TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation

Sebastian Günther
TU Darmstadt
Darmstadt, Germany
guenther@tk.tu-darmstadt.de

Florian Müller
TU Darmstadt
Darmstadt, Germany
mueller@tk.tu-darmstadt.de

Markus Funk
TU Darmstadt
Darmstadt, Germany
funk@tk.tu-darmstadt.de

Jan Kirchner
TU Darmstadt
Darmstadt, Germany
kirchner@tk.tu-darmstadt.de

Niloofar Dezfuli
TU Darmstadt
Darmstadt, Germany
dezfuli@tk.tu-darmstadt.de

Max Mühlhäuser
TU Darmstadt
Darmstadt, Germany
max@informatik.tu-darmstadt.de

Figure 1: *TactileGlove* prototype showing the (a) dorsum, and (b) palm of a user's hand. Red circles highlight the positions of the vibration actuators and blue indicates the position of the microcontroller.

ABSTRACT

With the recent advance in computing technology, more and more environments are becoming interactive. For interacting with these environments, traditionally 2D input and output elements are being used. However, recently interaction spaces also expanded to 3D space, which enabled new possibilities but also led to challenges in assisting users with interacting in such a 3D space. Usually, this challenge of communicating 3D positions is solved visually. This paper explores a different approach: spatial guidance through vibrotactile instructions. Therefore, we introduce TactileGlove, a smart glove equipped with vibrotactile actuators for providing spatial guidance in 3D space. We contribute a user study with 15 participants to explore how a different number of actuators and metaphors affect the user performance. As a result, we found that using a *Pull* metaphor for vibrotactile navigation instructions is preferred by our participants. Further, we found that using a higher number of actuators reduces the target acquisition time than when using a low number.

CCS CONCEPTS

• **Human-centered computing** → **User studies**; *HCI theory, concepts and models*;

KEYWORDS

Vibrotactile, Haptics, 3D-Space, Navigation, Spatial Guidance, Assistive Technology, Pull Push Metaphors

ACM Reference Format:
Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. 2018. TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation. In *PETRA '18: The 11th PErvasive Technologies Related to Assistive Environments Conference, June 26–29, 2018, Corfu, Greece.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3197768.3197785

1 INTRODUCTION

Searching and reaching for objects in close proximity is a common task in daily situations; from knowledge workers to artisans or even at the private desk. Users often need to identify objects or locations close to them to either use the object or to place in that area (e.g., locating a certain tool in a toolbox). The process of target acquisition is, thereby, inherently visual: users identify objects through their visual appearance [8]. However, this can get cumbersome and is not feasible in every situation. In particular, if objects are outside of the user's field of view, occluded by other objects or there is a high visual cluttering that makes the identification process even harder [23, 24]. The ability to locate a target successfully can further decrease due

---

PETRA '18, June 26–29, 2018, Corfu, Greece

ACM ISBN 978-1-4503-6390-7/18/06…$15.00
https://doi.org/10.1145/3197768.3197785

to environmental influences, such as dark environments, or if users have visual impairments.

The research community provides a large body of related work that proposes visual [2, 10] or auditory cues [3] for guidance. Visual guidance systems actively highlight objects of interest or guide users with augmented support [1, 2, 4]. Audio guidance systems make use of spatial audio that aims to steer the attention of users towards a target [12]. While practical and useful, the presented approaches have limitations: Visual guidance is not useful in situations where divided attention is needed, e.g., if a user has to focus on something different visually. This further increases if persons have disabilities, such as a visual impairment, which raises the urge for proper spatial guidance and navigation support. Persons with visual impairments cannot rely on visual cues guiding them towards objects. While this does not apply to auditory cues, audio guidance is not always efficient, such as environments with a lot of noise.

In recent years, related work tried to address those drawbacks through tactile guidance and haptic interfaces. Hereby, tactile displays actuate different regions of the body to guide a user towards a target, e.g., the wrist [32] or waist [11]. However, those approaches are often limited to spatial guidance in 2D environments [30] or as support for visual search tasks [21]. Most recently, considering spatial guidance for 3D spaces, Kaul et al. [15, 16] presented an approach to guide users through vibrotactile actuation on the user's head. While being a good example of spatial guidance, we think that mounting vibration actuators on the user's hand can further support a close-range direct target acquisition.

In this paper, we investigate the premise that such guidance systems for precise and direct targeting of objects in hand-reachable distances is still underexplored and can be improved by adding vibrotactile actuators to the user's hand providing full spatial navigation in a 3D space. We extend the expressiveness of spatial guidance by augmenting a glove with multiple actuators for an eyes-free assistive spatial guidance system called *TactileGlove* (cf. Figure 1). The contributions of our paper are (1) a vibrotactile glove for spatial navigation in a 3D space, and (2) the results of a user study, where we evaluate how efficient users can identify targets in the 3D space through vibrotactile actuation and how different layouts and metaphors (*Pull* and *Push*) affect spatial guidance.

After this introduction, we will give an overview of related work. Then, we introduce our concepts and prototype followed by our user study. Afterward, we discuss our findings and present guidelines for spatial guidance through vibrotactile navigation. We conclude this paper with a summary and future work.

2 RELATED WORK

The research community explored tactile guidance and feedback systems in a large body of related work. In the following, we present the relevant research categorized into two subsections. We first cover an overview of existing usage areas and vibrotactile systems and continue by presenting technology aspects, such as vibration patterns and mappings.

