COMPUTER-SUPPORTED MOVEMENT GUIDANCE:

INVESTIGATING VISUAL/VISUOTACTILE GUIDANCE AND INFORMING THE DESIGN OF VIBROTACTILE BODY-WORN INTERFACES

Vom Fachbereich Informatik der Technischen Universität Darmstadt genehmigte

Dissertation

zur Erlangung des akademischen Grades eines Doctor rerum naturalium (Dr. rer. nat.).

Eingereicht von
Hesham Nabil Abdelrahman Elsayed, M.Sc.

Erstreferent:	Prof. Dr. Max Mühlhäuser
Korreferent:	Prof. Dr. Martin Weigel
	Prof. Dr. Jan Gugenheimer

Tag der Einreichung:	27.01.2023
Tag der Disputation:	30.03.2023

Fachbereich Informatik
Telecooperation Lab
Technische Universität Darmstadt
Hochschulkennziffer D17

TECHNISCHE
UNIVERSITÄT
DARMSTADT

Elsayed, Hesham Nabil Abdelrahman : Computer-supported movement guidance: investigating visual/visuotactile guidance and informing the design of vibrotactile body-worn interfaces
Darmstadt, Technische Universität Darmstadt,
Jahr der Veröffentlichung der Dissertation auf TUprints: 2023
Tag der mündlichen Prüfung: 30.03.2023

ABSTRACT

This dissertation explores the use of interactive systems to support movement guidance, with applications in various fields such as sports, dance, physiotherapy, and immersive sketching. The research focuses on visual, haptic, and visuohaptic approaches and aims to overcome the limitations of traditional guidance methods, such as dependence on an expert and high costs for the novice. The main contributions of the thesis are (1) an evaluation of the suitability of various types of displays and visualizations of the human body for posture guidance, (2) an investigation into the influence of different viewpoints/perspectives, the addition of haptic feedback, and various movement properties on movement guidance in virtual environments, (3) an investigation into the effectiveness of visuotactile guidance for hand movements in a virtual environment, (4) two in-depth studies of haptic perception on the body to inform the design of wearable and handheld interfaces that leverage tactile output technologies, and (5) an investigation into new interaction techniques for tactile guidance of arm movements. The results of this research advance the state of the art in the field, provide design and implementation insights, and pave the way for new investigations in computer-supported movement guidance.

ZUSAMMENFASSUNG

Diese Dissertation untersucht die Verwendung interaktiver Systeme zur Unterstützung der Bewegungssteuerung mit Anwendungen in verschiedenen Bereichen wie Sport, Tanz, Physiotherapie und immersives Zeichnen. Die Forschung konzentriert sich auf visuelle, haptische und visuohaptische Ansätze und zielt auf die Überwindung von den Einschränkungen traditioneller Guidance Methoden, wie Abhängigkeit von Experten und hohe Kosten für Anfänger. Die wichtigsten Beiträge der Arbeit sind (1) eine Evaluierung der Eignung verschiedener Arten von Bildschirmen und Visualisierungen des menschlichen Körpers für Posture Guidance, (2) eine Untersuchung des Einflusses von unterschiedlichen Blickwinkeln/Perspektiven, der Darbietung von haptischen Reizen und verschiedener Bewegungseigenschaften auf die Bewegungssteuerung in virtuellen Umgebungen, (3) eine Untersuchung der Effektivität von visuohaptischer Steuerung für Handbewegungen in einer virtuellen Umgebung, (4) zwei vertiefende Studien zur haptischen Wahrnehmung am Körper, um das Design tragbarer und handgehaltenen Interfaces zu unterstützen, die haptische Ausgabetechnologien nutzen und (5) eine Untersuchung über neue Interaktionstechniken für die taktile Steuerung von Armbewegungen. Die Ergebnisse dieser Forschungsarbeit treiben den Stand der Technik im Bereich voran, liefern Erkenntnisse über Design und Implementierung und ebnen den Weg für neue Untersuchungen in der computerunterstützten Bewegungssteuerung.

ACKNOWLEDGMENTS

Looking back on the previous years, I am filled with immense gratitude for the support and guidance of so many individuals who have made this journey possible.

First and foremost, I would like to express my sincere gratitude to Max (Prof. Mühlhäuser, TU Darmstadt) for including me in his excellent group of researchers, for his advice and support throughout the years, and his belief in me that has been the driving force behind my success. I am amazed at how he finds the time to be there for every single person in his lab and I couldn't have wished for a better doctoral supervisor.

I am deeply indebted to Martin (Prof. Weigel, Technische Hochschule Mittelhessen) for his guidance and support throughout my journey. Our many fruitful conversations have been instrumental in shaping my scientific approach and significantly improving the quality of my ideas and research.

I would like to thank Jan (Prof. Gugenheimer, TU Darmstadt) for the valuable research advice and his time and effort serving as an examiner of this dissertation.

I would also like to extend my heartfelt thanks to all my colleagues at the Telecooperation Lab for creating a wonderful working environment. A special thank you to the current and previous members of the HCI group: Andrii, Domi, Flo, Jan, Julius, Karo, Markus, Martin, Niloo, Sepp, and Thomas. I am honored to have had the opportunity to work with such an incredible group of researchers. To Elke H and Elke R, thank you for the exceptional organizational support and for always fostering a positive and uplifting atmosphere.

Furthermore, I was extremely fortunate to have had the opportunity to work with researchers at the Honda Research Institute Europe during my doctoral studies. A special thank you to Herbert, Mathias, and Thomas.

Over the years, I have had the pleasure to work with many students and I am deeply grateful for the opportunity to have learned from each and every one of you.

Lastly, I would like to express my deepest gratitude to my family and friends for their unwavering love and support. Yassin, you have been a source of joy in my life.

This journey would not have been possible without the support of all the people mentioned. I am forever grateful for the role they have played in my life.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Part I

SYNOPSIS

1 INTRODUCTION

From guiding hand movements while drawing, to an expert demonstrating complex movements to novices, movement guidance plays an important role in our lives. Research in this area has the potential to revolutionize fields such as sports, dance, physiotherapy, immersive sketching, and various other forms of physical activities. Furthermore, in the field of Human-Computer Interaction (HCI), body-based interaction is foreseen to be the main modality for the next generation of displays. Although body movements in this case are initiated by users, users must initially learn how to utilize the interface. Computing devices can support the user by communicating the possibilities for interaction. Against this background, the present thesis contributes to the field of computer-supported movement guidance.

1.1 THE NEED FOR COMPUTER SUPPORT

Traditionally, a novice learns new movements under guidance of an expert. This guidance takes many forms, e.g. visually demonstrating a movement, verbally expressing instructions for moving certain body parts, and haptically guiding a novice through a movement. While this approach has proven to be effective, it depends on the availability of the expert and the novice at the same time and place, is limited by the attention span of expert/novice, and incurs high costs for the novice.

To overcome these limitations, a variety of novel approaches for movement guidance have been proposed. There are four basic strands of research in using computing devices to support movement guidance: (1) visual, (2) auditory, (3) haptic, and (4) multimodal guidance. Visual guidance has a long tradition and has been extensively researched. From video recordings of exercises, to interactive avatars in virtual reality that demonstrate movements to the user, visual guidance has proven to be very effective. However, visual guidance requires the user's attention to be directed at the display, which can limit the user's movements when using a 2D display. Audio-based guidance overcomes this limitation, but is often error-prone in the communication of complex movements. Haptic guidance does not require the visual attention of the user and can provide localized guidance cues directly on the body. However, compared to visual guidance, haptic guidance is less explored and is mostly limited to guidance of hand movements. Finally, multimodal approaches aim to combine visual, auditory, or haptic approaches to overcome the limitations associated with using a single type of guidance. Based on the requirements defined within this thesis, the focus of this dissertation is on visual, haptic, and visuohaptic approaches.

1.2 RESEARCH GAPS & SIGNIFICANCE OF RESEARCH

This thesis advances the state of the art in the field of computer-supported movement guidance with a focus on visual, haptic, and visuohaptic approaches. In the following, the six main contributions, the research gaps they address, and their significance is discussed.

The first contribution DISPLAY TYPES AND VISUALIZATIONS FOR POSTURE GUIDANCE concerns itself with the evaluation of the suitability of various types of flat displays and visualizations of the human body for posture guidance. Currently, users typically posses a diverse set of displays that include devices such as smartphones, tablets, and desktop computers. It was unclear, which of the many devices currently available to users can be leveraged for guidance. The literature lacked a systematic evaluation of the influence of display type on posture guidance. Furthermore, the literature lacked an investigation into the influence of using different visualizations of the human body. In this contribution, a systematic evaluation was carried out that shed light on the suitability of using different displays and visualizations for posture guidance. The results add to the body of knowledge in the literature by demonstrating the importance of the factors investigated, and paves the way for new investigations by researchers, e.g. building upon this work by including 3D displays, or investigating guidance of movements instead of static postures. For practitioners, the results are beneficial for the design and development of guidance systems.

While the first contribution investigates static postures on flat displays, the second contribution PERSPECTIVES IN VR FOR MOVEMENT GUIDANCE investigates guidance of movements using 3D displays. The transition from flat displays to head-mounted 3D displays enables a wide range of new interaction and visualization possibilities. Among the most important aspects to consider in this context is the choice of perspective used in a movement guidance system. Different perspectives that can be used with a 3D display include the first-person and third-person perspectives. The first-person perspective is analogous to how we see our bodies in the real world. The third-person perspective is an out-of-the-body view that is commonly used in games. This contribution investigates the influence of perspective, as well as other factors that arise when guiding movements instead of postures. The results highlight the importance of the choice of perspective for movement guidance, and provide concrete design guidelines that are beneficial to researchers and practitioners alike.

The first two contributions investigate movement guidance that is useful for a variety of fields - e.g. dancing, ballet, yoga, and rehabilitation. Next to these applications, drawing is a field where movement guidance can contribute significantly. HAPTIC ASSISTANCE FOR SKETCHING IN VR investigates the use of visuohaptic guidance for drawing in a virtual 3D environment. In comparison to 2D drawing, 3D drawing in virtual environments faces challenges such as the limited depth perception, higher hand-eye coordination required, and the lack of natural haptic feedback provided by surfaces. To overcome these limitations, approaches in the literature relied on force-feedback devices that can emulate interactions with physical surfaces where none exist. However, these devices are grounded, i.e. mounted on a stationary surface. Thus, users cannot move freely and are typically limited to a small interaction space. This contribution investigates an alternative approach, where haptic feedback is provided using vibrotactile and pneumatic actuators. With this approach, users are not restricted in their movements. The knowledge gained within this contribution can be directly leveraged by researchers and practitioners to provide more effective hand movement guidance in a virtual environment.

The next two contributions in this thesis investigate the influence of factors such as the spacing and arrangement of tactile actuators on haptic perception to inform some of the main design decisions required for on-body tactile interfaces. Tactile movement guidance is promising, however, work in this domain is sparse and mostly limited to guidance of hand movements. Among the hurdles that face researchers in this field is building economic tactile interfaces with respect to the number of actuators, the associated cost, required control wiring, and weight. Although most tactile actuators are lightweight and low-cost, using many actuators to cover a larger surface on the body would lead to a heavy and expensive setup with complicated wiring. In the field of haptics, research has shown that by leveraging tactile illusions it was possible to interpolate between physical actuators to produce sensations where no actuator exists. Based on this knowledge, SPACING OF VIBROTACTILE ACTUATORS ACROSS THE BODY investigates (1) the maximum spacing possible on major body locations where interpolation is still possible and (2) the minimum spacing where actuators can still be differentiated. This knowledge can be used to construct interfaces that are optimal in the number of actuators used and minimize weight, cost, and required control wiring. Extending this work, STATIONARY AND MOVING TACTILE SENSATIONS ON THE PALM investigates tactile interfaces on the palm. The knowledge gained within this contribution informs the design of wearable (e.g. gloves) and handheld (e.g. game controllers) tactile devices. Taken together, these contributions provide knowledge necessary for the construction of tactile output interfaces that are beneficial to movement guidance, as well as many other sub-fields within HCI.

While the previous contributions investigate the spacing required for constructing high-resolution tactile interfaces, the final contribution TACTILE VECTORS FOR OMNIDIRECTIONAL ARM GUIDANCE leverages this knowledge to investigate different interaction techniques for arm movement guidance. Prior work has used single vibrotactile actuators to communicate a movement direction to the user. This work investigates new concepts where two actuators are used to communicate a movement direction. The first actuator communicates the start point, while the second actuator communicates the endpoint of the direction vector. The knowledge gained within this contribution informs the choice of interaction technique for tactile movement guidance.

1.3 RESEARCH METHODOLOGY

The main methodology in this thesis is a controlled lab experiment - also referred to as a user study. User studies are carefully designed, conducted, and analyzed to answer the research questions and hypotheses formulated at the beginning of the research. During the design of these experiments, factors of interest to vary are determined (independent variables) and their influence measured using different metrics (dependent variables). Depending on the number of independent variables and their levels, different combinations (referred to as conditions) of these factors are possible. Other factors that are not included in the design as independent variables which could potentially influence the experiment are controlled. Furthermore, to prevent learning effects influencing the results of the user studies, the order of conditions is varied using a balanced Latin square. A within-subjects study design where participants experience all the different possible conditions is employed for all experiments in this thesis.

The typical sequence of events during conducting an experiment is as follows: (1) participants are welcomed to the lab and asked to provide consent for the collection of their data and to fill out a demographic questionnaire, (2) the task is briefly explained before participants start experiencing the different conditions, and (3) participants are required to fill out questionnaires either at the end or between conditions that measure further aspects concerning the user experience. During the user study, the defined dependent variables are collected by logging participants' actions as well as their answers to any questionnaires. To answer the research questions and hypotheses defined at the beginning of the experiment, the data is subsequently analyzed using inferential statistics. The statistical tests are either parametric - e.g. repeated measures analysis of variance (RM ANOVA) - or non-parametric - e.g. processing the data with the aligned rank transform (ART) procedure before conducting a RM ANOVA. The choice of statistical test depends on the design of the experiment (within-subjects or between-subjects), the number of independent variables, the number of levels of the independent variables, and whether the data fulfills the assumptions required for parametric tests. Qualitative data, such as participants opinions and comments, are summarized, structured and reported according to recurrent themes.

1.4 THESIS STRUCTURE

This cumulative dissertation is structured as follows. Part i, provides an introduction into the topic, an overview of the current state of the art based on selected related work, a detailed description of the contributions, a conclusion, and an outlook. Part ii lists the publications verbatim.

2 STATE OF THE ART

This chapter begins by defining the requirements for computer-supported movement guidance. A presentation and discussion of the current state of the art follows, excluding the contributions of this thesis. Research gaps are highlighted in the respective sections.

2.1 REQUIREMENTS

This section defines requirements for interaction in the context of computer-supported movement guidance that are used to inform the contributions of this thesis.

2.1.1 *Intuitive Guidance on a Sensory Level (**R1**)*

Much like an expert demonstrating a movement, the use of computing devices should allow beginners to quickly grasp information. The information should be presented in a way that does not require considerable cognitive load to interpret. Minimizing cognitive load has the advantage of leading to a faster reaction time and allows novices to become experts with the usage of an interface in a shorter amount of time.

2.1.2 *Localized Body-Related Feedback (**R2**)*

An expert can physically guide a novice through a movement, point to, or verbally express that the user should pay attention to certain body parts. This type of localized feedback is required to inform the novice of shortcomings in their performance of certain movements and to guide them towards improving the execution of these movements.

Approaches should therefore, whenever possible, use the opportunity to present on-body localized cues.

2.1.3 *Preservation of Self-Agency (**R3**)*

This thesis considers self-agency as an important requirement. Interaction technologies that reduce self-agency should therefore be avoided. Prominent examples of technologies to avoid are those that rely on body activation, e.g. exoskeletons [37], soft robotics [9], and EMS [36].

2.1.4 *Portability (**R4**)*

Approaches that allow relocation of the user carry several advantages. They enable a wide variety of application scenarios in a diverse set of environments, e.g practicing yoga in a park or physical rehabilitation at home. Interactive systems for movement guidance typically consist of (1) a sensing component (e.g. a camera) to perceive the state of the user's body, and (2) an output component (e.g. visual display) to give instructions based on the user's current state. Currently, portable motion capture can be achieved [57], making the choice of output technology decisive in whether an interactive system can be made portable.

2.1.5 *Wide Range of Usage Scenarios (**R5**)*

Systems and interaction techniques for movement guidance should not be limited to a certain set of movements, but should rather be able to support a wide variety of usage scenarios.

2.1.6 *High Accuracy Guidance (**R6**)*

Movement guidance systems and interaction techniques should, similar to natural interactions with an expert, communicate the movements to be performed with high accuracy.

