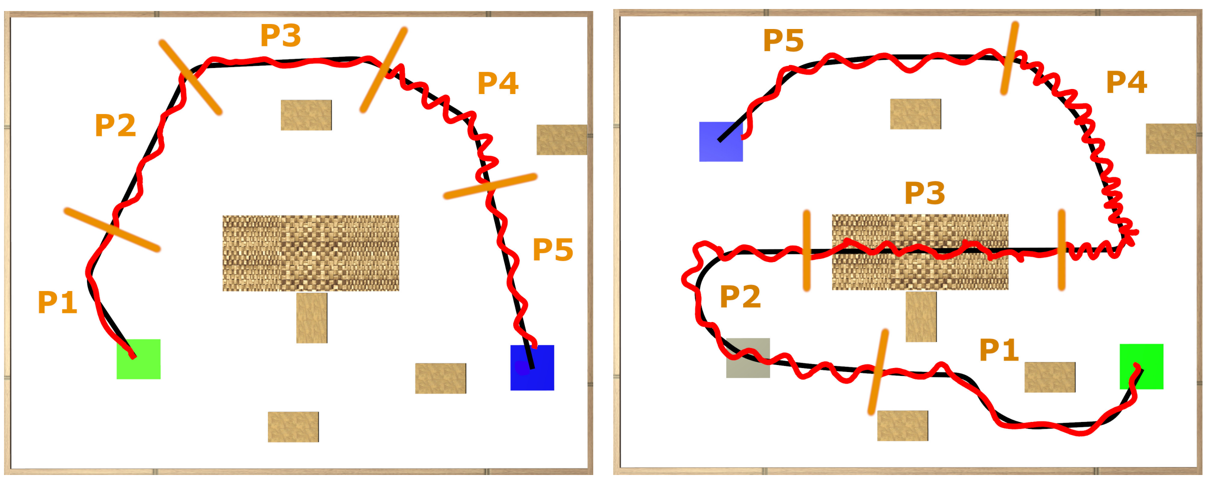


Fig. 18. Improved System Validation Experiment – wobble of different participants on way 5 (left) and way 1 (right). The red line shows the shoulder tracker average of the respective participant.

Fig. 18 shows the different wobbling patterns of the five participants around the optimal paths for an easy path (W5) and a more complicated path (W1). Each wobble from left to right and back represents two full steps.

8.5 Improved System Validation Experiment – Subjective results

Fig. 19 shows the results of our closing questionnaire from this experiment. Generally, these results are similar to the subjective results in the Obstacle Course Experiment. The participants generally agreed that they felt safe and that they liked the way of navigating, which felt intuitive for most of them. While they thought that the tactile feedback on the head was suitable, some had concerns about using the system regularly concerning