2.1 Vibrotactile Usage Areas

(Vibro-)tactile displays have been mounted to various body parts and researchers evaluated how different locations of actuators affect those systems. Karuei et al. [14] investigated the human sensation of vibration patterns on 13 different body parts which are common in other work, such as the foot [6, 27], the thigh [26], head [5, 17, 29], and wrists [25, 32]. As a result of this overview, the authors identified the wrist as most effective and best position to impress vibration stimuli. However, directly augmenting the user's hand was not covered, but are explored in several other publications. For example, Lehtinen et al. [21] explored the effects of a vibrotactile glove supporting visual search tasks while pointing. The authors presented a glove with four actuators positioned evenly on the palm and dorsum of the hand that allows directional guidance for 2D movements, such as left, right, up and down. Another work done by Krichna et al. [19] presented a glove for translating facial expressions to unique vibrotactile patterns for the fingers. However, those focus on visual search support or social aspects, such as emotions.

As another use case, vibrotactile gloves are used for pedestrian navigation or supporting full-body guidance. Uchiyama et al. [31] presented a vibrotactile glove for semi-autonomous wheelchair operations to guide persons with directional pulsing stimuli on a 3x3 vibration motor grid. Paneels et al. [25] mounted six vibration actuators on a horizontal plane augmenting the user's wrist and compared different vibration patterns for indoor navigation. Similar, Zelek et al. [33] built a vibrotactile glove for persons with visual impairments to support pedestrian navigation with obstacle avoidance.

However, to the best of our knowledge, there is almost no work on guiding persons with a high precision directly towards an object using vibrotactile navigation instructions. Existing work providing vibrotactile actuation is still underexplored regarding direct targeting and spatial guidance in 3D spaces. Most recently, Kaul et al. [15, 16] explored guidance in a 3D space by augmenting the user's head with vibration actuators. The authors evaluated their system against current Augmented Reality (AR) and audio guidance approaches, namely attention funnels [2] and a generic Head-Related Transfer Function (g-HRTF). Visual slightly performed better than vibrotactile, but both are comparable and outperform audio guidance. Similar, Kerdegari et al. [17] compared haptic and audio cues for head-mounted augmentation in low visibility environments, while Funk et al. [7] compared tactile, visual, and audio cues for error feedback during assembly tasks. In a follow-up study, Kosch et al. [18] evaluated those techniques for workers with cognitive impairments.

With regards to high-resolution guidance, Weber et al. [32] built a vibrotactile wristband and evaluated the effectiveness of the participants' ability to follow a predefined trajectory. Their prototype had six actuators located around the wrist. They found that vibrotactile feedback had some limitations during translation tasks compared to verbal communication, but performed better during rotational tasks. The paper showed positive effects on vibrotactile guidance, especially in situations when verbal guidance is limited. Further, the authors stated that it could be improved by reducing ambiguity by having additional information directly encoded in the vibrotactile patterns, such as distance.

As a conclusion, we think that vibrotactile guidance systems for precise and direct targeting of objects in hand-reachable distances is still underexplored and can be improved by adding actuators to the user's hand providing full directional navigation in a 3D space.

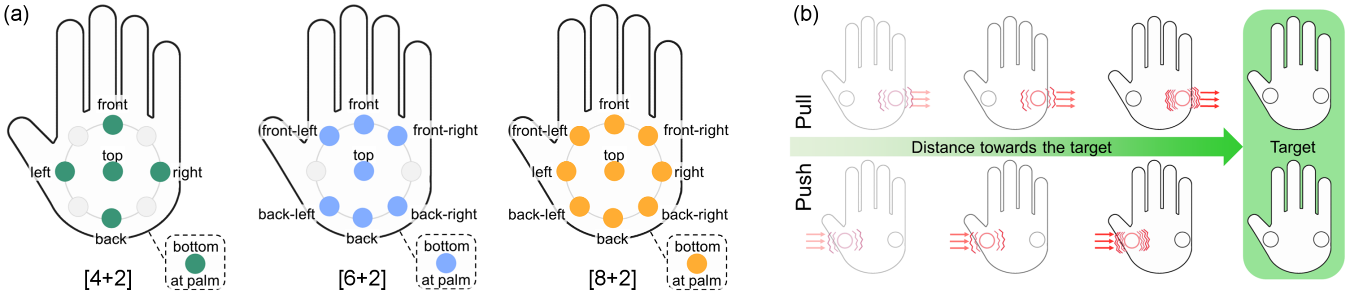


Figure 2: TactileGlove concept showing (a) the different layouts of the vibration actuators (green=4+2, blue=6+2, orange=8+2), and (b) how a user's hand is guided towards a target. Further, it shows the *Pull* metaphor where the closest vibration motors are actuated, and *Push* where the furthest are actuated. The closer the hand gets towards its destination, the higher the frequency. It completely suppresses any actuation once the target zone is reached.

2.2 Vibration Patterns and Mapping

When designing vibrotactile guidance systems, it is necessary to identify how vibration patterns affect the human body and how those stimuli should be presented. Therefore, the current research explored numerous vibration frequencies, modes, and intensities.

Lee et al. [20] evaluated the user's ability to perceive different vibration patterns and found that users are better at distinguishing pulsating vibration actuation than continuous. Further, they found that it was easier for users to distinguish and locate different actuators on the wrist for tactile notifications if the vibration pattern had clear pulses.

In addition to that, vibration patterns can be used to encode distance information. For this, Oron-Gilard et al. [22] found that increasing the actuation frequency, the closer a user gets towards a target performs best. They also stated that there should be a suppressed actuation once a user reached a target.

In our paper, we also want to elaborate the effects of different metaphors, namely *Pull* and *Push*. In an early work, Jansson et al. [13] evaluated tactile guidance of movement of different studies and showed that *Pull* metaphors seem to be more effective than *Push*. Further, in 2009 Spelmezan et al. [28] presented a language of tactile motion instructions for physical activities where users had to tell how they perceive the vibration actuation. In their work, the authors observed that users recognized them differently as either *Pull* or *Push*, but found no effect of both regarding learnability.