2.2 STATE OF THE ART

This section provides an overview of prior work, makes research gaps [RG] explicit, and summarizes how prior work addressed the requirements defined.

2.2.1 *Visual Guidance*

A considerable amount of work exists for visual guidance of body movements [2–4, 7, 8, 12, 14, 15, 21–25, 27, 34, 48, 49, 51, 53, 54, 58, 59]. All interaction techniques proposed in these publications aim at showing the user how to move, with the main differences being in the display, perspective, and visualization used.

The approaches either leveraged VR [3, 4, 8, 11, 15, 24–27, 29, 58, 59] or AR [2, 12, 21–23, 34, 48, 49, 51, 53, 54]. In AR, approaches were either on 2D [2, 12, 48, 49, 53, 54] or 3D displays [21–23]. Although AR typically refers to head-mounted displays that blend digital information with the real environment, it can also be achieved with 2D displays. For example by integrating digital information with the real environment as captured by the camera feed of a smartphone. 2D displays used by prior work varied from monitors for desktop computers [34, 53] to large wall-sized displays [54]. Furthermore, approaches used different perspectives, with a 2D mirror view of the user being most common [2, 12, 34, 53, 54] and first and third person views being limited to 3D displays [21–23]. In contrast to 3D displays which are currently mostly limited to HMDs, there is a diverse set of 2D displays available on the consumer market, with the smartphone being the most ubiquitous. However, how well these displays can be used for guidance remains unclear. Additionally, different visualizations of human postures and movements have been used by the approaches presented in the literature. For example, the human body can be visualized using a skeleton, where only the joint locations and connections between the joints are displayed. Another possibility is the use of a 3D body model, where further information is visible, e.g. concerning the body composition. A comparison between the different display types, as well as between the different visualization types is missing in the literature.

[RG1]: How does the choice of display type and visualization type influence the accuracy and the user experience of a guidance system?

In VR, prior work employed different perspectives for movement guidance. Among these were the first person [15, 24, 59] and third person perspectives [25, 26, 59]. The first person perspective displays to the user a view which is similar to our real world view of our bodies. Guidance in this case follows using superimposed visual cues overlayed on top of the user's body. In contrast, the third person view displays the user from an outside of the body view, similar to what a person sees observing the user. Although all these approaches show promise for guiding movements, it is unclear which perspective to use for guidance, as no comparison between the different perspectives exists for movement guidance.

[RG2]: How does the choice of perspective influence the accuracy and the user experience of a movement guidance system?

2.2.2 *Auditory Guidance*

Computer-based auditory guidance of movements is still in the early stages of development. Particularly, approaches to guiding movements with audio have been mostly verbal instruction using words [33], audio cues [40], and sonification [16]. Directions for advancing auditory guidance include investigating spatial auditory cues that communicate distance and direction for movement guidance. Although promising, this thesis did not contribute in this direction, as auditory guidance alone does not fulfill several of the requirements for computer-supported movement guidance previously defined.

2.2.3 *Haptic Guidance*

Similar to auditory guidance, haptic guidance is still in the early stages of development with respect to computer support. Prior work can be structured along the type of guidance: either tactile [1, 5, 13, 20, 28, 30, 32, 35, 38, 43–45, 50, 55] or kinesthetic [19, 36, 39, 41, 52].

Among the different tactile output technologies available for movement guidance, mainly vibrotactile interfaces were used. This is due to the fact that these interfaces are low-cost, lightweight, portable, have low-power consumption, and are able to leverage tactile illusions in order to mimic high-resolution tactile output with lower-resolution devices. However, other technologies exist that can stimulate the skin, e.g. ultrasonic [56] and pneumatic [10] actuation.

Tactile interaction techniques mainly employed the push and pull metaphors [20]. According to the push metaphor, a vibration on the body is interpreted by the user as a pushing force at that location. In contrast, the pull metaphor pulls the user at the location of the vibration. It should be noted that prior work differed in the usage of these metaphors. For example, the target direction for a movement can be anywhere between tangential and perpendicular to the skin. How to interpret these cues must be initially learned by the user. Changing the direction of guidance has been achieved by including several actuators in the interface to communicate different directions according to a particular metaphor. These metaphors were also extended to moving tactile sensations on the body [50]. Generally, guidance with tactile output technologies has been limited mostly to the hand and wrist. While hand movements are important for interacting with the environment, they only constitute a part of the movements our bodies are capable of. The above mentioned and other interaction techniques have not been extended to guidance of the many possible movements involving different body parts. A hurdle facing researchers in this context is the development of high-resolution tactile interfaces that are able to stimulate arbitrary locations on the body. It is clear that covering an entire surface of the body with actuators would not be optimal in terms of cost, weight, and required control wiring. A possible solution to this problem is the use of tactile illusions that allow interpolating between physical actuators to produce sensations where no actuator exists. However, it is critical to understand the spacing requirements to leverage these illusions. Placing actuators too far apart would lead to losing the ability to interpolate between them. Placing them too close together would again lead to high costs, a heavier interface, and more control wiring required. An understanding of the spacing requirements is missing in the literature.

[RG3]: What is the spacing required for vibrotactile actuators across the body?

Closing this research gap is crucial for the continued development of research utilizing (vibro)tactile displays for on-body information transmission in general and movement guidance in particular.

For movement guidance with kinesthetic displays, different approaches were introduced, e.g. exoskeletons [37], pneumatic actuation [19], and EMS [36]. In addition to movement guidance, prior work mainly utilized these displays as a means to simulate force feedback as part of interactions in a virtual/augmented environment. Among these approaches, EMS proves to be most promising for actuating users due to the lack of bulky mechanical components (exoskeletons/robotics) and of tubes that connect to an external air compressor (pneumatic). However, to be able to guide movements, the interface must take control of the user's body to demonstrate the movement. Currently, research shows that users tend to reject the use of EMS if they lose agency or perceive a high level of risk with the interface [46]. Therefore, this thesis does not investigate leveraging kinesthetic displays for movement guidance.

2.2.4 *Multimodal Guidance*

Approaches for multimodal guidance have mainly focused on either visuoauditory [33, 42] or visuohaptic [31, 41] displays. In visuoauditory displays, demonstration of movements used the visual channel, while auditory instructions provided feedback to improve users' imitation of displayed movements.

Literature about visuotactile guidance is rather sparse. A closer look at the existing publications in this field reveals that the limited knowledge about economic large-surface tactile surfaces (see RG 3) led to

Modality	Technique/Technology	Related Work	Requirements					
			R1	R2	R3	R4	R5	R6
visual	2D displays	[2, 12, 48, 49, 53, 54]	✔	○	✔	○	✔	○
visual	3D displays	[3, 4, 8, 11, 15, 21–27, 29, 58, 59]	✔	○	✔	○	✔	✔
auditory	verbal instruction	[42]	✖	○	✔	✔	✖	✖
auditory	audio cues	(tactile+audio) [40]	✖	○	✔	✔	✖	✖
auditory	sonification	(visual+audio) [47]	✖	○	✔	✔	✖	✖
haptic	vibrotactile	[1, 5, 13, 20, 28, 30, 32, 35, 38, 43–45, 50, 55]	✔	✔	✔	✔	✔	○
haptic	exoskeletons	[37]	✔	✔	○	○	○	✔
haptic	pneumatic	[19]	✔	✔	○	✖	✔	✔
haptic	EMS	[36]	✔	✔	✖	✔	✖	○
visuoauditory	2D displays + verbal instruction		✔	○	✔	○	✔	✖
visuoauditory	3D displays + verbal instruction	[33]	✔	○	✔	✖	✔	✔
visuotactile	2D displays + vibrotactile	[5, 6, 43]	✔	✔	✔	○	✔	○
visuotactile	3D displays + vibrotactile		✔	✔	✔	○	✔	✔
visuokinesthetic	2D displays + kinesthetic	[17, 39, 41]	✔	✔	○	○	✔	✔
visuokinesthetic	3D displays + kinesthetic	[18]	✔	✔	○	○	✔	✔

Table 2.1: Overview of state of the art with respect to the defined requirements. ✔indicates a fulfilled requirement. ○indicates partial fulfillment of a requirement. ✖indicates a requirement that is not fulfilled.

the limited body of research. In particular, tactile guidance in this context was mainly limited to arm movements, and the usefulness of vibrotactile guidance as part of visuotactile solutions remained rather unclear in general, even more so with respect to complex movements (see, e.g., Bark et al. [5] and Bark et al. [6])

[RG4]: Can tactile cues support users in the context of visuotactile interaction for movement guidance?

Visuokinesthetic interfaces used grounded (i.e. mounted on a stationary surface) devices to generate counter forces during guidance of arm movements [39]. This thesis focuses on visuotactile instead of visuokinesthetic interaction to avoid reducing the sense of agency.

2.3 CONCLUSION

Table 2.1 shows an overview of the state of the art with respect to the defined requirements. Considering unimodal approaches to movement guidance, it is clear that an accurate vibrotactile approach satisfies all requirements. It is not clear, however, if such an approach is possible. This thesis builds the foundation for investigations using high-resolution vibrotactile guidance. Considering multimodal approaches, combining 3D visual displays with vibrotactile feedback is promising. Moreover, from the perspective of VR versus AR, AR approaches allow for portability.

REFERENCES

[1] Marco Aggravi, Gionata Salvietti, and Domenico Prattichizzo. "Haptic wrist guidance using vibrations for Human-Robot teams." In: *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)* (Aug. 2016), pp. 113–118. ISSN: 1944-9437. DOI: 10.1109/ROMAN.2016.7745098.

[2] Fraser Anderson, Tovi Grossman, Justin Matejka, and George Fitzmaurice. "YouMove: Enhancing Movement Training with an Augmented Reality Mirror." In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST '13. New York, NY, USA: Association for Computing Machinery, 2013, pp. 311–320. ISBN: 978-1-4503-2268-3. DOI: 10.1145/2501988.2502045.

[3] Rahul Arora, Rubaiat Habib Kazi, Fraser Anderson, Tovi Grossman, Karan Singh, and George Fitzmaurice. "Experimental Evaluation of Sketching on Surfaces in VR." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. New York, NY, USA: ACM, 2017, pp. 5643–5654. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025474.

[4] R R Barioni, W Costa, A Aleluia, and V Teichrieb. "BalletVR: a Virtual Reality System for Ballet Arm Positions Training." In: *2019 21st Symposium on Virtual and Augmented Reality (SVR)*. 2019, pp. 10–16. DOI: 10.1109/SVR.2019.00018.

[5] Karlin Bark, Emily Hyman, Frank Tan, Elizabeth Cha, Steven A Jax, Laurel J Buxbaum, and Katherine J Kuchenbecker. "Effects of Vibrotactile Feedback on Human Learning of Arm Motions." In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 23.1 (Jan. 2015), pp. 51–63. ISSN: 1534-4320. DOI: 10.1109/TNSRE.2014.2327229.

[6] Karlin Bark, Preeya Khanna, Rikki Irwin, Pulkit Kapur, Steven A. Jax, Laurel J. Buxbaum, and Katherine J. Kuchenbecker. "Lessons in using vibrotactile feedback to guide fast arm motions." In:

2011 IEEE World Haptics Conference. 2011, pp. 355–360. DOI: 10.1109/WHC.2011.5945512.

[7] Olivier Bau and Wendy E Mackay. "OctoPocus: A Dynamic Guide for Learning Gesture-based Command Sets." In: *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology*. UIST '08. New York, NY, USA: ACM, 2008, pp. 37–46. ISBN: 978-1-59593-975-3. DOI: 10.1145/1449715.1449724.

[8] Jacky C P Chan, Howard Leung, Jeff K T Tang, and Taku Komura. "A Virtual Reality Dance Training System Using Motion Capture Technology." In: *IEEE Trans. Learn. Technol.* 4.2 (Apr. 2011). Place: Washington, DC, USA Publisher: IEEE Computer Society Press, pp. 187–195. ISSN: 1939-1382. DOI: 10.1109/TLT.2010.27.

[9] Chia-Yu Chen, Yen-Yu Chen, Yi-Ju Chung, and Neng-Hao Yu. "Motion Guidance Sleeve: Guiding the Forearm Rotation through External Artificial Muscles." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: Association for Computing Machinery, 2016, pp. 3272–3276. ISBN: 9781450333627. DOI: 10.1145/2858036.2858275.

[10] Kyung Yun Choi, Jinmo Lee, Neska ElHaouij, Rosalind Picard, and Hiroshi Ishii. "ASpire: Clippable, Mobile Pneumatic-Haptic Device for Breathing Rate Regulation via Personalizable Tactile Feedback." In: *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. CHI EA '21. Yokohama, Japan: Association for Computing Machinery, 2021. ISBN: 9781450380959. DOI: 10.1145/3411763.3451602.

[11] Philo Tan Chua, Rebecca Crivella, Bo Daly, Ning Hu, Russ Schaaf, David Ventura, Todd Camill, Jessica Hodgins, and Randy Pausch. "Training for Physical Tasks in Virtual Environments: Tai Chi." In: *Proceedings of the IEEE Virtual Reality 2003*. VR '03. Washington, DC, USA: IEEE Computer Society, 2003, pp. 87–. ISBN: 0-7695-1882-6.

[12] Christopher Clarke, Doga Cavdir, Patrick Chiu, Laurent Denoue, and Don Kimber. "Reactive Video: Adaptive Video Playback Based on User Motion for Supporting Physical Activity." In: *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. New York, NY, USA: Association for

Computing Machinery, 2020, pp. 196–208. ISBN: 978-1-4503-7514-6.

[13] Heather Culbertson, Julie M Walker, Michael Raitor, and Allison M Okamura. "WAVES: A Wearable Asymmetric Vibration Excitation System for Presenting Three-Dimensional Translation and Rotation Cues." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. New York, NY, USA: ACM, 2017, pp. 4972–4982. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025741.

[14] William Delamare, Thomas Janssoone, Céline Coutrix, and Laurence Nigay. "Designing 3D Gesture Guidance: Visual Feedback and Feedforward Design Options." In: 2016, pp. 152–159. DOI: 10.1145/2909132.2909260.

[15] Maximilian Dürr, Rebecca Weber, Ulrike Pfeil, and Harald Reiterer. "EGuide: Investigating Different Visual Appearances and Guidance Techniques for Egocentric Guidance Visualizations." In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '20. New York, NY, USA: Association for Computing Machinery, 2020, pp. 311–322. ISBN: 978-1-4503-6107-1. DOI: 10.1145/3374920.3374945.

[16] Alfred O. Effenberg, Ursula Fehse, Gerd Schmitz, Bjoern Krueger, and Heinz Mechling. "Movement Sonification: Effects on Motor Learning beyond Rhythmic Adjustments." In: *Frontiers in Neuroscience* 10 (2016). ISSN: 1662-453X. DOI: 10.3389/fnins.2016.00219.

[17] Marco Ewerton, David Rother, Jakob Weimar, Gerrit Kollegger, Josef Wiemeyer, Jan Peters, and Guilherme Maeda. "Assisting Movement Training and Execution With Visual and Haptic Feedback." In: *Frontiers in Neurorobotics* 12 (2018), p. 24. ISSN: 1662-5218. DOI: 10.3389/fnbot.2018.00024.

[18] David Feygin, Madeleine Keehner, and R Tendick. "Haptic guidance: Experimental evaluation of a haptic training method for a perceptual motor skill." In: *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*. IEEE. 2002, pp. 40–47.

[19] Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. "PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments." In: *Proceedings of the 2019 on Designing Interactive*

Systems Conference. DIS '19. New York, NY, USA: ACM, 2019, pp. 227–240. ISBN: 978-1-4503-5850-7. DOI: 10.1145/3322276.3322302.

[20] Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. "TactileGlove: Assistive Spatial Guidance in 3D Space Through Vibrotactile Navigation." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. PETRA '18. New York, NY, USA: ACM, 2018, pp. 273–280. ISBN: 978-1-4503-6390-7. DOI: 10.1145/3197768.3197785.

[21] Natsuki Hamanishi, Takashi Miyaki, and Jun Rekimoto. "Assisting Viewpoint to Understand Own Posture as an Avatar In-Situation." In: *Proceedings of the 5th International ACM In-Cooperation HCI and UX Conference*. CHIuXiD'19. New York, NY, USA: Association for Computing Machinery, 2019, pp. 1–8. ISBN: 978-1-4503-6187-3. DOI: 10.1145/3328243.3328244.

[22] Ping-Hsuan Han, Kuan-Wen Chen, Chen-Hsin Hsieh, Yu-Jie Huang, and Yi-Ping Hung. "AR-Arm: Augmented Visualization for Guiding Arm Movement in the First-Person Perspective." In: *Proceedings of the 7th Augmented Human International Conference 2016*. AH '16. New York, NY, USA: ACM, 2016, 31:1–31:4. ISBN: 978-1-4503-3680-2. DOI: 10.1145/2875194.2875237.