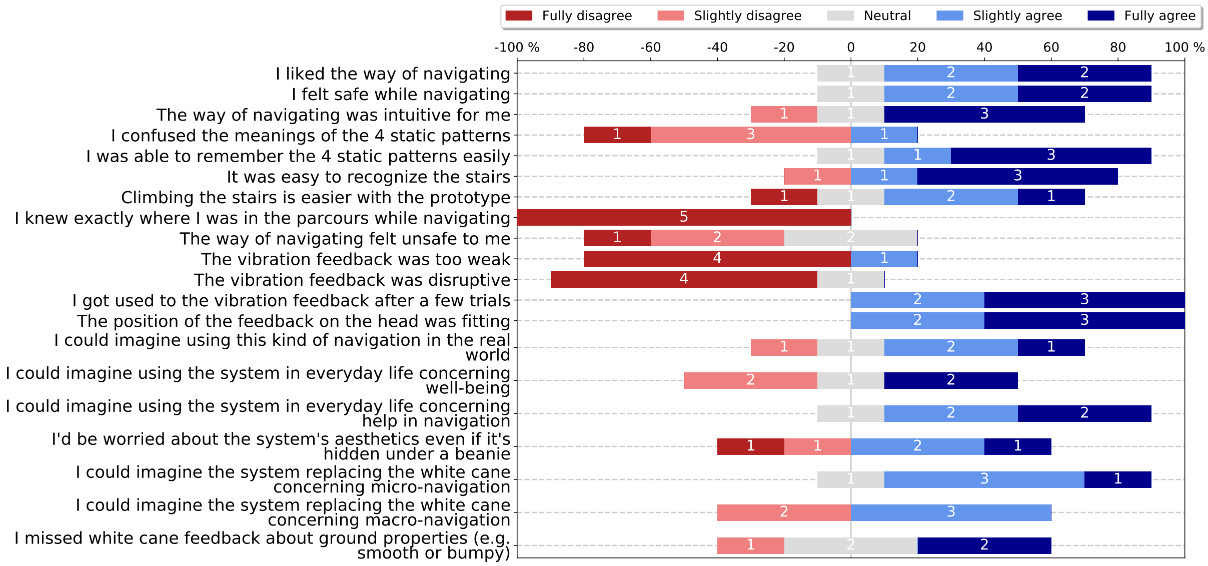


Fig. 19. Questionnaire results of the Improved System Validation Experiment.

well-being as the prototype is still somewhat clunky and uncomfortable to wear over more extended periods. A majority would worry about the system's aesthetics, even if it were hidden under a beanie. They were especially concerned about certain social situations, such as public presentations, dance parties, saunas, or swimming pools. Using the system feels more appropriate to the participants in other social situations such as closed or public rooms, walking through a city, cafes, restaurants, or at home.

P2 rated our system lower than the other participants regarding certain properties (intuitiveness, confusion of static patterns, safety, strength of vibration feedback). This was likely caused by the broken actuator cables and the resulting less intuitive continuous guidance signal, which also had a much lower intensity for P2 because of the broken actuator on the forehead.

Some of the participants stated that they could imagine using this kind of navigation in everyday life as well (presuming a suitable input tracking system, e.g., Apple ARKit [2] or Google ARCore [17]), and most judged that it could replace the white cane in micro navigation. However, two participants had concerns, primarily because they missed the white cane feedback about ground properties, which the system does not provide. Others stated that this was no issue as they judged that they get sufficient feedback on ground properties from their shoes.

In other verbal and written comments, participants stated that they could imagine using a further developed system based on our prototype in most social contexts if suitably disguised or hidden. All of them encouraged us to continue research in this direction, and P3 even mentioned feeling a bit bored at the end of the study because it was "too easy" to follow the directions and no total concentration, e.g., on the stairs, was necessary.

8.6 Improved System Validation Experiment – Discussion

Due to our experiment's nature, the low number of participants, and the considerable differences between participants, we first discuss each participant's results individually and highlight important characteristics of each participant that might influence results.

P1 was amongst the younger participants, quite physically fit, and had been fully blind since a young age. He was the fastest of the participants at an average duration of just 49.5 seconds per trial. Due to his duration and the narrow pathway between the obstacles C3, C4, and C5 (see 15), he hit a total of four obstacles and required assistance on the stairs three times due to the sharp turns right before the stairs, which in combination with his short duration caused him sometimes to be misaligned to the stairs in the first third of the study.

While P2 was physically fit, he had only been fully blind for three years before the experiment. He had difficulties keeping his concentration on the tactile signals since he liked to chat. He was very curious about the prototype on his head and kept touching it, resulting in a total of three broken actuator cables. Even though he was slower than most of the other participants, he required assistance on the stairs twice and hit seven obstacles during the experiment. We suppose his lower than average duration per trial is not just the result of broken actuator cables, but also of him only having been blind for three years in total, so he was somewhat cautious. We had to stop the experiment after 14 trials because of the broken actuator cables, and the participant had other appointments to attend to, so he could not wait for us to resolder the actuator cables. Due to the broken cables, his results have to be viewed with caution and have been excluded from the overall quantitative analysis.