3 TACTILEGLOVE: CONCEPT AND PROTOTYPE

In this paper, we present TactileGlove, which provides vibrotactile guidance for assistive scenarios where users have difficulties to navigate in 3D space. To be independent of scenes with high visual cluttering or insufficient environmental conditions, such as bad lighting, we focus on navigational actuation for the hand. This allows us to guide the hand for direct targeting objects in close range. Therefore, we attach vibrotactile motors directly onto a user's dorsum of the hand. Figure 2 shows the general concept of our proposed system.

To identify how we can guide a user most effectively, we explore how the number of actuators and vibration metaphor affect the performance, and how we can encode the direction and distance towards a target. Therefore, we can vary the number of vibration actuators in our system by enabling and disabling single actuators. In addition, we can also vary the navigation metaphor to either, *Push* or *Pull*, to find out which mental model fits best for spatial guidance with a glove. Inspired by Oron-Gilard et al. [22], we encode the distance by increasing the vibration frequency the closer the hand gets towards a target (see Figure 2b).

3.1 *Pull* and *Push* metaphors

Vibrotactile guidance can be perceived depending on the mental model of the users. It can be categorized in two opposing metaphors how vibrotactile actuation can guide a user: 1) *Pull*, and 2) *Push* (cf. Figure 2b).

Pull will always actuate those vibration motors that are *closest* to the target and is perceived as if the hand is dragged towards it. For example, the impression if the user is walking a dog and the dog is pulling the leash while the user is dragged behind.

Push will always actuate those vibration motors that are *furthest* to the target and is perceived as if the hand is pushed towards it. For example, this resembles a situation where someone would take the hand of the user and is pushing the hand away.

Both metaphors occur in daily situations and seem to have no impact on the learning curve for tactile guidance [28]. However, it is not clear which of the metaphors is more effective and efficient for guiding the hand. In this paper, we evaluate how users perceive each metaphor and which of them has better performance for vibrotactile guidance.

3.2 Number of vibration actuators

In an informal pre-study, we identified that navigating the hand towards a target is promising and that augmenting the most actuators on the dorsum of the hand is less intrusive. Therefore, we improved our design to cover of all directions in a 3D space by putting eight actuators in the form of an outer ring to the dorsum of the user's hand. In addition, we locate another actuator at the center of the dorsum and one at the user's palm. To evaluate the effects of different numbers of actuators, we enable or disable actuators on the outer ring, but always kept the *top* and *bottom* actuators.

To evaluate, how the number of actuators affects the performance, we added the possibility to enable and disable each of them. To cover every direction and to encode up and down directions, we decided to always enable the top and bottom actuators, and only change the number of enabled vibration motors on the outside of the dorsum. Moreover, this helps to make the guidance independent of the hand orientation as the system always points towards the target regardless of how the user rotates or holds their hand.

In total, we define three different layouts: 4+2, 6+2, and 8+2 (cf. Figure 2a):

- **4+2** In addition to the dorsum center and palm side actuators, only the front, back, left and right actuator are enabled. Therefore, each of the outer actuators had exactly 90 degrees spacing between each other.
- **6+2** In addition to the dorsum center and palm side actuators, only the front, back, front-left, front-right, back-left and back-right actuator are enabled.
- **8+2** All actuators are enabled and used for vibrotactile guidance. Therefore, each of the outer actuators had exactly 45 degrees spacing between each other.

3.3 Prototype

We built our vibrotactile glove based on a unisize fabric glove. For the vibrotactile actuation, we use ten small vibration motors stitched them to the inside of the glove. Eight of them are located on the dorsum of the hand in a radial layout with 45 degrees spacing. Another actuator is located in the center of the dorsum of the hand and one actuator is located at the user hand's palm. Each vibration actuator has a diameter of 10 mm and is operated at up to 3.3 V. To control them, we soldered each to a connector board with safety diodes. Through a custom-built clip, we connect them to an Arduino compatible microcontroller with Bluetooth support (RedBearLab Duo[1]). Further, it is wirelessly connected to a stationary workstation for processing the actuation. The update rate for the motors is at 60 Hz to adapt to fast position changes.

For the hand tracking during the study, we use an optical, infrared motion tracking system (OptiTrack[2]) which is mounted on the ceiling above the user. The glove is augmented with a custom array of four retroreflective markers to be recognized as unique trackables. For a real-world deployment, it could be possible to use systems that use external cameras or ultrasound technologies (e.g., similar to Sarissa Assistance Systems[3]).

To guarantee a full spheric coverage for every possible direction, we made the glove orientation independent from the vibration actuation. This means, that no matter how a user changes the orientation of the hand, the actuators will always point towards the actual target (depending on the *Pull* and *Push* metaphors).

Finally, to further increase the wearability for different hand sizes, we decided to cut off the finger sleeves of the glove. To tighten the glove, we added velcro to the wrist and to the bottom actuator. A detailed view of our prototype is given in Figure 1.

3.3.1 *Direction and distance encoding.*

To guide users towards a target in an efficient and understandable way, we improve the actuation by encoding the direction and distance towards a target directly into the vibration patterns. Adjusting the frequency helps to improve the spatial awareness how far the hand is from the target [22], while the intensity is used to indicate the direction of each actuator.

Therefore, we calculate a direction vector between the tracked hand and the target in the 3D space. In a next step, we map the direction vector to a vibration intensity for each enabled actuator and the corresponding frequency, based on the distance to the target. Therefore, each actuator position is compared to a certain target vector calculated through the dot-product of their normalized vectors. As a result, if the dot-product is 1, the actuator directly points towards the target. In contrast, if the dot-product is -1, the actuator points in the opposing direction. A dot-product of 0 occurs if both vectors are orthogonal. Since we know that this is equivalent to the cosine of the vector's angle, we can determine the angle between an actuator and the target.