[23] Ping-Hsuan Han, Yang-Sheng Chen, Yilun Zhong, Han-Lei Wang, and Yi-Ping Hung. "My Tai-Chi Coaches: An Augmented-Learning Tool for Practicing Tai-Chi Chuan." In: *Proceedings of the 8th Augmented Human International Conference on - AH '17*. 2017. ISBN: 978-1-4503-4835-5. DOI: 10.1145/3041164.3041194.

[24] Thuong N Hoang, Martin Reinoso, Frank Vetere, and Egemen Tanin. "Onebody: Remote Posture Guidance System Using First Person View in Virtual Environment." In: *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. NordiCHI '16. New York, NY, USA: ACM, 2016, 25:1–25:10. ISBN: 978-1-4503-4763-1. DOI: 10.1145/2971485.2971521.

[25] Felix Hülsmann, Cornelia Frank, Irene Senna, Marc O Ernst, Thomas Schack, and Mario Botsch. "Superimposed Skilled Performance in a Virtual Mirror Improves Motor Performance and Cognitive Representation of a Full Body Motor Action." In: *Frontiers in Robotics and AI* 6 (2019), p. 43. ISSN: 2296-9144. DOI: 10.3389/frobt.2019.00043.

[26] Felix Hülsmann, Jan Göpfert, Barbara Hammer, Stefan Kopp, Mario Botsch, Jan Philip Göpfert, Barbara Hammer, Stefan Kopp, and Mario Botsch. "Classification of motor errors to provide real-time feedback for sports coaching in virtual reality — A case study in squats and Tai Chi pushes." In: *Computers & Graphics* 76 (2018). DOI: 10.1016/j.cag.2018.08.003.

[27] Florian Jeanne, Yann Soullard, Ali Oker, and Indira Thouvenin. "EBAGG: Error-Based Assistance for Gesture Guidance in Virtual Environments." In: *2017 IEEE 17th International Conference on Advanced Learning Technologies (ICALT)*. 2017, pp. 472–476. DOI: 10.1109/ICALT.2017.32.

[28] Yeon Sub Jin, Han Yong Chun, Eun Tai Kim, and Sungchul Kang. "VT-ware: A wearable tactile device for upper extremity motion guidance." In: *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*. 2014, pp. 335–340. DOI: 10.1109/ROMAN.2014.6926275.

[29] Marcelo Kallmann, Carlo Camporesi, and Jay Han. "VR-Assisted Physical Rehabilitation: Adapting to the Needs of Therapists and Patients." In: *Virtual Realities: International Dagstuhl Seminar, Dagstuhl Castle, Germany, June 9-14, 2013, Revised Selected Papers*. Ed. by Guido Brunnett, Sabine Coquillart, Robert van Liere, Gregory Welch, and Libor Váša. Cham: Springer International Publishing, 2015, pp. 147–168. ISBN: 978-3-319-17043-5. DOI: 10.1007/978-3-319-17043-5_9.

[30] Pulkit Kapur, Mallory Jensen, Laurel J Buxbaum, Steven A Jax, and Katherine J Kuchenbecker. "Spatially distributed tactile feedback for kinesthetic motion guidance." In: *2010 IEEE Haptics Symposium*. 2010, pp. 519–526. DOI: 10.1109/HAPTIC.2010.5444606.

[31] Nicholas Katzakis, Jonathan Tong, Oscar Ariza, Lihan Chen, Gudrun Klinker, Brigitte Röder, and Frank Steinicke. "Stylo and Handifact: Modulating Haptic Perception through Visualizations for Posture Training in Augmented Reality." In: *Proceedings of the 5th Symposium on Spatial User Interaction*. SUI '17. New York, NY, USA: Association for Computing Machinery, 2017, pp. 58–67. ISBN: 978-1-4503-5486-8. DOI: 10.1145/3131277.3132181.

[32] Oliver Beren Kaul and Michael Rohs. "HapticHead: A Spherical Vibrotactile Grid Around the Head for 3D Guidance in Virtual and Augmented Reality." In: *Proceedings of the 2017 CHI Confer-*

ence on Human Factors in Computing Systems. CHI '17. New York, NY, USA: ACM, 2017, pp. 3729–3740. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025684.

[33] Iwan de Kok, Julian Hough, Felix Hülsmann, Mario Botsch, David Schlangen, and Stefan Kopp. "A Multimodal System for Real-Time Action Instruction in Motor Skill Learning." In: *Proceedings of the 2015 ACM on International Conference on Multimodal Interaction*. ICMI '15. New York, NY, USA: Association for Computing Machinery, 2015, pp. 355–362. ISBN: 978-1-4503-3912-4. DOI: 10.1145/2818346.2820746.

[34] Ting-Yang Lin, Chung-Hung Hsieh, and Jiann-Der Lee. "A Kinect-Based System for Physical Rehabilitation: Utilizing Tai Chi Exercises to Improve Movement Disorders in Patients with Balance Ability." In: *Proceedings of the 2013 7th Asia Modelling Symposium*. AMS '13. USA: IEEE Computer Society, 2013, pp. 149–153. ISBN: 978-0-7695-5101-2. DOI: 10.1109/AMS.2013.29.

[35] Janet van der Linden, Erwin Schoonderwaldt, Jon Bird, and Rose Johnson. "MusicJacket—Combining Motion Capture and Vibrotactile Feedback to Teach Violin Bowing." In: *IEEE Transactions on Instrumentation and Measurement* 60.1 (2011), pp. 104–113. DOI: 10.1109/TIM.2010.2065770.

[36] Pedro Lopes, Do$\backslash$uaa Yüksel, François Guimbretière, and Patrick Baudisch. "Muscle-plotter: An Interactive System Based on Electrical Muscle Stimulation That Produces Spatial Output." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. New York, NY, USA: ACM, 2016, pp. 207–217. ISBN: 978-1-4503-4189-9. DOI: 10.1145/2984511.2984530.

[37] Andrés Martínez, Brian Lawson, and Michael Goldfarb. "A Controller for Guiding Leg Movement During Overground Walking With a Lower Limb Exoskeleton." In: *IEEE Transactions on Robotics* 34.1 (2018), pp. 183–193. DOI: 10.1109/TRO.2017.2768035.

[38] Troy McDaniel, Morris Goldberg, Daniel Villanueva, Lakshmie Narayan Viswanathan, and Sethuraman Panchanathan. "Motor Learning Using a Kinematic-Vibrotactile Mapping Targeting Fundamental Movements." In: MM '11. New York, NY, USA: Association for Computing Machinery, 2011, pp. 543–552. ISBN: 978-1-4503-0616-4. DOI: 10.1145/2072298.2072369.

[39] Ronak R Mohanty, Ricardo M Castillo, Eric D Ragan, and Vinayak R Krishnamurthy. "Investigating Force-Feedback in Mid-Air Sketching of Multi-Planar Three-Dimensional Curve-Soups." In: *Journal of Computing and Information Science in Engineering* 20.1 (2019). ISSN: 1530-9827. DOI: 10.1115/1.4045142.

[40] Tony Morelli, John Foley, Luis Columna, Lauren Lieberman, and Eelke Folmer. "VI-Tennis: A Vibrotactile/Audio Exergame for Players Who Are Visually Impaired." In: *Proceedings of the Fifth International Conference on the Foundations of Digital Games*. FDG '10. New York, NY, USA: Association for Computing Machinery, 2010, pp. 147–154. ISBN: 978-1-60558-937-4. DOI: 10.1145/1822348.1822368.

[41] Dan Morris, Hong Tan, Federico Barbagli, Timothy Chang, and Kenneth Salisbury. "Haptic Feedback Enhances Force Skill Learning." In: *Proceedings of the Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. WHC '07. Washington, DC, USA: IEEE Computer Society, 2007, pp. 21–26. ISBN: 0-7695-2738-8. DOI: 10.1109/WHC.2007.65.

[42] Kyle Rector, Cynthia L Bennett, and Julie A Kientz. "Eyes-free Yoga: An Exergame Using Depth Cameras for Blind & Low Vision Exercise." In: *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*. ASSETS '13. New York, NY, USA: ACM, 2013, 12:1–12:8. ISBN: 978-1-4503-2405-2. DOI: 10.1145/2513383.2513392.

[43] Anke Verena Reinschluessel, Sarah Christin Cebulla, Marc Herrlich, Tanja Döring, and Rainer Malaka. "Vibro-Band: Supporting Needle Placement for Physicians with Vibrations." In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI EA '18. New York, NY, USA: ACM, 2018, LBW039:1–LBW039:6. ISBN: 978-1-4503-5621-3. DOI: 10.1145/3170427.3188549.

[44] Jose Salazar, Keisuke Okabe, and Yasuhisa Hirata. "Path-Following Guidance Using Phantom Sensation Based Vibrotactile Cues Around the Wrist." In: *IEEE Robotics and Automation Letters* 3.3 (2018), pp. 2485–2492. DOI: 10.1109/LRA.2018.2810939.

[45] Jose V Salazar Luces, Keisuke Okabe, Yoshiki Murao, and Yasuhisa Hirata. "A Phantom-Sensation Based Paradigm for Continuous Vibrotactile Wrist Guidance in Two-Dimensional Space."

In: *IEEE Robotics and Automation Letters* 3.1 (2018), pp. 163–170. DOI: 10.1109/LRA.2017.2737480.

[46] Ambika Shahu, Philipp Wintersberger, and Florian Michahelles. "Scenario-Based Investigation of Acceptance of Electric Muscle Stimulation." In: *Augmented Humans 2022*. AHs 2022. Kashiwa, Chiba, Japan: Association for Computing Machinery, 2022, pp. 184–194. ISBN: 9781450396325. DOI: 10.1145/3519391.3519416.

[47] Roland Sigrist. "Visual and auditory augmented concurrent feedback in a complex motor task." In: *Presence* 20.1 (2011), pp. 15–32.

[48] Rajinder Sodhi, Hrvoje Benko, and Andrew Wilson. "Light-Guide: Projected Visualizations for Hand Movement Guidance." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. New York, NY, USA: Association for Computing Machinery, 2012, pp. 179–188. ISBN: 978-1-4503-1015-4. DOI: 10.1145/2207676.2207702.

[49] Maur$\backslash$'$\backslash$icio Maur$\backslash$'$\backslash$icio Sousa, João Vieira, Daniel Medeiros, Artur Arsenio, and Joaquim Jorge. "SleeveAR: Augmented Reality for Rehabilitation Using Realtime Feedback." In: *Proceedings of the 21st International Conference on Intelligent User Interfaces*. IUI '16. New York, NY, USA: ACM, 2016, pp. 175–185. ISBN: 978-1-4503-4137-0. DOI: 10.1145/2856767.2856773.

[50] Daniel Spelmezan, Mareike Jacobs, Anke Hilgers, and Jan Borchers. "Tactile Motion Instructions for Physical Activities." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. New York, NY, USA: ACM, 2009, pp. 2243–2252. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1519044.

[51] Richard Tang, Xing-Dong Yang, Scott Bateman, Joaquim Jorge, and Anthony Tang. "Physio@Home: Exploring Visual Guidance and Feedback Techniques for Physiotherapy Exercises." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. New York, NY, USA: Association for Computing Machinery, 2015, pp. 4123–4132. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702401.

[52] Hsin-Ruey Tsai, Yuan-Chia Chang, Tzu-Yun Wei, Chih-An Tsao, Xander Chin-yuan Koo, Hao-Chuan Wang, and Bing-Yu Chen. "GuideBand: Intuitive 3D Multilevel Force Guidance on a Wristband in Virtual Reality." In: *Proceedings of the 2021 CHI Conference*

on Human Factors in Computing Systems. New York, NY, USA: Association for Computing Machinery, 2021. ISBN: 978-1-4503-8096-6.

[53] Eduardo Velloso, Andreas Bulling, and Hans Gellersen. "MotionMA: Motion Modelling and Analysis by Demonstration." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. New York, NY, USA: ACM, 2013, pp. 1309–1318. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2466171.

[54] Robert Walter, Gilles Bailly, and Jörg Müller. "StrikeAPose: Revealing Mid-Air Gestures on Public Displays." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. New York, NY, USA: Association for Computing Machinery, 2013, pp. 841–850. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2470774.

[55] Bernhard Weber, Simon Schätzle, Thomas Hulin, Carsten Preusche, and Barbara Deml. "Evaluation of a vibrotactile feedback device for spatial guidance." In: *2011 IEEE World Haptics Conference*. 2011, pp. 349–354. DOI: 10.1109/WHC.2011.5945511.

[56] Graham Wilson, Thomas Carter, Sriram Subramanian, and Stephen A. Brewster. "Perception of Ultrasonic Haptic Feedback on the Hand: Localisation and Apparent Motion." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 1133–1142. ISBN: 9781450324731. DOI: 10.1145/2556288.2557033.

[57] Weipeng Xu, Avishek Chatterjee, Michael Zollhoefer, Helge Rhodin, Pascal Fua, Hans-Peter Seidel, and Christian Theobalt. "Mo^2Cap^2 : Real-time Mobile 3D Motion Capture with a Cap-mounted Fisheye Camera." In: *IEEE Transactions on Visualization and Computer Graphics* (2019), pp. 1–1. ISSN: 1077-2626. DOI: 10.1109/TVCG.2019.2898650.

[58] Ungyeon Yang and Gerard Jounghyun Kim. "Implementation and Evaluation of "Just Follow Me": An Immersive, VR-based, Motion-training System." In: *Presence: Teleoper. Virtual Environ.* 11.3 (2002). Place: Cambridge, MA, USA Publisher: MIT Press, pp. 304–323. ISSN: 1054-7460. DOI: 10.1162/105474602317473240.

[59] Xingyao Yu, Katrin Angerbauer, Peter Mohr, Denis Kalkofen, and Michael Sedlmair. "Perspective Matters: Design Implications for Motion Guidance in Mixed Reality." In: *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 2020, pp. 577–587. DOI: 10.1109/ISMAR50242.2020.00085.

3 CONTRIBUTIONS

The previous chapter provided an overview of the state of the art and outlined important research gaps in the literature. This chapter summarizes the contributions of this thesis with respect to the defined research gaps.

3.1 DISPLAY TYPES AND VISUALIZATIONS FOR POSTURE GUIDANCE

The first contribution of this thesis was an investigation into the use of different 2D displays and visualizations for posture guidance (see Chapter P1). After the contribution statement, a brief description of the concept, prototype used, methodology, main findings, and a discussion of the results follows.

This contribution is based on the following publication:

Hesham Elsayed, Philipp Hoffmann, Sebastian Günther, Martin Schmitz, Martin Weigel, Max Mühlhäuser, and Florian Müller. "CameraReady: Assessing the Influence of Display Types and Visualizations on Posture Guidance." In: *Designing Interactive Systems Conference 2021*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1046–1055. ISBN: 9781450384766. DOI: 10.1145/3461778.3462026

Contribution Statement: I led the idea generation, experiment design and execution, the data analysis, and writing of the publication. *Philipp Hoffmann* implemented the system used during the evaluation and helped with the execution of the experiment under my supervision. *Florian Müller* assisted me with his excellent expertise in creating the scripts used for the data evaluation. All co-authors helped to improve the conceptual design and writing of the publication with valuable feedback.

3.1.1 *Concept & Prototype*

Users constantly interact with a variety of displays. This work investigated how and if these displays can be leveraged to enable posture guidance. The concept was straightforward: a user stood in front of a display and saw themselves with a superimposed target posture. After imitating the posture, the user could move on to the next posture with a clickable device held in the hand.

To this end, we developed a cross-platform system that displays to the user the posture to be imitated. The system consisted of a client application responsible for sending the camera feed to the server and displaying posture information, and a server application responsible for determining the current user posture from the feed. The system was used on a (1) smartphone, (2) tablet, (3) 24" desktop monitor (4) 55" TV, and (5) 72" large display. Furthermore, three different visualizations were supported: (1) a skeleton, (2) a silhouette, and (3) a 3D body model.

3.1.2 *Methodology*

We conducted a controlled experiment to evaluate the influence of display and visualization used on the accuracy, efficiency, and usability of posture guidance. 20 participants were recruited that took part in the experiment. The independent variables were the *display type* and the *visualization type*. The experiment followed a within-subjects design, where every participant experienced all conditions in a counterbalanced order. The dependent variables measured were the joint angle error, task completion time (TCT), and answers to a system usability scale (SUS) questionnaire. TCT was the time measured between the target posture being displayed to the user and the user signaling successful imitation of the posture. SUS is a commonly used questionnaire to measure the usability of a system. Aspects such as the complexity, ease of use, and willingness of the users to use the system often, are assessed. The result of an SUS questionnaire is a score between 0 - 100, where a score above 70 indicates an acceptable system [1]. Finally, in a closing questionnaire, we asked participants which visualizations and displays they preferred and collected comments on further features.