P3 was quite physically fit and had been fully blind since a young age, just like P1. His average duration per trial was a bit lower than P1's, but he managed to react perfectly to the tactile signals as apparent from his record low mean absolute deviation from the optimal path of just 4.1 cm, including a 1.5 cm systematic error (see Fig. 17). He required no assistance on the stairs and hit only a single obstacle along the way.

At age 70, P4 was the oldest of the participants. When he arrived, he was not aware that the obstacle course included stairs but still wanted to participate in the study when we told him the specifics. He usually climbs stairs using the railings and walks much more slowly than the other participants in the real world. This can be attributed to his age and visual impairment, which had only manifested six years ago. Furthermore, he also had some residual vision blocked by the sleeping mask that participants with residual vision had to wear during the experiment. His trials took much longer on average as he was very cautious, especially on the stairs. Still, he was able to follow the tactile signals very well, required no assistance on the stairs, and only hit a single obstacle. We stopped the experiment after half the trials were completed because P4 seemed exhausted. He asked to continue, but we did not want to risk him falling due to fatigue.

P5 was the youngest participant at 35 years old, technophile, and had been fully blind for ten years. He has a condition where his head is tilted slightly sideways and forwards. Due to this, we had to re-adjust the Vive tracker on his head after observing the first three trials, where he constantly walked to the right of the optimal path by a large margin. After the readjustment, he performed pretty well even though the data in Fig. 17 suggests that he now experienced a systematic error to the left side, as we slightly over-corrected his pose. He brushed more obstacles than the other participants due to his talkativeness and resulting fading concentration on the task.

Our improved system performed more accurately than the system used in the Obstacle Course Experiment. For example, in the Obstacle Course Experiment, the average absolute deviation from the optimal path was 9.3 cm on average (compare Figures 11, 12 and 17). With the improved system, the participants scored an average absolute deviation from the optimal path of only 5.7 cm, which is considerably lower than in the Obstacle Course Experiment (excluding P2 due to broken cables as discussed above) and only a little more than the usual shoulder wobble while walking, as shown in Fig. 18. This is not only the result of the improved system but also because the systematic directional error decreased to an average absolute of 1.9 cm (SD=0.8 cm). The systematic error decreased compared to the Obstacle Course Experiment, even though we still did not perform a sophisticated user-specific calibration, as explained in the Obstacle Course Experiment's discussion. However, we were aware of the systematic error and ensured to place the prototype perfectly on our participants' heads this time, ruling out one of the three influences towards the error. We also pre-calibrated the Vive tracker position on the prototype and only had to adjust it once for P5, as discussed above.

In terms of obstacle hits, we can conclude that even with some distraction through occasional talking while conducting the study, none of the participants hit obstacle C1 or the wall when passing through the 115 cm wide gap between the wall and C1. Only a single participant hit C1 when passing through the 89 cm wide gap between

C1 and the stairs as he was distracted by talking. Regarding the gap between C3, C4, and C5, when coming from the left, some participants hit C4, and when coming from the right, they either hit C3 or C5. These obstacle hits were usually the cause of a short distraction period and resulting slower reactions to the tactile signal, causing the participants to miss the rather sharp turn or execute it too late. We explicitly expected some obstacle hits as we deliberately designed this study to measure the maximum precision we could achieve with the system. With this in mind, we were positively surprised about the low number of obstacle hits and that there occurred only two obstacle brushes at C3 or C5 when coming from the left. The gap is 71 cm wide, while the hip widths of the participants were between 40 and 50 cm, leaving only very little room for error.

We found the minimal safety distance between obstacles without distraction to be about 89 cm (as one of the participants hit C1 while being distracted), and even with distraction through talking, every single participant managed to always safely pass through the 115 cm gap between the wall and C1, so we can assume this to be a safe distance between obstacles with distraction through talking. Our system worked better for participants who were (a) fully blind for a long time and (b) younger than the average. Age negatively influences reaction time and perceived strength of the tactile signals. Our only participant with residual vision (P4) was extra cautious at blocking the residual vision. P4 felt uncomfortable wearing a sleeping mask in the experiment. Furthermore, we observed that the longer participants had been blind in their lifetime, the more courageous and faster they were in terms of walking speed, even without the white cane.