The **intensity** is defined by the resulting angle towards the target and improves the **direction** encoding. As boundaries, we use an angle of 60 degrees (equivalent to a cosine of 0.5) to only actuate the needed motors. We define full intensity for a cosine of 1 (directly pointing towards the target) and no actuation if the angle is bigger than 60 degrees. Thus, the lower the angle, the higher its frequency.

The **frequency** is used to encode the **distance** towards the target. Since we use pulsating stimulation, we define it as a period length in milliseconds that is 500 times the distance in meters. Thus, a distance equal to one meter has a vibration frequency of 2 Hz, while a distance of 10 cm has a frequency of 20 Hz. However, if the distance is smaller than 7.5 cm, we completely suppress the signal to indicate that the user reached the target.

4 EVALUATION

We conducted a user study to explore the following questions for vibrotactile guidance in hand-reachable distances:

1. How do *Pull* and *Push* metaphors affect spatial guidance?
2. How do different numbers of actuators affect spatial guidance?

4.1 Study Design

To answer the research questions above, we designed a user study following a mixed repeated measures design with two independent variables: number of vibration actuators (3 levels: 4+2, 6+2, and 8+2) and which guidance metaphor to follow (2 levels: *Push* and *Pull*). As dependent variables, we measure the Task Completion Time (TCT), the number of errors, and the perceived cognitive load using the Raw NASA-TLX (RTLX) [9]. The TCT is defined as the time a user needs to identify a target and confirms it with a confirmation button. The number of errors is defined as the number of targets that were not correctly identified (outside of target zone) while a user pressed the confirmation button. We counterbalanced the number of vibration actuators using a Balanced Latin Square. Further, we changed the whether the participants start with the *Push* or the *Pull* metaphor after each participant.

---

[1] RedBearLab Duo https://redbear.cc/product/wifi-ble/redbear-duo.html, last accessed 01/23/2018

[2] http://www.optitrack.com, last accessed 01/23/2018

[3] https://www.sarissa.de/en/, last accessed 01/23/2018

4.2 Task

To compare the different conditions in our user study, we designed a simple target acquisition task with six conditions in total. In each condition, the participants started by identifying 5 training targets and continued with 27 invisible targets in hand-reachable distances. All targets were aligned in a cube subdivided into $3 \times 3 \times 3$ sections with an edge length of 20 cm each, similar to a large Rubiks cube (cf. Figure 3). We did not disclose the exact position to the participants and told them to locate the targets as fast as possible. We alternated the order of the metaphors between each subject, hence, a participant started either with three *Pull* conditions followed by three *Push* conditions, or vice-versa. Within each of those conditions, we counterbalanced the number of actuators. This results in a total of $2 \times 3 \times (5+27) = 192$ trials per participant.

Further, we wanted the participants to focus completely on the vibration actuation and reduce any visual interferences. Therefore, we used an eye-mask to blindfold the participants. It also suppressed the effect that users look at subtle movements of single actuators through their vibration.

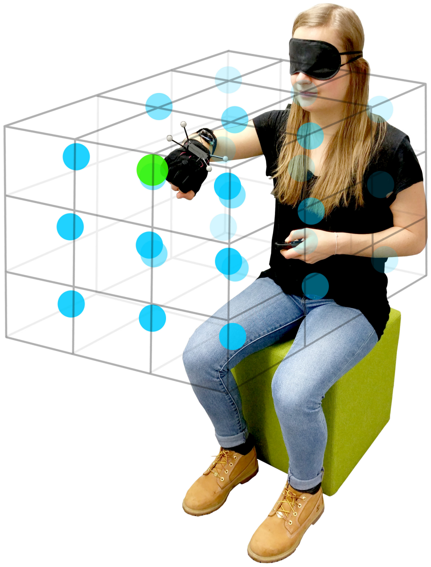


Figure 3: Setup of the study with a participant wearing the prototype, an eye-mask and holding the presenter. The cube in front shows the arrangement of the circular target zones. The green ball indicates an active target.

4.3 Procedure

After welcoming the participants, we gave a short introduction on the concept and introduced them to our *TactileGlove* system. We explained that they have to identify given targets in close range blindfolded. For this, we explained them the difference between the *Pull* and *Push* metaphor. Further, we made them familiar with the different numbers of active actuators (4+2, 6+2, or 8+2). We then kindly asked to fill out a consent form and a short demographic questionnaire including a pseudonym, age, gender, and experience with vibrotactile systems.

Afterwards, we asked the participants to have a seat on a non-moving stool and assisted them with putting on the glove on their right hand. We continued by briefly showing them a rough interaction space. Therefore, we could guarantee that no participant urges to stand up or tried to reach behind them, where no target is located. However, we did not tell them the exact arrangement nor the distribution of the targets. In a next step, we handed them a presenter for the left hand which the participants used to confirm a target and could proceed to the next.

Before starting with the first condition, we blindfolded them and actuated each vibrotactile motor one by one to make the participants familiar with the vibration patterns. To assure that they have enough time to get a feeling for each position, they had to tell us when we should introduce the next motor.

Once they confirmed that they understood the procedure, we started the first condition by telling the participant the active metaphor (*Pull* or *Push*) and how many actuators are enabled (4+2, 6+2, or 8+2). Each condition started with five identical training trials unknown to the participants. After the training trials, the condition continued seamlessly with the actual 27 targets. The participants were in complete control of the whole process by confirming a reached target and to proceed to the next trial with the presenter.

A condition terminated by giving an audio signal and the participants could remove the eye-mask. In addition, we asked for their feedback and impression of the system backed by using the Raw NASA-TLX [9]. If needed, they could also take a break before proceeding with the next condition.