3.1.3 *Main Findings*

Regarding the choice of display type, we found that larger displays led to more accurate guidance and higher usability ratings with very little differences going from desktop monitors to large displays. However, contrary to the current state of the art, where smartphones have been rarely used for posture guidance, they proved to be still usable and resulted in only a 12% decrease from larger displays.

Regarding the choice of visualization type, we could not find a difference in the joint angle error between the different visualizations. However, 3D body models showed higher usability ratings compared to a skeleton visualization.

3.1.4 *Discussion*

The aim of this contribution was to investigate the accuracy, efficiency, and usability of different displays and visualizations for posture guidance. The deciding factor for the accuracy was the screen size which determines the size of the guidance cues in the user's visual field. Based on the experiment setup and the displays used, the size of the displays in users' visual fields could be calculated. Table 3.1 outlines these values. A visual angle of 7° in height and 9° in width proved to be the size after which little improvement is obtained in terms of accuracy. This finding informed the minimum size of the display relative to the user for accurate posture guidance. Taking a broader view, accuracy of posture guidance on 2D displays appeared to be limited in general, with average angle errors over 20°. This might be attributed in part to the missing depth information when using 2D screens to display 3D information. Efficiency was comparable across all displays and visualizations. However, usability as measured using the system usability scale questionnaire increased with an increasing

Table 3.1: Angle errors, TCT, and SUS scores across all displays and visualizations used in the experiment. The table reports the mean values μ, and the standard deviations σ.

Display	Visual Angle		Visualization	Angle Error		TCT		SUS	
	height	width		μ	σ	μ	σ	μ	σ
Smartphone	6.94°	3.26°	average	24.06°	3.91°	4.03s	1.71s	74.43	17.44
Tablet	5.77°	8.35°	average	22.82°	3.94°	4.06s	2.56s	82.21	10.21
Desktop Monitor	6.69°	8.84°	average	21.05°	4.54°	3.90s	2.28s	82.12	12.23
TV	11.13°	19.64°	average	21.22°	4.49°	4.13s	1.85s	85.19	12.66
Wall-sized Display	22.06°	19.64°	average	21.07°	3.88°	4.35s	1.87s	88.32	10.94
			skeleton	22.18°	4.26°	4.00s	1.96s	79.16	15.91
			silhouette	22.25°	4.47°	4.10s	2.05s	82.95	13.82
			3D body model	21.73°	4.22°	4.18s	2.22s	85.15	10.19

display size, even beyond the threshold where little accuracy increase is obtained.

Taken together, this was the first contribution in the literature to systematically evaluate the influence of different display types, different visualization types, and their combinations on posture guidance. The results shed light on the required minimum display size, the differences between visualizations, and posture guidance on 2D displays.

3.2 PERSPECTIVES IN VR FOR MOVEMENT GUIDANCE

The second contribution of this thesis investigated how different perspectives influence movement guidance in virtual 3D environments (see Chapter P2). After the contribution statement, a brief description of the concept, prototype used, methodology, main findings, and a discussion of the results follows.

This contribution is based on the following publication:

Hesham Elsayed, Kenneth Kartono, Dominik Schön, Martin Schmitz, Max Mühlhäuser, and Martin Weigel. "Understanding Perspectives for Single- and Multi-Limb Movement Guidance in Virtual 3D Environments." In: *28th ACM Symposium on Virtual Reality Software and Technology*. VRST '22. Tsukuba, Japan: Association for Computing Machinery, 2022. DOI: 10.1145/3562939.3565635

Contribution Statement: I led the idea generation, experiment design and execution, the data analysis, and writing of the publication. *Kenneth Kartono* implemented the system used during the evaluation and helped with the execution of the experiment under my supervision. All co-authors helped to improve the conceptual design and writing of the publication with valuable feedback.

3.2.1 *Concept & Prototype*

With 3D displays, several perspectives were introduced in the literature for guidance. This contribution investigated how the choice of perspective influenced the accuracy and user experience of movement guidance. A first person view was analogous to how we see our own bodies in real life. A third person view showed the user from a position behind and above the user, similar the perspective used in games. In all cases, guidance cues were superimposed over the user's current body. Furthermore, the concept in this contribution consisted of two phases for movement guidance: (1) demonstrate and (2) perform. In the first phase, the user saw the movement superimposed over their body. In the second phase, the user was required to replicate the movement with the correct movement properties, namely the path and speed. In addition to the visual cues, feedback was provided in the form of changing the color of body parts and using vibrations at the wrists and ankles.

We implemented a virtual scene where users were able to see themselves from the different perspectives. In addition to the first- and third-person perspectives, we implemented a variant of the third-person perspective that further displayed a screen with multiple views of the user.

3.2.2 *Methodology*

We conducted a controlled experiment to evaluate the influence of perspective and various movement properties on the accuracy of movement guidance. 18 participants took part in the experiment. The independent variables were *perspective*, *movement complexity*, *movement direction*, *movement speed*, and *feedback*. In total, the factors resulted in 162 (3 × 3 × 3 × 2 × 3) conditions. Movement complexity referred to the number of body parts involved in the movement to be performed. This ranged from one-arm movements to both arms and a leg. Movement direction referred to the direction in which the body parts moved, which was either forward, backward, or sideways. Movement speed was either fast or slow. The addition of feedback was also investigated, with the following levels: no feedback, haptic feedback, and color feedback. The experiment followed a within-subjects design, where every participant experienced all conditions in a counterbalanced order. The dependent variable measured was the joint angle error. After performing the experiment, participants were asked to fill out a survey that contained the following questions:

S1 What is your opinion on using a VR system to learn new movements?

S2 Which would you prefer: a VR system, a TV application or a real class for learning new movements? Why?

S3 Which perspective did you like the most in VR? Why?

S4 Which feedback did you like the most? Why?

S5 Did you find any aspects frustrating while using VR for motion guidance? Which?

S6 Are there further features you would like to see in a VR movement guidance application? Which?

3.2.3 *Main Findings*

Contrary to posture guidance, we found that a third-person perspective outperformed a first person perspective for movement guidance. The main reason for this was the fact that with movement guidance, time played an important role, while with posture guidance, users could rotate their heads freely until fully perceiving the posture. Furthermore, we found that multiple views helped users perform movements more accurately, but only with a slight improvement compared to a third person perspective without multiple views. Regarding movement complexity, the results indicated that single-limb movements can be performed more accurately than multiple-limb movements. Movement direction depended on the movement complexity, where one-arm movements showed comparable performance for the different directions, while for both arms and a leg, sideways movements led to the highest errors and backward movements led to the lowest errors. Feedback showed comparable performance across all levels. Similarly, fast and slow movements were comparable.

Concerning the qualitative results, participants expressed willingness to use VR for movement guidance. In cases where a real class was preferred, the main reason was the presence of an expert to guide the user. Otherwise, participants found that VR gave them independence that would not have been possible in a real class. In line with the quantitative results, all participants expressed a preference for using a third person perspective. Haptic feedback was preferred by the majority of our participants, however, they found difficulties interpreting the information communicated by the feedback.

3.2.4 *Discussion*

The aim of this contribution was to investigate how different perspectives and movement properties influenced movement guidance in virtual environments. Prior work had shown that a first person perspective was beneficial for posture and path guidance. This work was the first contribution to investigate different perspectives for movement guidance. Contrary to posture and path guidance, where users were not under time constraints, our findings showed that for movement guidance a third person perspective should be preferred. Additionally, the angle errors obtained in this contribution are considerably lower that those in the previous contribution, which demonstrated the advantage of using 3D displays.

The addition of haptic feedback did not lead to a significant accuracy increase in the presence of visual guidance, although qualitatively preferred by the majority of our users. A possible explanation for this could be the design of the haptic feedback. Haptic cues communicated inaccurate performance of a movement to the user, but not how to correct the movement. The design can be improved by providing intuitive correction information, e.g. using the push and pull metaphors.

3.3 HAPTIC ASSISTANCE FOR SKETCHING IN VR

The third contribution investigated whether tactile cues can improve hand path guidance in the presence of visual guidance (see Chapter P3). After the contribution statement, a brief description of the concept, prototype used, methodology, main findings, and a discussion of the results follows.

This contribution is based on the following publication:

Hesham Elsayed, Mayra Donaji Barrera Machuca, Christian Schaarschmidt, Karola Marky, Florian Müller, Jan Riemann, Andrii Matviienko, Martin Schmitz, Martin Weigel, and Max Mühlhäuser. "VRSketchPen: Unconstrained Haptic Assistance for Sketching in Virtual 3D Environments." In: *26th ACM Symposium on Virtual Reality Software and Technology*. VRST '20. Virtual Event, Canada: Association for Computing Machinery, 2020. ISBN: 9781450376198. DOI: 10.1145/3385956.3418953

Contribution Statement: I led the idea generation, experiment design and execution, the data analysis, and writing of the publication. *Christian Schaarschmidt* implemented the system used during the evaluation and helped with the execution of the experiment under my supervision. All co-authors helped to improve the conceptual design and writing of the publication with valuable feedback.

3.3.1 *Concept & Prototype*

Next to artistic movement (e.g. dancing and ballet) and exercises (phsical rehabilitation, yoga, and tai-chi), drawing is a third major field where movement guidance can contribute significally. Example use cases for adults include learning to draw or to construct. In addition, in comparison to the previous contributions where ex-ante guidance was investigated, drawing naturally provides ex-post feedback, where users can see the results of their movements and the accuracy achieved.

As to drawings -or arm movements- on a flat 2D surface, it can be assumed that straightforward visual guidance is highly effective. However, several challenges arise when drawing in 3D, such as the higher hand-eye coordination required and the lack of haptic feedback provided by a physical surface. This is the area that the third contribution of this thesis examined.

It is worth noting that movement guidance in this context is beneficial to both (1) the standard usage of 3D drawing, e.g. adding 3D hand-drawings to VR scenes, or sketching artistic and engineering prototypes in-situ for a real environment using AR, and (2) as a means for guidance of arm movements that are three-dimensional in nature, e.g. interaction gestures, artistic, or excercise movements.

The concept of this contribution took inspiration from our interactions on surfaces in real life and extended this to support movements in 3D in a virtual environment. While moving our fingers or a tool on a surface we intuitively feel the texture of the surface. To emulate this feeling, we built a pen that has a vibrotactile actuator embedded in its tip to generate mid-air textures. Furthermore, at the moment our fingers touch a surface we feel the pressure resulting from the contact. We equipped the pen with a pneumatic actuator that inflated to emulate the pressure resulting from contact with a surface.

We 3D printed a pen with a compartment at the tip to fit a vibrotactile actuator and a contact spot for the finger on which an inflatable balloon can be attached. Moreover, we constructed a virtual scene where the user could see a virtual surface to draw on.

3.3.2 *Methodology*

We conducted a controlled experiment to evaluate the influence of tactile feedback on the accuracy of a sketching task in a virtual environment. 20 participants were recruited for the experiment. The sketching task was to trace shapes displayed in front of them in a virtual environment. The independent variables of the experiment were *type of feedback* and *type of surface*. Feedback varied between no feedback, vibrotactile textures, pneumatic force feedback, a combination of both types of haptic feedback, and snapping. Snapping referred to projecting the users' strokes on the surface. Type of surface varied between flat and curved surfaces. The experiment followed a within-subjects design, where every participant experienced all conditions in a counterbalanced order. The dependent variables measured were the 2D error (the distance between the drawn shape and the displayed shape on the drawing surface), depth error (the distance between the drawn shape and the displayed shape perpendicular to the drawing surface), 3D error (the distance between the drawn shape and the displayed shape), and drawing time (the time measured between the first point and the last point of the drawn shape). We collected qualitative feedback on the perceived convenience and confidence ratings while using the pen. Furthermore, we collected users' ratings regarding their willingness to use the pen while sketching in VR.

3.3.3 *Main Findings*

We found that the addition of tactile feedback reduced users' 2D errors while tracing shapes on virtual surfaces compared to no feedback and the state-of-the-art technique snapping. Concerning depth error, the tactile conditions led to a significant decrease compared to no feedback. Similarly, the tactile conditions led to a decrease in 3D error compared to no feedback. However, the addition of the tactile modalities led to a higher drawing time compared to the other conditions. Taken together, the tactile conditions could provide effective motion assistance while tracing paths in 3D. Finally, users expressed a high degree of willingness to use tactile feedback while sketching in a virtual environment.

3.3.4 *Discussion*

The aim of this contribution was to investigate whether the addition of tactile cues could improve path guidance in the presence of visual cues. Our investigation was the first contribution in the literature to show that tactile feedback improved sketching in virtual environments. In addition, it became evident that the design of haptic feedback plays a critical role in its effectiveness for movement guidance.

3.4 SPACING OF VIBROTACTILE ACTUATORS ACROSS THE BODY

The fourth contribution of this thesis investigated the spacing required between vibrotactile actuators at various body locations (see Chapter P4). After the contribution statement, a brief description of the concept, prototype used, methodology, main findings, and a discussion of the results follows.

This contribution is based on the following publication:

Hesham Elsayed, Martin Weigel, Florian Müller, Martin Schmitz, Karola Marky, Sebastian Günther, Jan Riemann, and Max Mühlhäuser. "VibroMap: Understanding the Spacing of Vibrotactile Actuators across the Body." In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4.4 (Dec. 2020). DOI: 10.1145/3432189

Contribution Statement: I led the idea generation, experiment design and execution, the data analysis, and writing of the publication. I also implemented the prototypes. All co-authors helped to improve the conceptual design and writing of the publication with valuable feedback.

3.4.1 *Concept & Prototype*

The main goal of this contribution was to determine the spacing requirements for vibrotactile actuators. To achieve this goal, psychophysical experiments were conducted that measure the perception of tactile sensations on the body. On the one hand, it was important to measure whether interpolation between actuators was possible with a particular spacing. This was straightforward to accomplish by asking users what they felt. On the other hand, it was necessary to measure the perceived location of a tactile sensation in order to calculate the localization error. To allow users to accurately input this perceived location, we combined the use of digital pen and paper attached to the prototype for direct input on the body. Our prototype consisted of vibrotactile actuators attached to one side of a piece of cloth and digital paper attached to the other side. Using a digital pen, users could enter the location of a vibration in an intuitive way. Our prototype consisted of

10 vibrotactile actuators equally spaced on a piece of textile. A second variant with 6 vibrotactile actuators was used for the wrist due to the smaller circumference compared to other body parts.

3.4.2 *Methodology*

We conducted two controlled experiments to determine the spacing required between vibrotactile actuators across the body. Each experiment was performed with 24 participants and used the same prototype.

In the first experiment, we quantified the maximum distances possible for vibrotactile actuators while still preserving the ability to generate high-resolution tactile output using phantom sensations. Phantom sensations refer to the tactile illusion where neighboring vibrations on the skin are not perceived as distinct, but rather at a single location between the actual vibration locations. The independent variables of the experiment were the *body location* and the *orientation* of the prototype. Body locations included the wrist, forearm, upper arm, back, stomach, thigh, and leg. The orientations tested included longitudinal (along the body part) and transverse (around the body part) orientations. The experiment followed a within-subjects design, where every participant experienced all conditions in a counterbalanced order. The dependent variable measured was the threshold distance. To compute the threshold, we used a one-interval two-alternative forced-choice paradigm using a one-up one-down adaptive staircase procedure. In other words, users felt two locations vibrating and were required to indicate whether they felt a single or two points. For every response of feeling distinct points, the distance between the vibrations was decreased. Upon perceiving a single point, a reversal was recorded and the distance was increased. After six reversals the threshold was computed to be the average of the reversals.

In the second experiment, we quantified the minimum distances possible for vibrotactile actuators while still ensuring that they could be discriminated. The independent variables were *body location* and *orientation* of the prototype. Body locations included the wrist, forearm, upper arm, stomach, thigh, and leg. Orientation was either longitudinal or transverse on the body part. The experiment followed a within-subjects design, where every participant experienced all conditions in a counterbalanced order. The dependent variable was the localization error. The task was to feel a vibration and indicate the perceived location on the digital paper using the digital pen. The localization error was determined as the distance between the actual and the perceived locations. The minimum distances for the body parts were computed to be the upper 95% confidence intervals multiplied by a factor of two to account for the localization errors of two vibrotactile actuators.