9 OVERALL DISCUSSION

In summary, we identified four suitable static tactile patterns around the head for four fundamental navigation instructions (START, STOP, UP, DOWN). In a series of experiments, the patterns were shown to be easily recognizable, intuitive, and easy to remember. In preparation for the Obstacle Course Experiment, we implemented these patterns in conjunction with a continuous guidance pattern and an additional ATTENTION pattern (similar to STOP). Our initial tests for the Obstacle Course Experiment revealed that an additional ATTENTION pattern is essential to keep users focused on the task. This was not obvious from our informal interview and only surfaced after we conducted several preliminary tests in the Obstacle Course Experiment with other researchers, who kept losing concentration when they tried to give us feedback while navigating.

In the Obstacle Course Experiment, we guided sighted but blindfolded and real VIPs through an obstacle course, including stairs. Due to our observations in the Obstacle Course Experiment, we discarded the initially designed START pattern in later experiments because users were aware that the navigation was working when any kind of tactile stimulus was presented. We gained valuable insights into improving our system and further optimized our static patterns in the Static Patterns Refinement Study. The precise definitions of the final static pattern parameters are given in Section 7.5.

Finally, we incorporated all identified improvements into our system and validated it with another set of five VIPs in the Improved System Validation Experiment. We showed that the designed static patterns for essential navigation instructions, in combination with the continuous guidance feedback to find objects around the user from [28], work very well to keep VIPs on a predefined path in a complex micro-navigation task. With an average absolute deviation of 5.7 cm, the Improved System Validation Experiment participants diverged only slightly from the optimal path than the usual shoulder wobbling. Even when the user is distracted by talking, the safe distance between obstacles was determined to be 115 cm, which is less than the typical width of sidewalks [56].

When comparing our final system with related work, it can be stated that it performs better than any macro-navigation vibrotactile head, belt, or foot systems (e.g., [20, 44, 52, 59]). This is to be expected because of the low tracking accuracy of GPS. The only other work we are aware of that used an indoor tracking system with decent accuracy (< 10 cm) for a micro-navigation task is Flores et al. [16]. They did not include any obstacles or stairs in their study, and their paths only included two turns, each in an empty space. They measured an average absolute distance to the optimal path using their tactile belt of 49 cm and compared it to auditory guidance in the same study, which resulted in an average distance of 61 cm. Our system performed an order of magnitude better at 5.7 cm average absolute distance to the optimal path, including a 1.9 cm average systematic error. A sophisticated per-user calibration may reduce this systematic error. The increased precision comes at the price of a slower walking speed (0.23 m/s vs. 0.46 m/s in [16]). This is likely a result of our course, including stairs and obstacles. Moreover, the participants in our final experiment had a relatively high average age of 55.4 years.

Due to our system's high precision, it allows use cases in new scenarios that were not possible with prior systems [16] (e.g., navigating through a crowded bar, through a festival, or on a sidewalk while avoiding obstacles and other people). Our approach also presents itself as a highly effective *anti-veering tool* for VIPs. Veering off an intended path is a common issue for VIPs [12]. Even with all the turns and the stairs in our obstacle course, the average absolute deviation from the optimal path at 5.7 cm is still better than other anti-veering tools that just use a straight line as an experimental condition (e.g., [12], 9 cm deviation, using a 6-actuator vibrotactile strap on the forehead).