After completing all six conditions, we assisted the participants by taking off the glove and asked to fill out a final questionnaire. Hereby, they should subjectively rate each condition and give feedback on the system. Additionally, they could submit further comments on positive aspects and things to improve. We also wanted to know if they can think of other use-cases. The whole procedure took approximately 60 minutes per participant.

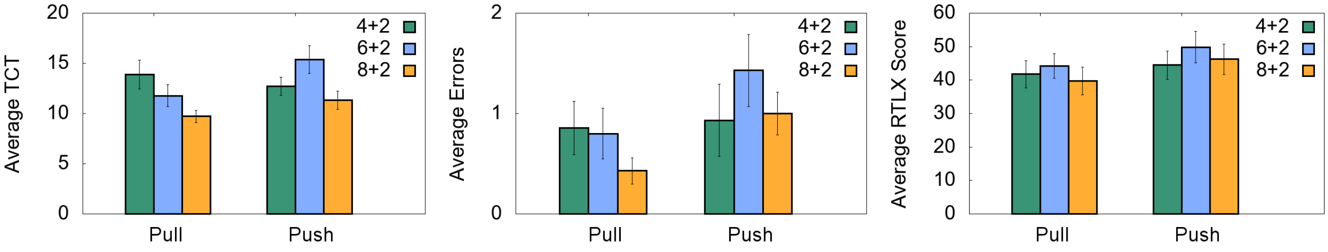
4.4 Participants

We recruited 15 participants (6 female) with an average age of 25.5 years ($SD = 3.8$, ranging from 20 to 33). All of them were right-handed. The average hand length was 18.4 cm with a hand diameter of 20.6 cm. When asked about their experience with vibrotactile systems and feedback, the majority told us that they have no prior experience (11/15, 73%). Only one answered to have work with vibrotactile guidance before, while the remaining three had experience through haptic feedback in games. Besides snacks and drinks, we did not provide compensation for the participants.

4.5 Results

We statistically compared the Task Completion Time (TCT), the Error Rate (ER), and the Raw NASA-TLX (RTLX) score according to the used metaphor and the number of used motors using a two-way ANOVA. We filtered the results for outliers by excluding data points with $\mu > 3 \times SD$, this led to excluding 6 data points for TCT and 3 data points for ER.

Considering the TCT, the *Pull* metaphor ($M = 11.84$s, $SD = 4.63$s) was slightly faster than the *Push* metaphor ($M = 13.24$s, $SD = 4.55$s).



(a) (b) (c)

Figure 4: The average Task Completion Time (a), the average Error Rate, and the average Raw NASA-TLX score according to the different metaphors and number of motors being used. All error bars depict the standard error.

Within the *Pull* metaphor, the prototype with all 8 motors active performed best ($M = 9.72$s, $SD = 2.33$s), followed by 6 motors ($M = 11.78$s, $SD = 4.26$s) and 4 motors ($M = 13.89$s, $SD = 5.77$s). Interestingly, in the *Push* metaphor, the 8 motors performed best ($M = 11.33$s, $SD = 3.48$s), followed by the 4 motors ($M = 12.69$s, $SD = 3.40$s) and the 6 motors ($M = 15.38$s, $SD = 5.50$s). The two-way ANOVA could not find a significant interaction effect between number of motors and metaphor, $F(2,78) = 2.172$, $p > 0.05$. A simple main effect analysis revealed that there was a significant main effect between the used number of motors ($p = 0.02$), however there was no significant difference with regard to the used metaphor ($p > 0.05$). A post-hoc test revealed a significant difference regarding TCT between 4 and 8 motors and between 6 and 8 motors. The results are depicted in Figure 4a.

Regarding the number of missed targets (the ER), the *Pull* metaphor ($M = .7$, $SD = .89$) led to less missed targets than the *Push* metaphor ($M = 1.33$, $SD = 1.92$). Within the *Pull* metaphor, the prototype with all 8 motors active led to the least number of errors ($M = .43$, $SD = .51$), followed by 6 motors ($M = .8$, $SD = 1.01$) and 4 motors ($M = .86$, $SD = 1.03$). Interestingly for the *Push* metaphor, the prototype with the 4 active motors performed best ($M = .93$, $SD = 1.44$), followed by the 8 motors ($M = 1.0$, $SD = .85$) and the 6 motors ($M = 2.07$, $SD = 2.82$). The two-way ANOVA test could not find a significant interaction effect between number of motors and metaphor, $F(2,82) = 1.193$, $p > 0.05$. A simple main effect analysis revealed that there was no significant main effect between the used number of motors ($p > 0.05$), however there was a significant difference with regard to the used metaphor ($p = 0.048$). A graphical overview is shown in Figure 4b.

Finally, considering the RTLX score, the *Pull* metaphor ($M = 42.02$, $SD = 16.34$) led to a lower RTLX score than the *Push* metaphor ($M = 46.9$, $SD = 17.81$). Within the *Pull* metaphor, the 8 motor prototype ($M = 39.87$, $SD = 16.78$) led to the lowest RTLX score, followed by 4 motors ($M = 41.93$, $SD = 16.34$) and 6 motors ($M = 44.27$, $SD = 14.55$). However, for the *Push* metaphor, the 4 motors prototype ($M = 44.49$, $SD = 16.91$) led to the lowest RTLX score, followed by 8 motors ($M = 46.25$, $SD = 18.06$) and 6 motors ($M = 49.97$, $SD = 19.20$). A two-way ANOVA could not find a significant interaction effect between the number of motors and metaphor, $F(2,84) = .108$, $p > 0.05$. Also, there were no significant main effects for the RTLX score. Results are also depicted in Figure 4c.

4.5.1 Qualitative Feedback.

During the study, the participants were free to give comments on everything they like, dislike or experience. In addition, we prepared a final questionnaire in which we asked the participants what they liked while using the glove and what could be improved. Another text field for other comments was optional.