3.4.3 *Main Findings*

		Wrist		Forearm		Upperarm		Back		Stomach		Thigh		Leg	
		Longitudinal	Transverse	Logitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
Localization Error	Mean	1.58 cm	1.27 cm	1.90 cm	1.50 cm	2.21 cm	1.75 cm	-	-	3.16 cm	1.74 cm	2.09 cm	1.72 cm	2.20 cm	1.60 cm
	95% CI	[1.32 , 1.83]	[1.02 , 1.53]	[1.65 , 2.16]	[1.24 , 1.75]	[1.96 , 2.47]	[1.50 , 2.0]	-	-	[2.91 , 3.41]	[1.48 , 1.99]	[1.84 , 2.35]	[1.46 , 1.97]	[1.95 , 2.46]	[1.35 , 1.86]
Threshold Distance	Mean	4.32 cm	4.20 cm	7.35 cm	6.77 cm	7.34 cm	7.05 cm	9.22	7.30	7.87 cm	6.59 cm	7.41 cm	6.58 cm	7.29 cm	6.37 cm
	95% CI	[3.55 , 5.10]	[3.43 , 4.98]	[6.57 , 8.12]	[6.00 , 7.54]	[6.56 , 8.11]	[6.27 , 7.82]	[8.44 , 9.99]	[6.52 , 8.07]	[7.09 , 8.64]	[5.82 , 7.36]	[6.64 , 8.18]	[5.81 , 7.36]	[6.52 , 8.07]	[5.59 , 7.14]

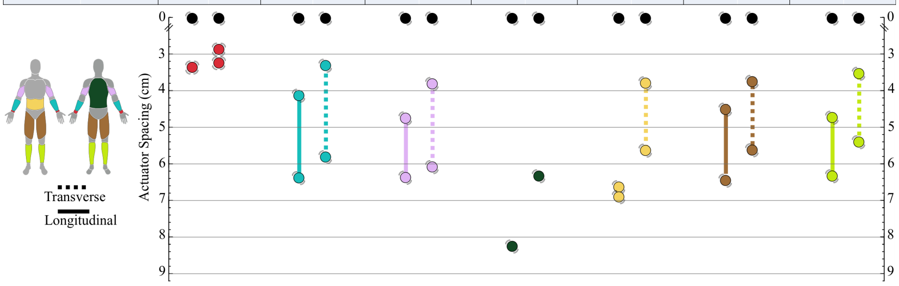


Figure 3.1: Minimum and maximum distances from both experiments.

Figure 3.1 shows the main findings from both experiments. In general, locations towards the body extremities showed higher sensitivity to vibrotactile stimulation. Considering the orientation, participants showed higher sensitivity when using a transverse orientation, this resulted in lower minimum and maximum values over body parts in comparison to a longitudinal arrangement of vibrotactile actuators. These findings were in line with experiments on touch sensitivity, however the absolute values for vibrotactile stimulation differed considerably

3.4.4 *Discussion*

The aim of this contribution was to construct a map of the required spacing between vibrotactile actuators across body parts and orientations. This was the first systematic investigation in the literature informing on the required spacing between actuators. Based on this knowledge, tactile displays can be constructed and novel interaction techniques for movement guidance can be investigated. The focus of this contribution was on stationary sensations, i.e. vibrations that do not change their position over time. The next contribution extended this work by also evaluating moving tactile sensations.

3.5 STATIONARY AND MOVING TACTILE SENSATIONS ON THE PALM

The fifth contribution of this thesis investigated varying the layout and spacing of actuators on the perception of tactile sensations on the palm to inform the design of handheld vibrotactile interfaces (see Chapter P5). After the contribution statement, a brief description of the concept, prototype used, methodology, main findings, and a discussion of the results follows.

This contribution is based on the following manuscript:

Hesham Elsayed, Martin Weigel, Florian Müller, George Ibrahim, Jan Gugenheimer, Martin Schmitz, Sebastian Günther, and Max Mühlhäuser. *Understanding Stationary and Moving Direct Skin Vibrotactile Stimulation on the Palm*. 2023. DOI: 10.48550/ARXIV.2302.08820

Contribution Statement: I led the idea generation, experiment design and execution, the data analysis, and writing of the manuscript. *George Ibrahim* implemented the systems used during the evaluation and helped with the execution of the experiments under my supervision. All co-authors helped to improve the conceptual design and writing of the manuscript with valuable feedback.

3.5.1 *Concept & Prototype*

In this contribution, we extended the concept from the previous contribution by measuring localization of vibrations on a 2D surface. A 3D printed grid-shaped prototype printed with flexible TPU filament allowed the attachment of vibrotactile actuators on the one side. On the other side digital paper allowed for entering perceived locations. The prototype was designed to be used on the palm of the hand. Furthermore, in contrast to the previous contribution, which was limited to stationary sensations, we included both stationary and moving sensations.

3.5.2 *Methodology*

We conducted two controlled experiments which used the same prototypes.

The first experiment was conducted with 16 participants and aimed to evaluate the influence of the following independent variables on the perception of stationary tactile sensations: *configuration*, *X*, *Y*, and *intensity*. Configuration was the layout and number of actuators which varied between four, six, nine, and 15 actuators. X was the location of the stimulus on the x-axis (width of the palm), which had five levels corresponding to five columns. Y was the stimulus position on the y-axis (length of the palm) and had nine levels, resulting in nine rows. Intensity was controlled by adjusting the amplitude of the vibrations and varied between 50% of the maximum amplitude of the vibrotactile actuator and 100%. As the number of distinct points that can be generated by the prototype was larger than the number of available actuators, phantom sensations were used to interpolate between the positions of the physical actuators. The experiment followed a within-subjects design, where every participant experienced all conditions in a counterbalanced order. The dependent variables measured were (1) the euclidean distance between the perceived and actual vibrations, (2) the deviation along the x-axis, (3) the deviation along the y-axis, (4) whether the correct location among the 45 possible locations was selected, and (5) the number of perceived points. The task was to indicate where a vibration was perceived on the palm and express whether it was at a single or multiple locations.

The second experiment was conducted with 20 participants and aimed to evaluate the influence of the following independent variables on the perception of moving tactile sensations: *resolution* of the interface and *direction* of movement of the sensation. Resolution had 10 levels: 2 x 4, 3 x 6, 4 x 8, 5 x 10, 6 x 12, 7 x 14, 8 x 16, 9 x 18, 10 x 20, and 11 x 22. The direction was either up, down, left, and right. The experiment followed a within-subjects design, where every participant experienced all conditions in a counterbalanced order. The dependent variables measured were (1) accuracy (whether the correct direction was identified), (2) accuracy for horizontal movements, (3) accuracy for vertical movements, and (4) the task completion time measured as the time between the end of the vibration and the user's response. The task was to feel a moving vibration and indicate the direction of movement.

3.5.3 *Main Findings*

The main findings from the first experiment that investigated *stationary* tactile sensations could be summarized as follows:

- 9 actuators resulted in comparable localization performance of stationary sensations as 15 actuators.
- 15 actuators resulted in improved perception of phantom sensations at a single location.
- 9 and 15 actuators led to more accurate localization at target location. 4 and 6 actuators led to more frequent localization at the edges.
- Localizing sensations along the width of the palm was more accurate than along the length.
- A 3×3 resolution could be accurately recognized.
- Lower intensity vibrations resultedd in improved perception of phantom sensations at a single location.
- Vibrotactile sensitivity on the palm deviated considerably from touch.

The findings from the second experiment on *moving* tactile sensations could be summarized as follows:

- A 2×4 resolution resulted in high recognition accuracy.
- A 5×10 resolution enabled higher resolution output while still maintaining high accuracy.

- Higher vibrotactile sensitivity was observed for moving compared to stationary sensations.

A considerable deviation in absolute values of vibrotactile sensations and touch stimulation was also observed in the case of moving sensations.

3.5.4 *Discussion*

The aim of this contribution was to investigate tactile perception on the palm to inform the design and usage of palm-based tactile interfaces. This was the first contribution in the literature to systematically investigate the perception of stationary and moving sensations on the palm. In addition to considerably contributing to the future of palm-based displays for movement guidance, many application scenarios for tactile displays can be found which involve using the hands to interact with the environment. Guidelines for stationary sensations with palm-based tactile displays can be summarized in the following:

- A smaller (approximately 2:1 ratio) inter-actuator spacing should be used along the width of the palm than the length.
- A 3×3 grid of points could be used for significantly *accurate* interactions on the palm.
- Favor the use of a tactile display consisting of nine actuators with a spacing of 2.5 cm along the width and 5 cm along the length for accurate interactions.
- A high number (spacing $\leq$ 2.5 cm) of actuators should be used for expressive interactions.
- Lower intensity vibrations resulted in a higher probability of perceiving a phantom sensation at a single location.

For moving sensations, we derived the following:

- Accurate interactions with *moving* sensations can be achieved with a 2×4 resolution.

- A resolution of 5×10 maintained a reasonable recognition accuracy. This resolution could be used to generate more expressive sensations.

3.6 TACTILE VECTORS FOR OMNIDIRECTIONAL ARM GUIDANCE

The sixth and final contribution of this thesis investigated tactile guidance of arm movements based on the required spacing of actuators (see Chapter P6). After the contribution statement, a brief description of the concept, prototype used, methodology, main findings, and a discussion of the results follows.

This contribution is based on the following publication:

Hesham Elsayed, Martin Weigel, Johannes Semsch, Max Mühlhäuser, and Martin Schmitz. "Tactile Vectors for Omnidirectional Arm Guidance." In: *Augmented Humans 2023*. AHs '23. Glasgow, United Kingdom: Association for Computing Machinery, 2023. DOI: 10.1145/3582700.3582701

Contribution Statement: I led the idea generation, experiment design and execution, the data analysis, and writing of the publication. *Johannes Semsch* implemented the system used during the evaluation and helped with the execution of the experiment under my supervision. All co-authors helped to improve the conceptual design and writing of the publication with valuable feedback.

3.6.1 *Concept & Prototype*

This contribution investigated two novel interaction techniques for tactile guidance of arm movements. The techniques leveraged two vibrotactile actuators to communicate the start- and endpoints of a direction vector for movement. In comparison to prior work (push and pull metaphors), where only a single actuator was used to indicate a movement direction, these techniques aim to communicate movement directions with higher accuracy. The first interaction technique - Sequential Tactile Vectors (STV) - activated two actuators sequentially, while the second interaction technique - Continuous Tactile Vectors (CTV) - produced a vibrotactile illusion of movement between the actuators. In order to support communication of arbitrary movement directions, a high resolution tactile grid was constructed based on the spacing requirements of the arm (see Chapter P4). Establishing the position of the actuators and the arm was achieved using an optical motion capture system.

3.6.2 *Methodology*

We conducted a controlled lab experiment to evaluate accuracy of guidance and the user experience (workload and subjective ratings for intuitiveness, confidence, and willingness to use) while using the current state of the art methods push and pull, as well as the new interaction techniques STV and CTV. The experiment was performed with 16 right-handed participants. The independent variables of the experiment were *guidance method* and *target*. Guidance methods included push, pull, STV, and CTV. The targets were uniformly distributed targets on a one-meter radius sphere centered at the midpoint of the arm. This resulted in a total of 26 targets. The experiment followed a within-subjects design and conditions were presented in counterbalanced order. The dependent variable was the angle error measured between the target direction and the actual direction of movement of the participant's arm. Further user ratings were collected for the different guidance methods regarding the perceived workload, intuitiveness, confidence, and willingness to use of the guidance method.

3.6.3 *Main Findings*

We found that STV resulted in a lower angle error in comparison to all other guidance methods. Targets towards the left were more accurately guided than targets towards the right. Targets upward of the arm were more accurately guided than horizontal and downward targets. Guidance of arm movements toward backward targets was more accurate than forward and sideway movements. Regarding user ratings of workload, the pull method resulted in lower workload in comparison to push, STV, and CTV. For intuitiveness ratings, the pull method was rated better than push and CTV. Similarly for confidence and willingness to use ratings, users were more confident and more willing to use pull as a guidance method in comparison to CTV.

3.6.4 *Discussion*

This contribution investigated two new interaction techniques for vibrotactile guidance of arm movements. This was the first contribution in the literature to systematically investigate guidance of arm movements with push, pull, STV, and CTV. The findings showed that STV should be preferred for higher accuracy and that pull should be preferred to improve subjective user ratings. Furthermore, more accurate guidance can be achieved for certain movement directions depending on the guidance method. This information can inform the design of gesture sets to be used in the context of vibrotactile guidance. Taken together, this contribution provided valuable insights regarding tactile movement guidance and paved the way for further novel interaction techniques.

REFERENCES

[1] Aaron Bangor, Philip T Kortum, and James T Miller. "An empirical evaluation of the system usability scale." In: *Intl. Journal of Human–Computer Interaction* 24.6 (2008), pp. 574–594.

[2] Hesham Elsayed, Mayra Donaji Barrera Machuca, Christian Schaarschmidt, Karola Marky, Florian Müller, Jan Riemann, Andrii Matviienko, Martin Schmitz, Martin Weigel, and Max Mühlhäuser. "VRSketchPen: Unconstrained Haptic Assistance for Sketching in Virtual 3D Environments." In: *26th ACM Symposium on Virtual Reality Software and Technology*. VRST '20. Virtual Event, Canada: Association for Computing Machinery, 2020. ISBN: 9781450376198. DOI: 10.1145/3385956.3418953.

[3] Hesham Elsayed, Philipp Hoffmann, Sebastian Günther, Martin Schmitz, Martin Weigel, Max Mühlhäuser, and Florian Müller. "CameraReady: Assessing the Influence of Display Types and Visualizations on Posture Guidance." In: *Designing Interactive*

Systems Conference 2021. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1046–1055. ISBN: 9781450384766. DOI: 10.1145/3461778.3462026.

[4] Hesham Elsayed, Kenneth Kartono, Dominik Schön, Martin Schmitz, Max Mühlhäuser, and Martin Weigel. "Understanding Perspectives for Single- and Multi-Limb Movement Guidance in Virtual 3D Environments." In: *28th ACM Symposium on Virtual Reality Software and Technology*. VRST '22. Tsukuba, Japan: Association for Computing Machinery, 2022. DOI: 10.1145/3562939.3565635.

[5] Hesham Elsayed, Martin Weigel, Florian Müller, George Ibrahim, Jan Gugenheimer, Martin Schmitz, Sebastian Günther, and Max Mühlhäuser. *Understanding Stationary and Moving Direct Skin Vibrotactile Stimulation on the Palm*. 2023. DOI: 10.48550/ARXIV.2302.08820.

[6] Hesham Elsayed, Martin Weigel, Florian Müller, Martin Schmitz, Karola Marky, Sebastian Günther, Jan Riemann, and Max Mühlhäuser. "VibroMap: Understanding the Spacing of Vibrotactile Actuators across the Body." In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4.4 (Dec. 2020). DOI: 10.1145/3432189.

[7] Hesham Elsayed, Martin Weigel, Johannes Semsch, Max Mühlhäuser, and Martin Schmitz. "Tactile Vectors for Omnidirectional Arm Guidance." In: *Augmented Humans 2023*. AHs '23. Glasgow, United Kingdom: Association for Computing Machinery, 2023. DOI: 10.1145/3582700.3582701.

4 CONCLUSION AND OUTLOOK

This thesis advanced the state of the art in the field of movement guidance. Visual, vibrotactile, and mixed stimuli were investigated. Knowledge gained within these contributions can be used for many application scenarios, e.g. sports, dance, physiotherapy, immersive sketching, and for body-based interaction. The first three contributions answered fundamental research questions regarding the use of visual and visuotactile interfaces for movement guidance. The next two contributions laid the foundation for designing wearable and handheld tactile interfaces that enable new investigations in the field of tactile guidance. The final contribution investigated new concepts for tactile movement guidance.

4.1 ACHIEVEMENTS

This thesis closed crucial research gaps in the field of computer-supported movement guidance, providing guidelines for the choice of display and technology, visualization of guidance information, and the design and usage of tactile interfaces.

In cases where coarse guidance is sufficient, i.e with the main goal being to get the user to move their limbs in a specific range of motion, rather than precise and accurate movements, the usage of common devices such as a smartphone or a tablet can already be appropriate. This can be the case in physical rehabilitation. For more demanding application scenarios, such as golf, baseball, or tennis training, where precise guidance in terms of posture and technique are required, large displays or virtual reality technology should be preferred. While using VR to guide movements involving several limbs, an out-of-the-body view of the trainee should be used. For even more demanding applications, such as surgical training, the use of VR technology combined with tactile feedback can be investigated.

While visual interfaces are dominantly used in research, they are not always appropriate, e.g. for users with visual impairments, in different environments where visual cues are difficult due to dust, smoke, darkness or being underwater, and for activities where the visual cues can distract the user, such as driving, snowboarding, and climbing. In these cases, tactile guidance can be an alternative. Research in this direction was rather sparse, and faced challenges regarding designing interfaces that are economic in terms of cost, weight, and required control wiring. This thesis provided concrete guidelines for designing tactile interfaces that are optimal in this respect and introduced new concepts for tactile movement guidance. Researchers and practitioners now have the knowledge of the arrangement, number, and spacing between actuators required for an effective tactile display on the body.