9.1 Limitations

Noise is still an important factor when working with vibration actuators around the head as noise is transferred via bone conduction and especially loud and possibly disruptive near the ear openings (as also reported in [28]). Even though most of our VIP participants were very optimistic about the noise and told us that it did not bother them, we suppose that this is probably not the case for everyone in a larger sample of the VIP population. When designing a prototype to be used by VIPs, we have to consider this limitation more than with sighted people because VIPs rely on hearing a lot more and would probably be disoriented by loud noises next to their ears. An alternative are specialized voice coil actuators [32] that allow controlling amplitude and frequency independently. These can heavily reduce the audible noise by working at lower frequencies and higher amplitudes at the cost of a larger form-factor. Working at higher amplitudes is required because the vibration perception threshold decreases dramatically as vibration frequency decreases [23].

Our prototype's current aesthetics should undoubtedly be improved before being used in any real-world social situation. A miniaturized version of HapticHead integrated into a beanie (similar to [14]) would mostly solve the aesthetics issue and reduce the concerns of our study participants.

This paper does not evaluate the effect of different hair densities on tactile pattern recognition or guidance precision. Related work found no significant effect of hair density on localization performance on the head [14]. Furthermore, while [42] did find a significant effect of hair density on vibration perception threshold, as long as a tactile display operates above that threshold, as our prototype did, this should have no substantial influence on localization performance [14]. Our experiment participants had very different hair densities, except for the last validation experiment, where all participants were male and had relatively light hair. We chose not to evaluate a possible effect of different hair densities as we did not have a systematic sample of different hair densities and thus not enough data to draw reliable conclusions on this aspect. While we expect a small effect of strong or curly hair on our four static patterns' recognition accuracy, we do not expect a significant effect on the continuous guidance stimulus, as this stimulus is present on the forehead if the user is following the path.

10 CONCLUSION AND FUTURE WORK

We presented a tactile micro-navigation system with substantially higher precision than prior work. Aside from the limiting factors mentioned earlier, our study participants were quite content with the system as is, stating a feeling of safety and intuitiveness with the navigational method. With a further refined and adequately integrated system, more training, and combined with a proper self-contained indoor and outdoor tracking method, our tactile guidance approach may eventually improve the lives of many VIPs. It provides a viable information channel about the best path around obstacles in addition to information obtained by the white cane. A robust, commercial variant of the system may potentially fully replace the white cane, but users should still carry a foldable backup white cane with them in case of, e.g., a battery failure.

While our system is primarily intended for VIPs, other use cases that require precise tactile guidance are feasible with the same system. Possible use cases include guidance for firefighters or other personnel operating in low-vision environments, guidance in virtual and augmented reality scenarios where navigation instructions should not occupy the visual and auditory channels, and guidance and warnings for jet or drone pilots. Navigation in 3D spaces with the same system is achievable, as hinted at in [28], but this needs to be verified in future work.

Future work may investigate a variety of exciting research directions. Our system may be combined with a system that detects moving obstacles and *prevent future dynamic collisions* by warning the user through the STOP pattern or dynamically guide the user around the moving obstacle. Our system could also be improved by using specialized voice coil actuator types such as [32] for lowering the audible noise through lower frequencies or using regular linear resonant actuators (LRAs), as both of these options offer significantly faster reaction times to changes in voltage, compared to the ERM actuators we used. Switching to a voice coil based actuator type (e.g., [32] or LRAs) will allow users to react slightly faster (~100 ms) to changes of the guidance stimulus, which should further improve the guidance precision.

Finally, research should be conducted on how accurate a navigation system has to be for different micro-, macro-, and combined navigation scenarios. We concentrated on developing a tactile system with maximum precision. However, this maximum precision may not always be necessary or desirable, and users may still trust micro navigation systems with less precision depending on the scenario. A significant advantage of a system with less precision may be that it requires less user attention. We imagine an adaptive system, which decreases or increases the strength of the continuous guidance stimulus. The adaptive system may even fully turn it off if the user follows the optimal path within a certain margin of error. This adaptation may depend on the current environment and possible obstacles (e.g., 5 m in a large open area, 25 cm on a sidewalk, and 10 cm in a bar).

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