In general, spatial guidance through vibrotactile actuation was completely new for the participants, but they found it well suited for this form of interaction (*"it is an interesting experience to use this glove"* (P2)). There was a strong consensus that vibration feedback is very intuitive and the idea of eyes-free spatial guidance was highly appreciated. Further, they described it as easy-to-use as *"it is quite simple, can instantly be understood and used"* (P5).

The high success rates were confirmed by the users, saying *"it eventually brings you to the target and gives you a feeling of success"* (P4). Interestingly, some participants thought they performed better during *Push* conditions, but felt more confident with *Pull*. However, we could observe that, in all described cases, *Pull* still performed better.

The participants were generally very confident and pleased with the glove. One participant said *"it is lightweight and fits my hand very well"* (P15) and another one described the glove as very comfortable (*"cuddly"*, P10). However, a few persons with smaller hands expressed that the vibration motors could be tighter to the skin (*"put motors closer to skin"* (P1), *"motors should be tighter"* (P13). This probably resulted because of just having a unisize glove instead of differently sized prototypes respecting the user's hand size.

Some participants reported that they have issues with distinguishing single actuators. The position of the top and back motor were sometimes impressed as to close to each other. This also occurred with the top and bottom actuators (*"the localization of the vibrators on the back of the hand are a bit difficult to differentiate from up and down"*, P12). Hereby, users had the impression that *"the lower vibration motor felt stronger"* (P12) and *"the impression on the back side of the hand was harder"* (P7). However, we identified that this seems to be especially the case if participants have slim hands.

4.5.2 Feedback on use-cases.

We asked the participants in which real-world situations they can imagine to use such a system. Participants were very curious and especially praised the potential for assisting persons with disabilities, such as visually impaired. They acclaimed that *"hands are free for other work and it can be done blind-folded"* (P7). One highlighted the good perception for navigating in 3D space (*".. the possibility of an interface to the 3D space"*, P4). This was the most commonly identified scenario and the participants provided a wide range of related real-world examples. Ranging from generic situations, such as *"finding objects without looking"* (P2) or *"support for visual search"* (P10) to *"positioning an object precisely with vibration help"* (P7). One subject named a very precise example in which *"visually impaired persons have to find buttons like door-openers in public transport or at traffic lights"* (P3). A different situation that applies to not only disabilities, was using the system for finding *"groceries in a supermarket"* (P12).

An interesting aspect some of the participants mentioned was to use it for educational purposes, such as painting tutorials where the hand is guided to draw something. P11 told that it could be even used for learning hand-writing in school, while P7 suggested *"to teach driving"*. Similar, participants also named industrial situations as real-world scenarios where *"some kind of physical interaction is required"* (P1), such as *"medical tasks like surgeries"* (P13) or *"maintenance tasks [..] at a machine"* (P5). However, one user wants it to be *"more robust to be used in industrial scenarios"* (P13).

As a suggestion for future work, P6 had the idea of using the glove for haptic feedback in AR and Virtual Reality (VR) scenarios. Moreover, the participant added the idea to increase the number of actuators and put it to *"a finger-granularity which might be good to feel virtual objects and perceive them as haptic"*. Considering AR, three participants (P6, P8, P15) suggested to use it for gaming purposes but did not go into detail any further.

5 DISCUSSION AND GUIDELINES

Based on the results of our study, we identified several results that answer the questions how the number of actuators and the used metaphor affect the performance of users while using our vibrotactile system, which we discuss in the following.

We could show that navigation through vibrotactile actuation on the hand is feasible in 3D space. Users were quickly able to learn the vibration patterns and identify targets around them. However, the process of target acquisition can be further improved in terms of speed. Hence, we plan to improve our design by more distinguishable patterns, especially for the up and down actuation. In addition, users reported that the vibration frequency should have a higher base value if the target is still in far range since low frequencies are harder to recognize. Based on the findings from our study, we present a set of design guidelines for vibrotactile guidance of the user's hand in 3D space.

Prefer *Pull* over *Push*: *Pull* had in almost every case a better overall performance than the *Push* metaphor. In terms of TCT, *Pull* was faster than *Push* in most cases besides during the *4+2* motors conditions. This is also affirmed by the lower error rates in *Pull* conditions. With regards to the user feedback, *Pull* was preferred by the majority and described as more natural. This was also indicated by the better RTLX scores.

Use a high number of actuators: Using *8+2* actuators had the highest resolution on the hand and also resulted in the fastest TCT for both, *Pull* and *Push*. This was especially the case for *Pull* conditions where adding more actuators always led to lower TCT. However, for *Pull*, *4+2* was faster than *6+2*, but still slower than the full enabled *8+2* motors. Similar, the average errors made by users decreased when using more actuators in every case for *Pull* conditions. However, users described having only a few motors as better distinguishable, but it took them longer to identify targets. They rated *4+2* and *8+2* conditions similar, but did not like the *6+2* conditions.

Provide actuators in all four cardinal directions: Another finding based on the user feedback is to support vibration actuators in all four cardinal directions on the hand (compare with a compass). This is further indicated by the fact that users performed better in almost every condition featuring such a layout (*4+2* and *8+2*). Users often had issues following the vibration patterns if there was no clear left or right during the *6+2* conditions and performed worst during those conditions. This was also backed by the better results of the RTLX scores for *4+2* and *8+2*.