In addition, this thesis paved the way for a variety of novel directions for future work. The first contribution assessed the accuracy and usability of different 2D displays and visualizations for posture guidance. With the influence of these factors now available in the literature, the scientific community can move forward with novel investigations, such as the use of smartphone devices or desktop monitors to guide ergonomic postures of users and prevent injuries.

The second contribution assessed the accuracy and user experience of different perspectives for movement guidance in VR. New directions for research include investigating novel perspectives, e.g. by combining a first-person and third-person view of the user, and investigating the influence of perspective on coarse and fine-grained movements, e.g. will a third-person perspective still be better for guiding precise hand movements? Furthermore, based on the results, researchers now have the knowledge necessary for improving visuotactile guidance in VR. Tactile feedback should not only communicate where but also how the user should correct their movements. A virtual expert that guides users proved to be a promising research direction (see Section 4.2.1) for making VR movement training even more attractive to users.

The third contribution assessed visuotactile guidance for 3D drawing in a virtual environment. This contribution enables novel directions for research in several domains. For immersive sketching, researchers can build on this work by evaluating new complex drawing scenarios, optimizing the tactile feedback, e.g. investigating other tactile textures, and investigating novel feedback technologies that can influence the user experience and creativity, e.g. adding thermal feedback. In the domain of visuotactile hand movement guidance, the advantage of tactile feedback in the presence of visual guidance was not clear. With the knowledge in this contribution, researchers can now investigate leveraging tactile feedback for novel application scenarios such as surgical training.

For both tactile and visuotactile movement guidance, investigations into novel interaction techniques that leverage high-resolution tactile output on the body (see Section 4.2.2) are enabled by the knowledge in the fourth and fifth contributions. The sixth contribution is a first step in this direction that evaluated new concepts for tactile-based movement guidance.

4.2 FUTURE WORK

In addition to the research directions outlined in the previous section, starting points for further work are described in the following.

4.2.1 *Modeling Expert Knowledge*

General quantitative metrics such as angle error and deviation in 3D position are useful for evaluating the accuracy of movement guidance. However, beyond the use of these metrics, human experts rely on their experience to judge the important aspects to be considered in a movement, such as depth of a squat, or elbow position during a bench press. Future approaches should therefore attempt to incorporate this knowledge in the design of interaction techniques and systems for movement guidance.

4.2.2 *Interaction Techniques for Tactile Guidance*

Tactile guidance is promising due to the localized feedback and portability. Future work should investigate further novel interaction techniques enabled by the use of high-resolution tactile feedback.

A possible research direction could be coupling users' movements to tactile output on the body. For example by encoding the position of limbs via spatial tactile feedback, i.e. depending on the position of a limb, a particular location on the body is haptically stimulated. This mapping between body movement and spatial tactile stimulation can be initially learned by the user through ex-post feedback. After which, ex-ante guidance can be provided as the user has learned to translate the location of tactile stimulation to a movement.

Another promising research direction is the use of virtual force to guide movements. Virtual force is a tactile illusion that results from asymmetric vibrations on the body that cause a user to perceive a force in the absence of an actual physical force. Initial investigations have already been presented in the literature leveraging this illusion [1].

Finally, this thesis provided information on how tactile interfaces should be designed. Further studies should be conducted to determine where these interfaces can be best placed on the body, while minimizing the size of the interface, i.e. only covering surfaces that are necessary for guidance cues.

REFERENCES

[1] Heather Culbertson, Julie M Walker, Michael Raitor, and Allison M Okamura. "WAVES: A Wearable Asymmetric Vibration Excitation System for Presenting Three-Dimensional Translation and Rotation Cues." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. New York, NY, USA: ACM, 2017, pp. 4972–4982. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025741.

Part II

PUBLICATIONS

P1

CAMERAREADY: ASSESSING THE INFLUENCE OF DISPLAY TYPES AND VISUALIZATIONS ON POSTURE GUIDANCE

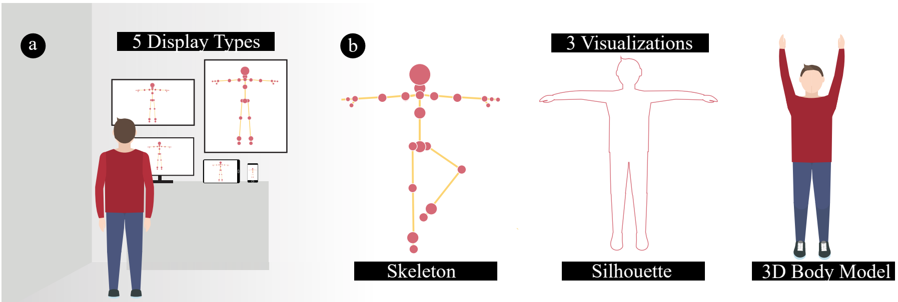


Figure P1.1: We introduce CameraReady, a mobile and cross-platform posture guidance system. We use CameraReady to evaluate the influence of (a) five different display types and (b) three visualizations on user performance.

ABSTRACT

Computer-supported posture guidance is used in sports, dance training, expression of art with movements, and learning gestures for interaction. At present, the influence of display types and visualizations have not been investigated in the literature. These factors are important as they directly impact perception and cognitive load, and hence influence the performance of participants. In this paper, we conducted a controlled experiment with 20 participants to compare the use of five display types with different screen sizes: smartphones, tablets, desktop monitors, TVs, and large displays. On each device, we compared three common visualizations for posture guidance: skeletons, silhouettes, and 3d body models. To conduct our assessment, we developed a mobile and cross-platform system that only requires a single camera. Our results show that compared to a smartphone display, larger displays show a lower error (12%). Regarding the choice of visualization, participants rated 3D body models as significantly more usable in comparison to a skeleton visualization.

P1.1 INTRODUCTION

Traditionally, users learn new movements by following instructions of an experienced coach. While this approach has proven to be effective [32], it depends on the availability of the coach and the user at the same time and place, and is limited by the attention span of coach/user and high costs. Moreover, during the recent pandemic's time, traditional training with a coach becomes even more unlikely.

Recent advances in sensing and actuation technologies have led to the development of a wide-range of posture guidance applications [1, 3, 15, 17, 19, 21, 25, 29, 36, 42] to alleviate the limitations of the traditional approach. Sports training [16, 39], physiotherapy [36], martial arts [18], dance training [8, 30] and interacting with user interfaces [40] have been supported by digital posture guidance.

Smartphones and tablets carry sensors that can be leveraged, e.g., to adjust user balance [14]. While research has investigated mobile sensors for input [14, 38], it remains unclear if the visual output of such devices that is limited (e.g., small display size) is suitable for posture guidance. Desktop monitors and television sets have been shown to be useful, but commodity devices do not offer the sensing capabilities required. Immersive displays can be used to visualize movements in first and third person perspectives. However, transferring movements learned from VR to the real world is limited [26].

In this work, we assess the influence of display types and visualizations on user performance. To this end, we present a mobile system with a simple setup that works cross-platform. We used our system to conduct a controlled experiment in a lab environment with 20 participants, where we used five displays (smartphones, tablet, desktop monitor, TV, and large display) commonly found on the consumer market and three visualizations (skeletons, silhouettes, and 3D body models) commonly found in the literature. As part of our results, we identified that posture guidance is more accurate and more usable using larger displays and that 3D body models are more usable in comparison to a skeleton visualization.

In summary, the contributions of this paper are two-fold:

- A mobile, cross-platform system for posture guidance. This system, called CameraReady, enables scientific research on posture guidance across a wide variety of devices. We contribute this system as an open source framework to accelerate future research in that domain.
- A controlled experiment to evaluate the influence of display types and visualizations on user performance. The findings show that larger displays lead to higher user accuracy in comparison to a smartphone and have higher usability scores. Furthermore, the use of a 3D body model as visualization leads to higher usability scores compared to a skeleton visualization.

P1.2 RELATED WORK

This work relates to motion guidance, display types, visualizations, and motion capture systems. In the following, we discuss approaches for motion guidance and their limitations, the various displays and visualizations currently used, as well as systems used for motion capture.

P1.2.1 *Motion Guidance*

A large body of research exists on supporting users while learning new movements [1, 17, 19, 25, 36]. Use-cases range from physiotherapy [36], sports [16, 18, 39] and dance training [8, 30] to learning gestures for interaction [6, 33, 40]. In the traditional setting, users are supported by a coach. This enhances the learning experience by targeting these factors: (1) observational practice, (2) the user's focus of attention, (3) feedback and self-controlled practice [32]. However, due to the limitations of the traditional approach, such as requiring the presence

Mocap	Display	Visualization	
wearable sensors	life-sized display	skeleton	Anderson et al. [1]
depth sensor	desktop monitor	avatar	Badler et al. [3]
camera-based	life-sized display	avatar	Bailenson et al. [4]
wearable sensors	life-sized display	avatar	Barioni et al. [5]
marker-based	desktop monitor	avatar, skeleton	Chan et al. [8]
marker-based	life-sized display	avatar	Chua et al. [9]
wearable sensors	life-sized display		Da Gama et al. [10]
marker-based	life-sized display	skeleton, avatar	Dürr et al. [11]
wearable sensors		skeleton, avatar	Elsayed et al. [12]
camera-based	desktop monitor		Fourie and Haar [13]
marker-based	life-sized display	skeleton	Hamanishi et al. [16]
camera-based	life-sized display	avatar	Han et al. [17]
camera-based	life-sized display	avatar	Han et al. [18]
wearable sensors	life-sized display	skeleton	Hoang et al. [19]
marker-based	life-sized display	avatar	Hülsmann et al. [22]
wearable sensors	life-sized display		Kallmann et al. [24]
marker-based	life-sized display	avatar	Katzakis et al. [25]
wearable sensors	desktop monitor	silhouette	Lin et al. [27]
wearable sensors		skeleton	Marquardt et al. [30]
wearable sensors	life-sized display		Sodhi et al. [33]
marker-based	life-sized display		Sousa et al. [34]
wearable sensors	desktop monitor	skeleton	Tadayon et al. [35]
marker-based	desktop monitor	skeleton	Tang et al. [36]
wearable sensors	life-sized display		Tao et al. [37]
wearable sensors	desktop monitor	skeleton	Velloso et al. [39]
wearable sensors	desktop monitor	avatar	Wei et al. [41]
depth sensor	life-sized display	avatar	Yang and Kim [42]
wearable sensors	life-sized display	silhouette	Walter et al. [40]

Table P1.1: Overview of posture guidance approaches using skeletons, silhouettes and avatars for visualizations; life-sized displays, such as public displays and immersive displays, and desktop monitors for output; and depth sensors, wearable sensors, camera-based and marker-based motion capture for input.

of both coach and user, high costs for the users, limited attention span of coach (worsened in a group learning scenario), approaches have been proposed to overcome these problems. Recordings of training sessions help users learn new movements at home, but suffer from a lack of control over feedback and the user's focus of attention. Combining sensing technology for input and visual displays for output has the potential to overcome these issues by providing adequate feedback and guiding the user's attention appropriately. In this work, we assess the influence of display types and visualizations on posture guidance applications.

P1.2.2 *Display Types*

This work investigates the effect of display type on posture guidance. Among the most common display types found on the consumer market are (1) smartphones, (2) tablets, (3) desktop monitors, (4) TVs and (5) large displays. In the following we discuss work done on posture guidance using these devices.

Smartphones

At present, little or no work is available that utilizes capabilities of modern smartphones for posture guidance. Research projects use the smartphones built-in accelerometer and gyroscope sensors, in combination with audio instructions to help users adjust their posture [14, 38]. This helps, for instance, for rehabilitation by improving balance of users and hence their stance. Products on the market use smartphones synchronously with wearable sensors for ergonomics, e.g. UPRIGHT GO [1]. Very little research has been done on using visual input and output capabilities currently present in modern smartphones. Startups, such as Onyx [2], use the smartphone's camera to aid users in their training by providing statistics on simple exercises, but offer no digital guidance. In this research we use the RGB camera of the smartphone for tracking the user's posture. More advanced camera options like depth-cameras are being introduced in some smartphones, but are not yet widely available.

1 https://www.uprightpose.com
2 https://www.onyx.fit/

Tablets

Similar to smartphones, tablets carry accelerometers and gyroscope sensors that can be used to help users with exercises, e.g. Plankpad [3]. However, tablets cannot be stored in pockets. This limits their use in applications, such as balance improvement [14] or improvement of golf swings [38]. On the other hand, tablets offer a larger screen size that can be used to help users during full-body posture guidance.

Desktop Monitors

Platforms such as YouTube [4] have made workout routines accessible on all types of displays, e.g. POPSUGAR Fitness [5]. They are often watched on desktop monitors, due to their larger size compared to mobile devices. While using this approach has little or no hurdles for many users (a desktop monitor and an internet connection), video content lacks on user feedback, which is crucial while learning to perform new movements correctly. Most of today's desktop monitors can be easily extended with a webcam for input, which enables the posture tracking applications envisioned in this paper.

Television Sets

TV sets are suitable for full-body workouts at home due to their large screen sizes. Similar to desktop monitors, approaches that use a TV for posture guidance, e.g using video feed of a trainer, lack on user feedback. Research has, therefore, introduced approaches that overcome this limitation, e.g. for physiotherapy [36].

Wall-sized & Immersive Displays

As a consequence of the high potential impact of posture guidance on many of applications, a lot of research has been done looking into interaction techniques with public displays, virtual and augmented environments. Public displays help users learn gestures for interaction [40]. VR and AR enable posture guidance using both first and

3 https://plankpad.com/
4 https://www.youtube.com/
5 https://www.youtube.com/channel/UCBINFWq52ShSgUFEoynfSwg

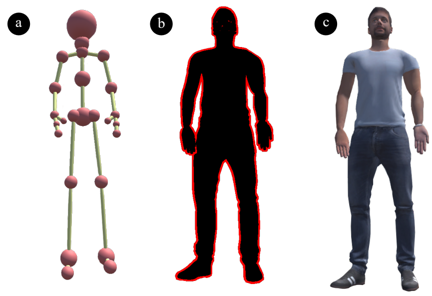


Figure P1.2: Visualizations used for posture guidance: (a) skeleton, (b) silhouette and (c) 3D body model.

third person perspectives [17, 19]. Currently, transferring movements learned in VR to the real world [26], as well as the use of different visualizations is not well understood.

Current approaches for posture guidance are designed for use in a particular setup with one type of display. Although most approaches target full-body posture guidance, some approaches, e.g. [17], aim at guiding only limb movements. With CameraReady, we introduce a cross-platform system for multiple display sizes that offers full-body posture guidance, is self-contained, mobile and person independent.

P1.2.3 *Visualizations*

In the following, visualizations commonly found in the literature are discussed. An overview of the visualizations and related work can be seen in Figure P1.2 and Table P6.1, respectively.

Skeletons

A skeleton visualizations offers a simple, abstract representation of the joints in the human body. Joints are connected by abstract representations of bones. By using this body representation, details of body composition and deformation are lost. These can serve as additional indicators for depth information, which is important when using a 2D screen to display a 3D body posture. On the other hand, by abstracting away information a user could perceive a body posture faster. An overview of research using skeletons as a visualization for posture guidance can be found in Table P6.1.

Silhouettes

A silhouette visualization shows the outline of the human body. Information about joint locations, body composition and deformation are not displayed. This might make perceiving depth information even more challenging in comparison to a skeleton visualization. Examples of research using silhouettes can be seen in Table P6.1.

3D Body Models

A 3D body model offers the most detailed representation of the human body among the mentioned categories. This visualization can be very realistic, e.g. by matching body composition [28] and deformation [31] during motion, or less realistic, e.g., by using a virtual avatar Barioni et al. [5]. It is unclear how the differences between these visualizations influence posture guidance applications.

P1.2.4 *Motion Capture*

Approaches for motion sensing can be categorized into (1) marker-based, (2) markerless, and (3) wearable sensors. Next, advantages and disadvantages of these categories are discussed.

Marker-based

Marker-based approaches rely on the use of retro-reflective markers and a set of high speed cameras for precise motion capture. Marker-based systems are affected by occlusion, not mobile and require the user to wear markers. Optitrack [6] and Vicon [7] offer marker-based motion capture systems.

Markerless

Classically, human posture estimation using camera images has been accomplished by feature engineering and extraction from images [15].

6 https://optitrack.com/
7 https://www.vicon.com/

More recently, approaches using deep neural networks have been introduced to overcome some of the problems of hand-crafted features used by, e.g. depth cameras. Camera-based methods, however, are affected by occlusion, are computationally demanding and in cases where a more complex setup, e.g., The Captury [8] is required, mobility is reduced.

Wearable Sensors

Using wearable sensors, human posture estimation free from occlusion problems can be achieved [3, 21, 29, 42]. These systems are also usually highly mobile, but suffer from problems such as drift when using inertial measurement units (IMU) and require users to wear bulky equipment. An example provider of motion capture systems with wearable sensors is Xsens [9].

P1.2.5 *Summary*

A multitude of display types are available to support the development of posture guidance applications. Hurdles that stop the use of ubiquitous smartphones include the small screen size and limited computation power. However, little research has investigated the use of these devices for this purpose. Desktop monitors and TV sets have been used previously, but are limited in their sensing capabilities. Immersive displays, in particular, VR environments are limited in their capacity to teach users new movements that are transferable to the real world [26]. Common to all displays, the influence of the visualization used is not well understood.

P1.3 CAMERAREADY

In the following, we describe our mobile cross-platform system for posture guidance on various display types. The system is motivated by three example application scenarios, which we use to elicit five design requirements. Afterwards, we discuss our implementation, the

8 https://thecaptury.com
9 https://www.xsens.com/

neural network we use for pose estimation, and evaluate the accuracy of this approach.

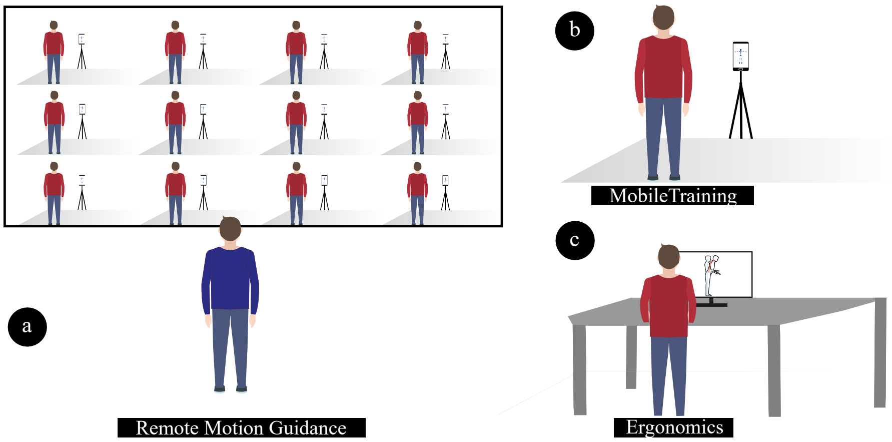


Figure P1.3: Example application scenarios of CameraReady.

P1.3.1 *Example Application Scenarios*

We present a set of example application scenarios that show the utility of CameraReady for motion guidance.

P1.3.1.1 *Remote Motion Coaching*

One of the major disadvantages of traditional coaching is the necessity of physical presence. With CameraReady a coach can remotely teach users in real-time with the possibility of offering feedback (Figure P1.3a). In comparison to a pre-recorded video feed of the coach, this approach allows active support during the learning process. This also makes it possible to make use of algorithms for automatic classification of errors [23].

P1.3.1.2 *Computer-supported Mobile Training*

In addition to real-time support by a coach, CameraReady can use automated algorithms to support users in practicing new and previously learned movements in the comfort of their homes and outside (Figure P1.3b). This can be used for example while practicing Yoga for showing correct postures and highlighting errors in the user's posture.

In comparison to remote motion coaching, the focus here is not on supporting a 2-way communication channel between a coach and a user, but on supporting mobile training scenarios without necessarily requiring a coach.

P1.3.1.3 *Ergonomics*

While interacting with displays, ergonomics is a very important factor [2]. CameraReady can augment the display with information on incorrect postures and guide users in performing necessary adjustments to prevent short- and long-term injuries (Figure P1.3c).

P1.3.2 *Design Requirements*

Based on our example application scenarios we extracted the following five design requirements for our system:

P1.3.2.1 *Full-Body Guidance*

Most movements in sports, martial arts, and dance require movements of the full body. Hence, our system needs to give guidance for full-body postures. In addition, some modes could be supported for specialized training of a specific body part by ignoring movement of the other body parts.

P1.3.2.2 *Cross-platform*

Many people own or have access to a wide variety of digital devices, including smartphones, tablets, notebooks, and TVs, which can be used for computer-supported mobile training. The system should work on a large variety of these devices to allow the user to chose his/her preferred training setup. For sensing, the system should require no special equipment, such as optical tracking systems or depth cameras. Instead, the system should work with a single-camera setup, which is already included in most commercial devices.

P1.3.2.3 *Self-Contained*

The system should consist of a single device and not require a complex setup, especially in mobile training scenarios. Moreover, it should avoid attachment of wearable sensors on the user, since the additional weight might change the body perception and could make some movements more difficult to execute and learn.

P1.3.2.4 *Mobile*

The posture guidance system should be mobile to allow for assistance in many environments, e.g. outside in a park or in a fitness center. Hence, the system should work on smaller-sized displays and should be able to work battery operated.

P1.3.2.5 *Person Independent*

In some of our envisioned setups the device might be shared by multiple people. For example, a television might be used by all members of a family and an ergonomics trainer for a machine could support factory workers. Hence, the system should not be personalized to a specific user. This also allows multiple users to share the same system. For example, a in-person training could use the system to show the specifics of a posture, before asking the student to imitate the movement.

P1.3.3 *Implementation*

Our implementation of CameraReady consists of two parts. First, a client application running on Android or Windows 10, and second, a server application running on Windows 10. Client applications were responsible for sending the camera feed to the server for evaluation and displaying the visualizations. We used Unity distribution 2019.3.15f1 for compatibility between client-server applications. Unity Neural Networking Package Barracuda [10] was used for running the neural

10 https://docs.unity3d.com/Packages/com.unity.barracuda@0.3/manual/index.html

network, uTextureSendReceive [11] for handling camera feed and Unity Mirror Networking [12] for synchronisation of variables, game object positions and network messages. We open-source CameraReady to accelerate future research in the area of visual posture guidance on Github [13].

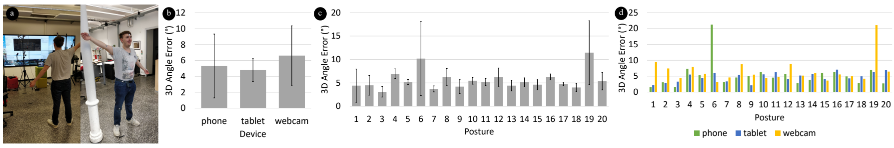


Figure P1.4: (a) Setup used in our neural network evaluation, (b) 3D angle errors across devices, (c) 3D angle errors per posture, and (d) 3D angle errors for devices and postures combined.

P1.3.4 *Neural Network Evaluation*

We used a neural network implemented by Yukihiko Aoyagi [14] for real-time (up to 60 fps) pose estimation. This approach uses MobileNetV3 [20]. We chose this network over OpenPose [7] as it detects human postures in 3D without requiring a setup with multiple cameras. We further conducted an evaluation of the performance of this network on 3D joint angle error. To do so, the postures used during the experiment were performed while wearing retro-reflective markers and being tracked by an Optitrack V100:R2 motion capture system. Additionally, the devices used during the experiment captured images of the postures. A total of 60 postures and images were collected: 20 per smartphone, tablet, and webcam. Estimation of the neural network was compared to ground truth data collected from Optitrack. Figure P1.4a shows the setup and Figure P1.4b-d show the results of our evaluation. The neural network had an average error of 5.57° over all joints, postures and devices used making it comparable to a Microsoft Kinect [37].

11 https://github.com/BarakChamo/uTextureSendReceive
12 https://mirror-networking.com/
13 https://gitlab.com/ph-industries/CameraReady
14 https://github.com/digital-standard/ThreeDPoseTracker

P1.4 EXPERIMENT

We conducted a controlled lab experiment to investigate the influence of different visualizations and display types on the accuracy, efficiency and usability of posture guidance. In particular, we aim to answer the following hypotheses:

H1 Larger displays lead to higher user accuracy.

H2 Larger displays lead to lower task completion time (TCT).

H3 Larger displays lead to higher usability ratings.

H4 Visualizations with a higher level of detail lead to higher user accuracy.

H5 Visualizations with a higher level of detail lead to lower TCT.

H6 Visualizations with a higher level of detail lead to higher usability ratings.

P1.4.1 *Participants*

We recruited 20 participants (13 Male, 5 Female, 1 Diverse and 1 participant did not specify) aged between 21 and 43 years (M = 25.25, SD = 5.30). 15 participants are practicing or had prior experience with posture training exercises. Participation in our experiment was voluntary and no compensation was offered. There were some sweets in the lab, if participants wanted to have some.

P1.4.2 *Design*

We used a within-subject design with *display type* (smartphone, tablet, desktop monitor, TV, and large display) and *visualization type* (skeletons, silhouettes and 3D body models) as independent variables. We counterbalanced the order of *display type* and *visualization type* using a 5x10 and a 3x6 balanced Latin square. Displays were shown in the order determined by the 5x10 balanced Latin square. Within each display condition, the order of visualizations was taken from the 3x6

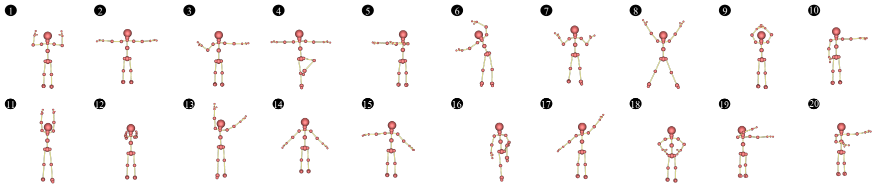


Figure P1.5: Postures used in our experiment.

Latin balanced square. Remaining visualization combinations were transferred to the next display condition. By using this approach, we conducted the experiment with 20 participants instead of 30. For each combination of levels of independent variables, participants performed 20 postures from a baseline dataset [12] in randomized order. Figure P1.5 shows the postures. This resulted in a total of 300 postures per participant.

P1.4.3 *Procedure*

To prevent the spread of COVID-19, all materials used in the experiment were disinfected and the lab was aired for a minimum of 30 minutes between participants. After welcoming and obtaining informed consent from our participants, we collected their demographic data. Then, we explained the task and provided a brief overview of the procedure. The task was to stand at a particular location looking at a display and imitate the visible posture. After each condition, participants filled out a System Usability Scale (SUS) questionnaire. Finally, participants filled out a questionnaire asking for their favorite display type and visualization and their reasoning. The questionnaire also asked for feedback and comments on the overall experience and suggestions for improving the system.

P1.4.4 *Apparatus*

We used a Zotac Magnus EN1060K all-in-one computer with an NVIDIA GeForce GTX 1060 graphics card while running our experiment. During the experiment participants had to signal that they are ready to start, and confirm that they performed the required posture. Interactions of the participants with the system were performed by pressing any button on a Logitech Presenter R400. We used five commonly available devices to represent the five display types:

- *Smartphone*: Google Pixel 3 with a 5.5" screen (2,280 x 1,080). We used the ultra wide front camera with a focal length of 2.03mm (2448 x 3264). The phone was placed 1.20m away from the participant. This distance was determined from pilot tests as the distance where a 1.80m tall person is fully visible with limbs stretched.
- *Tablet*: Microsoft Surface Pro 4 with a 12.3" screen (2,736 x 1,824). We used the built-in Intel AVStream 2500 camera (2560 x 1440) with a x0.62 wide lens to increase field of view. Participants stood 2.0m away from the tablet, in order to be fully visible.
- *Desktop monitor*: HP 24" display (1920 x 1080) and a Logitech QuickCam Pro 9000 (1600 x 1200) with a 3.7mm focal length. 3.5m distance was required between participants and the webcam.
- *TV*: We used a NEC Multisync UN551VS 55" display (1920 x 1080) for the TV condition, and a Logitech QuickCam Pro 9000 was used for input.
- *Large display*: We used two NEC Multisync UN551VS 72" vertically stacked for the large display condition and a Logitech Quickcam Pro 9000 was used for input.

P1.4.5 *Data Analysis*

We analyzed the recorded data using a two-way repeated measures ANOVA with *display type* and *visualization type* as the two independent factors. We tested the data for normality with Shapiro Wilk's test and found no significant deviations. Where Mauchly's test indicates a violation of the assumption of sphericity, we corrected the tests using the Greenhouse-Geisser method and report the ϵ. When significant effects are revealed, we use Bonferroni corrected pairwise t-tests for post-hoc analysis.

P1.5 RESULTS

This section details on the results of varying our independent variables *display type* and *visualization type* on the dependent variables error, Task Completion Time (TCT), and SUS scores.

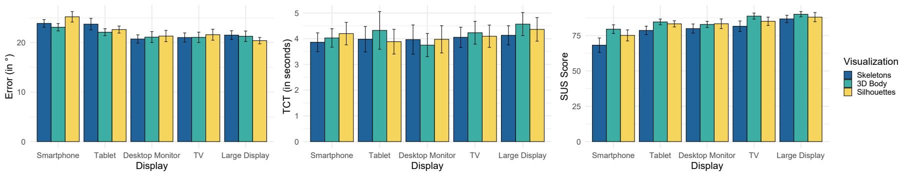


Figure P1.6: Error, TCT, and SUS scores of users across visualizations and displays used. Error bars are the standard errors.

P1.5.1 *Error*

We analysed the average 3D joint angle error of participants after imitating postures. A 2-way repeated measures ANOVA showed a significant main effect of *visualization* ($F_{1.75,31.52}$ = 3.94, p < .05, ϵ = 0.88 , η^2 = 0.005) and *display* ($F_{1.58,28.44}$ = 5.26, p < .05, ϵ = 0.40 , η^2 = 0.10). Post-hoc tests revealed no significant differences between skeletons (M = 22.18°, SE = 4.26°), silhouettes (M = 22.25°, SE = 4.47°) and 3D body models (M = 21.73°, SE = 4.22°); while confirming significant differences between smartphone (M = 24.06°, SE = 3.91°) and desktop monitors (M = 21.05°, SE = 4.54°, p < .01), TVs (M = 21.22°, SE = 4.49°, p < .05) and large displays (M = 21.07°, SE = 3.88°, p < .01). We found no interaction effects between *visualization* and *display* ($F_{3.00,53.92}$ = 2.62, p > .05).

P1.5.2 *Task Completion Time (TCT)*

We measured TCT as the time participants took to transition from a neutral to the displayed posture. A 2-way repeated measures ANOVA showed no significant main effects for both *visualization* ($F_{2,36}$ = 1.42 , p > 0.05) and *display* ($F_{4,72}$ = 0.60, p > 0.05). Participants were on average quicker with skeletons (M = 4.00s, SE = 1.96s), than silhouettes (M = 4.10s, SE = 2.05s) and 3D body models (M = 4.18s, SE = 2.22s). The desktop monitor display had the lowest TCT on average (M = 3.90s, SE = 2.28s), followed by smartphone (M = 4.03s, SE = 1.71s), tablet (M = 4.06s, SE = 2.56s), TV (M = 4.13s, SE = 1.85s), and large displays (M = 4.35s, SE = 1.87s).

P1.5.3 *System Usability Scale (SUS)*

After each condition, we assessed usability of our system by asking participants to fill out a SUS. A SUS score ranges from 0 - 100, with higher scores showing higher usability. We found significant main effects for *visualization* ($F_{1.48,16.33}$ = 5.37, $p < .05$, $\epsilon = 0.74$, $\eta^2 = 0.06$) and *display* ($F_{1.55,17.10}$ = 6.41, $p < .05$, $\epsilon = 0.39$, $\eta^2 = 0.164$) on SUS scores. Post-hoc tests showed a significant difference between skeletons (M = 79.16, SE = 15.91) and 3D body models (M = 85.15, SE = 10.19, p < .05). Usability of smartphone (M = 74.43, SE = 17.44) compared to tablet (M = 82.21, SE = 10.21, p < .05), TV (M = 85.19, SE = 12.66, p < 0.01), and large display (M = 88.32, SE = 10.94, p < 0.001) was also significant. No interaction effects between *visualization* and *display* ($F_{3.25,35.80}$ = 2.57, $p > .05$) were found.

P1.5.4 *User Feedback*

In the final questionnaire, we asked participants which visualizations and displays they found most appealing and collected comments on additional features from our users.