6 CONCLUSION

In this paper, we investigated the premise that spatial guidance systems for precise and direct targeting of objects in hand-reachable distances is still underexplored and can be improved by adding vibrotactile actuators to the user's hand providing full spatial navigation in a 3D space. Therefore, we presented *TactileGlove*, a novel wearable guidance system using vibrotactile actuation. Through a user study with 15 participants, we found that using the *Pull* metaphor for designing vibrotactile navigation instructions for 3D spaces leads to fewer errors than the *Push* metaphor. Further, we found that using more actuators for communicating vibrotactile navigation instructions leads to a better performance considering the Task Completion Time. Based on the findings of the user study, we propose guidelines for designing vibrotactile feedback for 3D space navigation and discuss the implications for assistive technology.

In future, we want to explore the effect of our system for persons with visual impairments and how it can be used to assist them in daily situations. In addition, we plan to add more distinct vibration patterns to support commands, such as rotating the hand. As a further improvement, we plan to combine the vibrotactile actuation of a user's hand with visual AR and VR environments.

7 ACKNOWLEDGEMENTS

We thank Vanessa Stenner, Nils Dycke and Niklas Mast for their support. This work was supported by the German Federal Ministry of Education and Research (BMBF) SWC "ARkTiP" (01IS17050).

REFERENCES

[1] Patrick Baudisch and Ruth Rosenholtz. 2003. Halo: A Technique for Visualizing Off-screen Objects. In *Proceedings of the conference on Human factors in computing systems - CHI '03 (CHI '03)*. ACM Press, New York, New York, USA, 481. https://doi.org/10.1145/642611.642695

[2] Frank Biocca, Arthur Tang, Charles Owen, and Fan Xiao. 2006. Attention Funnel: Omnidirectional 3D Cursor for Mobile Augmented Reality Platforms. In *Proceedings of the SIGCHI conference on Human Factors in computing systems - CHI '06 (CHI '06)*. ACM Press, New York, New York, USA, 1115. https://doi.org/10.1145/1124772.1124939

[3] Megan L. Brown, Sandra L. Newsome, and Ephraim P. Glinert. 1989. An experiment into the use of auditory cues to reduce visual workload. *ACM SIGCHI Bulletin* 20, SI (mar 1989), 339–346. https://doi.org/10.1145/67450.67515

[4] Andreas Butz, Michael Schneider, and Mira Spassova. 2004. SearchLight – A Lightweight Search Function for Pervasive Environments. In *Pervasive*, Vol. 3001. Springer, 351–356. https://doi.org/10.1007/978-3-540-24646-6_26

[5] Michal Karol Dobrzynski, Seifeddine Mejri, Steffen Wischmann, and Dario Floreano. 2012. Quantifying Information Transfer Through a Head-Attached Vibrotactile Display: Principles for Design and Control. *IEEE Transactions on Biomedical Engineering* 59, 7 (jul 2012), 2011–2018. https://doi.org/10.1109/TBME.2012.2196433

[6] Corinna Feeken, Merlin Wasmann, Wilko Heuten, Dag Ennenga, Heiko Müller, and Susanne Boll. 2016. ClimbingAssist: direct vibro-tactile feedback on climbing technique. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing Adjunct - UbiComp '16*. ACM, ACM Press, New York, New York, USA, 57–60. https://doi.org/10.1145/2968219.2971417

[7] Markus Funk, Juana Heusler, Elif Akcay, Klaus Weiland, and Albrecht Schmidt. 2016. Haptic, Auditory, or Visual?: Towards Optimal Error Feedback at Manual Assembly Workplaces. In *Proceedings of the 9th ACM International Conference on PErvasive Technologies Related to Assistive Environments - PETRA '16*. ACM Press, New York, New York, USA, 1–6. https://doi.org/10.1145/2910674.2910683

[8] Kalanit Grill-Spector and Nancy Kanwisher. 2005. Visual Recognition: As Soon as You Know It Is There, You Know What It Is. *Psychological Science* 16, 2 (feb 2005), 152–160. https://doi.org/10.1111/j.0956-7976.2005.00796.x

[9] Sandra G Hart. 2006. Nasa-Task Load Index (NASA-TLX); 20 Years Later. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 50. Sage Publications Sage CA: Los Angeles, CA, 904–908. https://doi.org/10.1177/154193120605000909

[10] Steven J. Henderson and Steven Feiner. 2009. Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret. In *2009 8th IEEE International Symposium on Mixed and Augmented Reality*. IEEE, IEEE, 135–144. https://doi.org/10.1109/ISMAR.2009.5336486

[11] Wilko Heuten, Niels Henze, Susanne Boll, and Martin Pielot. 2008. Tactile wayfinder: a non-visual support system for wayfinding. In *Proceedings of the 5th Nordic conference on Human-computer interaction building bridges - NordiCHI '08*. ACM Press, New York, New York, USA, 172. https://doi.org/10.1145/1463160.1463179

[12] Simon Holland, David R. Morse, and Henrik Gedenryd. 2002. AudioGPS: Spatial Audio Navigation with a Minimal Attention Interface. *Personal and Ubiquitous Computing* 6, 4 (sep 2002), 253–259. https://doi.org/10.1007/s007790200025

[13] Gunnar Jansson. 1983. Tactile Guidance of Movement. (jan 1983), 37–46 pages. https://doi.org/10.3109/00207458309148644

[14] Idin Karuei, Karon E MacLean, Zoltan Foley-Fisher, Russell MacKenzie, Sebastian Koch, and Mohamed El-Zohairy. 2011. Detecting vibrations across the body in mobile contexts. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11 (CHI '11)*. ACM Press, New York, New York, USA, 3267. https://doi.org/10.1145/1978942.1979426

[15] Oliver Beren Kaul and Michael Rohs. 2016. HapticHead: 3D Guidance and Target Acquisition Through a Vibrotactile Grid. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16 (CHI EA '16)*. ACM Press, New York, New York, USA, 2533–2539. https://doi.org/10.1145/2851581.2892355

[16] Oliver Beren Kaul and Michael Rohs. 2017. HapticHead: A Spherical Vibrotactile Grid Around the Head for 3D Guidance in Virtual and Augmented Reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17 (CHI '17)*. ACM Press, New York, New York, USA, 3729–3740. https://doi.org/10.1145/3025453.3025684

[17] Hamideh Kerdegari, Yeongmi Kim, and Tony J Prescott. 2016. Head-Mounted Sensory Augmentation Device: Comparing Haptic and Audio Modality. In *Conference on Biomimetic and Biohybrid Systems*. Springer, 107–118. https://doi.org/10.1007/978-3-319-42417-0_11

[18] Thomas Kosch, Romina Kettner, Markus Funk, and Albrecht Schmidt. 2016. Comparing Tactile, Auditory, and Visual Assembly Error-Feedback for Workers with Cognitive Impairments. In *Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility - ASSETS '16*. ACM, ACM Press, New York, New York, USA, 53–60. https://doi.org/10.1145/2982142.2982157

[19] Sreekar Krishna, Shantanu Bala, Troy McDaniel, Stephen McGuire, and Sethuraman Panchanathan. 2010. VibroGlove: An Assistive Technology Aid for Conveying Facial Expressions. In *Proceedings of the 28th of the international conference extended abstracts on Human factors in computing systems - CHI EA '10 (CHI EA '10)*. ACM Press, New York, New York, USA, 3637. https://doi.org/10.1145/1753846.1754031

[20] Seungyon "Claire" Lee and Thad Starner. 2010. BuzzWear: alert perception in wearable tactile displays on the wrist. In *Proceedings of the 28th international conference on Human factors in computing systems - CHI '10*. ACM Press, New York, New York, USA, 433. https://doi.org/10.1145/1753326.1753392

[21] Ville Lehtinen, Antti Oulasvirta, Antti Salovaara, and Petteri Nurmi. 2012. Dynamic tactile guidance for visual search tasks. In *Proceedings of the 25th annual ACM symposium on User interface software and technology - UIST '12 (UIST '12)*. ACM Press, New York, New York, USA, 445. https://doi.org/10.1145/2380116.2380173

[22] Tal Oron-Gilad, Joshua L Downs, Richard D Gilson, and Peter A Hancock. 2007. Vibrotactile Guidance Cues for Target Acquisition. *IEEE Transactions on Systems, Man and Cybernetics, Part C (Applications and Reviews)* 37, 5 (sep 2007), 993–1004. https://doi.org/10.1109/TSMCC.2007.900646

[23] John Palmer. 1995. Attention in Visual Search: Distinguishing Four Causes of a Set-Size Effect. *Current Directions in Psychological Science* 4, 4 (aug 1995), 118–123. https://doi.org/10.1111/1467-8721.ep10772534

[24] John Palmer, Cynthia T Ames, and Delwin T Lindsey. 1993. Measuring the effect of attention on simple visual search. *Journal of Experimental Psychology: Human Perception and Performance* 19, 1 (1993), 108–130. https://doi.org/10.1037/0096-1523.19.1.108

[25] Sabrina Paneels, Margarita Anastassova, Steven Strachan, Sophie Pham Van, Saranya Sivacoumarane, and Christian Bolzmacher. 2013. What's around me? Multi-actuator haptic feedback on the wrist. In *2013 World Haptics Conference (WHC)*. IEEE, IEEE, 407–412. https://doi.org/10.1109/WHC.2013.6548443

[26] Yael Salzer, Tal Oron-Gilad, and Adi Ronen. 2010. Vibrotactor-Belt on the Thigh – Directions in the Vertical Plane. *Haptics: Generating and Perceiving Tangible Sensations* (2010), 359–364. https://doi.org/10.1007/978-3-642-14075-4_53

[27] Maximilian Schirmer, Johannes Hartmann, Sven Bertel, and Florian Echtler. 2015. Shoe me the Way: A Shoe-Based Tactile Interface for Eyes-Free Urban Navigation. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '15*. ACM, ACM Press, New York, New York, USA, 327–336. https://doi.org/10.1145/2785830.2785832

[28] Daniel Spelmezan, Anke Hilgers, and Jan Borchers. 2009. A language of tactile motion instructions. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '09*. ACM, ACM Press, New York, New York, USA, 1. https://doi.org/10.1145/1613858.1613896

[29] Hiroaki Tobita and Takuya Kuzi. 2012. SmartWig: wig-based wearable computing device for communication and entertainment. In *Proceedings of the International Working Conference on Advanced Visual Interfaces - AVI '12*. ACM, ACM Press, New York, New York, USA, 299. https://doi.org/10.1145/2254556.2254613

[30] Koji Tsukada and Michiaki Yasumura. 2004. ActiveBelt: Belt-Type Wearable Tactile Display for Directional Navigation. In *International Conference on Ubiquitous Computing*. Springer, 384–399. https://doi.org/10.1007/978-3-540-30119-6_23

[31] Hajime Uchiyama, Michael A. Covington, and Walter D. Potter. 2008. Vibrotactile Glove guidance for semi-autonomous wheelchair operations. In *Proceedings of the 46th Annual Southeast Regional Conference on XX - ACM-SE 46 (ACM-SE 46)*. ACM Press, New York, New York, USA, 336. https://doi.org/10.1145/1593105.1593195

[32] Bernhard Weber, Simon Schatzle, Thomas Hulin, Carsten Preusche, and Barbara Deml. 2011. Evaluation of a vibrotactile feedback device for spatial guidance. In *2011 IEEE World Haptics Conference*. IEEE, 349–354. https://doi.org/10.1109/WHC.2011.5945511

[33] John S. Zelek. 2005. Seeing by touch (haptics) for wayfinding. *International Congress Series* 1282 (2005), 1108–1112. https://doi.org/10.1016/j.ics.2005.06.002