P1.5.4.1 *Preferences & Perceptions*

A 3D body model was favoured by 40% of our participants as they found posture to be "easy to recognize" (P12), "clearer in comparison to other visualizations" (P5), and "most visible" (P10). 30% of the participants preferred skeletons as they "covered the least of my body and allowed me to estimate how I was positioned" (P1), had a "good mixture between transparency and overlay" (P3) and other visualizations had "a different shoulder position" (P2). Remaining participants preferred silhouettes as they were "most visible" (P16) and offered the "easiest (way) to see what to do" (P11). Large displays were the favorite display type by 90% of our users as they "made the recognition of the displayed poses effortless" (P1), were "similar to an expert showing you an exercise" (P3), and offered an improvement in comparison to other displays "the smaller the screen size the harder to read the pose" (P15). The remaining 10% of our users preferred the use of TV as it was "very pleasant to use" (P13).

P1.5.4.2 *Suggested Features*

In the end, we asked participants if they would like to see additional features in a posture guidance. Participants suggested a *"color-coded avatar to show how well which joint imitates the shown pose"* (P1) and using colors to clarify in the skeleton visualization *"if joints are in front or behind other joints"* (P2). One participant suggested a *"transparency function to see your own pose better"* (P3). The participants also expressed a need for *"a display of the progress"* (P13). The progress could be used as a *"verification that the pose is well done"* (P6) and *"to see how many positions are still remaining [to increase motivation]"* (P5). Participants further suggested combining progress indication with *"visuo-auditory feedback to show that you have taken the right posture"* (P5). Participants proposed multi-view visualisations since *"poses that use depth are difficult to imitate"* (P14). For example, *"a second display that shows the pose from the side"* (P14) might be useful. Moreover, participants suggested *"animations how to get to a certain pose"* (P20). Lastly, participants suggested the use of a female avatar *"for a better alignment of posture"* (P5).

P1.6 DISCUSSION

In this section, we discuss quantitative and qualitative results of our experiment. In general, our results show the feasibility of posture guidance using all displays and visualizations presented in this paper. We observed significant differences in usability scores and user accuracy across devices and visualizations. In addition to our quantitative results, users expressed clear preferences to larger devices.

P1.6.1 *Display Types*

We found that larger devices were rated as more usable by participants. Therefore we can accept **H3**. Regarding accuracy of imitating postures, larger devices such as desktop monitors, TVs, and large displays showed lower errors in comparison to a smartphone (12.51%, 11.80% and 12.43%, respectively). These results support **H1** when comparing a smartphone to other devices. However, when comparing tablet, desktop monitor, TV and large display we cannot support **H1**. Contrary to our hypothesis, smartphones can be used for full body posture guidance. Although lower than large displays, smartphones received a SUS score of 74 and had comparable TCT. TCT was comparable across all displays, hence we cannot support **H2**.

P1.6.2 *Visualizations*

Considering the influence of visualization on posture guidance, we found no significant differences that show superiority of a particular visualization. Our initial hypothesis (**H4**) was that more detailed visualizations lead to lower error, which was not reflected in our quantitative results but was mentioned by our participants. Depth information (i.e., how body parts are relatively arranged) was not clear to participants when using skeletons and silhouettes. Moreover, SUS scores showed 3D body models to be more usable than skeletons, hence we can accept **H6**. Regarding TCT, all visualizations had comparable performance. Therefore, we cannot support **H5**.

P1.6.3 *Subjective Preferences*

In line with related work, users expressed the need for multi-view visualizations [36], color coding of misaligned body parts [19], and audio instructions [1]. Participants further commented on useful features, e.g., addition of transparency of the visualization to make a person's own posture more visible, color coding depth information, and animating the visualization to see the motion required.

P1.7 LIMITATIONS

We are confident that our result provide valuable insights into the influence of different visualizations and display types on the accuracy and efficiency of posture guidance systems. However, design as well as the results of our experiment impose some limitations and starting points for future work.

P1.7.1 *Real-World Applicability*

In this paper, we investigated the accuracy, efficiency and usability of posture guidance systems in a lab setting. We chose this approach to focus on the mere influence of the factors and to exclude external influences. While we are convinced that our results make a strong contribution to the future of such systems, we also acknowledge that other settings might yield other results. Therefore, further work is necessary to understand how these results are transferable to in-the-wild settings.

P1.7.2 *Real-Time Feedback*

CameraReady uses various visualizations for posture guidance. This guidance is currently limited to static postures that communicate the target posture to the user. Future work should, therefore, investigate the addition of live feedback to further support the user, as well as animations that make the transition between postures more intuitive.

P1.7.3 *Recognition Accuracy*

Lastly, we used a neural network for mocap. This approach is not as precise as a marker-based system, however opens the door to a variety of interesting application scenarios in HCI. We are confident that this limitation will will be solved by advances in the area of computer vision.

P1.8 CONCLUSION

We presented CameraReady, a mobile system with a simple setup that works cross-platform. We have assessed the feasibility of our system in a controlled lab experiment, using different visualizations found in the literature and various displays found on the consumer market. Our results indicate that CameraReady can be used for posture guidance across different screen sizes and visualizations. While larger displays and a 3D body model visualization show highest usability scores, other devices and visualizations also proved to be usable in terms of our participants' SUS scores and accuracy.

REFERENCES

[1] Fraser Anderson, Tovi Grossman, Justin Matejka, and George Fitzmaurice. "YouMove: Enhancing Movement Training with an Augmented Reality Mirror." In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST '13. New York, NY, USA: Association for Computing Machinery, 2013, pp. 311–320. ISBN: 9781450322683. DOI: 10.1145/2501988.2502045.

[2] Myroslav Bachynskyi, Gregorio Palmas, Antti Oulasvirta, Jürgen Steimle, and Tino Weinkauf. "Performance and Ergonomics of Touch Surfaces: A Comparative Study Using Biomechanical Simulation." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: Association for Computing Machinery, 2015, pp. 1817–1826. ISBN: 9781450331456. DOI: 10.1145/2702123.2702607.

[3] Norman Badler, Michael Hollick, and John Granieri. "Real-Time Control of a Virtual Human Using Minimal Sensors." In: *Center for Human Modeling and Simulation* 2 (1993). DOI: 10.1162/pres.1993.2.1.82.

[4] Jeremy Bailenson, Kayur Patel, Alexia Nielsen, Ruzena Bajscy, Sang-Hack Jung, and Gregorij Kurillo. "The Effect of Interactivity on Learning Physical Actions in Virtual Reality." In: *Media Psychology* 11.3 (2008), pp. 354–376. DOI: 10.1080/15213260802285214.

[5] R R Barioni, W Costa, A Aleluia, and V Teichrieb. “BalletVR: a Virtual Reality System for Ballet Arm Positions Training.” In: *2019 21st Symposium on Virtual and Augmented Reality (SVR)*. 2019, pp. 10–16. DOI: 10.1109/SVR.2019.00018.

[6] Olivier Bau and Wendy E Mackay. “OctoPocus: A Dynamic Guide for Learning Gesture-based Command Sets.” In: *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology*. UIST ’08. New York, NY, USA: ACM, 2008, pp. 37–46. ISBN: 978-1-59593-975-3. DOI: 10.1145/1449715.1449724.

[7] Z. Cao, G. Hidalgo Martinez, T. Simon, S. Wei, and Y. A. Sheikh. “OpenPose: Realtime Multi-Person 2D Pose Estimation using Part Affinity Fields.” In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* (2019).

[8] Jacky C P Chan, Howard Leung, Jeff K T Tang, and Taku Komura. “A Virtual Reality Dance Training System Using Motion Capture Technology.” In: *IEEE Trans. Learn. Technol.* 4.2 (Apr. 2011), pp. 187–195. ISSN: 1939-1382. DOI: 10.1109/TLT.2010.27.

[9] Philo Tan Chua, Rebecca Crivella, Bo Daly, Ning Hu, Russ Schaaf, David Ventura, Todd Camill, Jessica Hodgins, and Randy Pausch. “Training for Physical Tasks in Virtual Environments: Tai Chi.” In: *Proceedings of the IEEE Virtual Reality 2003*. VR ’03. Washington, DC, USA: IEEE Computer Society, 2003, pp. 87–. ISBN: 0-7695-1882-6.

[10] Alana Elza Fontes Da Gama, Thiago Menezes Chaves, Lucas Silva Figueiredo, Adriana Baltar, Ma Meng, Nassir Navab, Veronica Teichrieb, and Pascal Fallavollita. “MirrARbilitation.” In: *Comput. Methods Prog. Biomed.* 135.C (2016), pp. 105–114. ISSN: 0169-2607. DOI: 10.1016/j.cmpb.2016.07.014.

[11] Maximilian Dürr, Rebecca Weber, Ulrike Pfeil, and Harald Reiterer. “EGuide: Investigating Different Visual Appearances and Guidance Techniques for Egocentric Guidance Visualizations.” In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’20. New York, NY, USA: Association for Computing Machinery, 2020, pp. 311–322. ISBN: 9781450361071. DOI: 10.1145/3374920.3374945.

[12] Hesham Elsayed, Martin Weigel, Julius von Willich, Markus Funk, and Max Mühlhäuser. “APS: A 3D Human Body Posture Set as a Baseline for Posture Guidance.” In: *Proceedings of the*

12th ACM International Conference on PErvasive Technologies Related to Assistive Environments. PETRA '19. New York, NY, USA: Association for Computing Machinery, 2019, pp. 353–357. ISBN: 9781450362320. DOI: 10.1145/3316782.3324012.

[13] Margaux Fourie and Dustin van der Haar. "Ballet Pose Recognition: A Bag-of-Words Support Vector Machine Model for the Dance Training Environment." In: *Information Science and Applications 2018*. Ed. by Kuinam J Kim and Nakhoon Baek. Singapore: Springer Singapore, 2019, pp. 317–325. ISBN: 978-981-13-1056-0.

[14] C. Franco, A. Fleury, P. Y. Gumery, B. Diot, J. Demongeot, and N. Vuillerme. "iBalance-ABF: A Smartphone-Based Audio-Biofeedback Balance System." In: *IEEE Transactions on Biomedical Engineering* 60.1 (2013), pp. 211–215.

[15] Wenjuan Gong, Xuena Zhang, Jordi Gonzàlez, Andrews Sobral, Thierry Bouwmans, Changhe Tu, and El-hadi Zahzah. "Human Pose Estimation from Monocular Images: A Comprehensive Survey." In: *Sensors* 16.12 (2016). ISSN: 1424-8220. DOI: 10.3390/s16121966.

[16] Natsuki Hamanishi, Takashi Miyaki, and Jun Rekimoto. "Assisting Viewpoint to Understand Own Posture as an Avatar In-Situation." In: *Proceedings of the 5th International ACM In-Cooperation HCI and UX Conference*. CHIuXiD'19. New York, NY, USA: Association for Computing Machinery, 2019, pp. 1–8. ISBN: 9781450361873. DOI: 10.1145/3328243.3328244.

[17] Ping-Hsuan Han, Kuan-Wen Chen, Chen-Hsin Hsieh, Yu-Jie Huang, and Yi-Ping Hung. "AR-Arm: Augmented Visualization for Guiding Arm Movement in the First-Person Perspective." In: *Proceedings of the 7th Augmented Human International Conference 2016*. AH '16. New York, NY, USA: ACM, 2016, 31:1–31:4. ISBN: 978-1-4503-3680-2. DOI: 10.1145/2875194.2875237.

[18] Ping-Hsuan Han, Yang-Sheng Chen, Yilun Zhong, Han-Lei Wang, and Yi-Ping Hung. "My Tai-Chi Coaches: An Augmented-Learning Tool for Practicing Tai-Chi Chuan." In: *Proceedings of the 8th Augmented Human International Conference on - AH '17*. 2017. ISBN: 9781450348355. DOI: 10.1145/3041164.3041194.

[19] Thuong N Hoang, Martin Reinoso, Frank Vetere, and Egemen Tanin. "Onebody: Remote Posture Guidance System Using First Person View in Virtual Environment." In: *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. NordiCHI '16.

New York, NY, USA: ACM, 2016, 25:1–25:10. ISBN: 978-1-4503-4763-1. DOI: 10.1145/2971485.2971521.

[20] Andrew Howard, Ruoming Pang, Hartwig Adam, Quoc Le, Mark Sandler, Bo Chen, Weijun Wang, Liang-Chieh Chen, Mingxing Tan, Grace Chu, Vijay Vasudevan, and Yukun Zhu. "Searching for MobileNetV3." In: Oct. 2019, pp. 1314–1324. DOI: 10.1109/ICCV.2019.00140.

[21] Yinghao Huang, Manuel Kaufmann, Emre Aksan, Michael J Black, Otmar Hilliges, and Gerard Pons-Moll. "Deep Inertial Poser: Learning to Reconstruct Human Pose from Sparse Inertial Measurements in Real Time." In: *SIGGRAPH Asia 2018 Technical Papers*. SIGGRAPH Asia '18. New York, NY, USA: ACM, 2018, 185:1–185:15. ISBN: 978-1-4503-6008-1. DOI: 10.1145/3272127.3275108.

[22] Felix Hülsmann, Cornelia Frank, Irene Senna, Marc O Ernst, Thomas Schack, and Mario Botsch. "Superimposed Skilled Performance in a Virtual Mirror Improves Motor Performance and Cognitive Representation of a Full Body Motor Action." In: *Frontiers in Robotics and AI* 6 (2019), p. 43. ISSN: 2296-9144. DOI: 10.3389/frobt.2019.00043.

[23] Felix Hülsmann, Jan Göpfert, Barbara Hammer, Stefan Kopp, and Mario Botsch. "Classification of motor errors to provide real-time feedback for sports coaching in virtual reality — A case study in squats and Tai Chi pushes." In: *Computers & Graphics* 76 (Aug. 2018). DOI: 10.1016/j.cag.2018.08.003.

[24] Marcelo Kallmann, Carlo Camporesi, and Jay Han. "VR-Assisted Physical Rehabilitation: Adapting to the Needs of Therapists and Patients." In: *Virtual Realities: International Dagstuhl Seminar, Dagstuhl Castle, Germany, June 9-14, 2013, Revised Selected Papers*. Ed. by Guido Brunnett, Sabine Coquillart, Robert van Liere, Gregory Welch, and Libor Váša. Cham: Springer International Publishing, 2015, pp. 147–168. ISBN: 978-3-319-17043-5. DOI: 10.1007/978-3-319-17043-5_9.

[25] Nicholas Katzakis, Jonathan Tong, Oscar Ariza, Lihan Chen, Gudrun Klinker, Brigitte Röder, and Frank Steinicke. "Stylo and Handifact: Modulating Haptic Perception through Visualizations for Posture Training in Augmented Reality." In: *Proceedings of the 5th Symposium on Spatial User Interaction*. SUI '17. New

York, NY, USA: Association for Computing Machinery, 2017, pp. 58–67. ISBN: 9781450354868. DOI: 10.1145/3131277.3132181.

[26] Danielle Levac, Meghan Huber, and Dagmar Sternad. "Learning and transfer of complex motor skills in virtual reality: a perspective review." In: *Journal of NeuroEngineering and Rehabilitation* 16 (Dec. 2019). DOI: 10.1186/s12984-019-0587-8.

[27] Ting-Yang Lin, Chung-Hung Hsieh, and Jiann-Der Lee. "A Kinect-Based System for Physical Rehabilitation: Utilizing Tai Chi Exercises to Improve Movement Disorders in Patients with Balance Ability." In: *Proceedings of the 2013 7th Asia Modelling Symposium*. AMS '13. USA: IEEE Computer Society, 2013, pp. 149–153. ISBN: 9780769551012. DOI: 10.1109/AMS.2013.29.

[28] Matthew Loper, Naureen Mahmood, Javier Romero, Gerard Pons-Moll, and Michael J. Black. "SMPL: A Skinned Multi-Person Linear Model." In: *ACM Trans. Graphics (Proc. SIGGRAPH Asia)* 34.6 (Oct. 2015), 248:1–248:16.

[29] T von Marcard, B Rosenhahn, M J Black, and G Pons-Moll. "Sparse Inertial Poser: Automatic 3D Human Pose Estimation from Sparse IMUs." In: *Comput. Graph. Forum* 36.2 (2017), pp. 349–360. ISSN: 0167-7055. DOI: 10.1111/cgf.13131.

[30] Zoe Marquardt, João Beira, Natalia Em, Isabel Paiva, and Sebastian Kox. "Super Mirror: A Kinect Interface for Ballet Dancers." In: *CHI '12 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '12. New York, NY, USA: Association for Computing Machinery, 2012, pp. 1619–1624. ISBN: 9781450310161. DOI: 10.1145/2212776.2223682.

[31] Sang Il Park and Jessica K. Hodgins. "Data-Driven Modeling of Skin and Muscle Deformation." In: *ACM Trans. Graph.* 27.3 (Aug. 2008), pp. 1–6. ISSN: 0730-0301. DOI: 10.1145/1360612.1360695.

[32] Charles Shea and Rebecca Lewthwaite. "Motor skill learning and performance: A review of influential factors." In: *Medical education* 44 (Jan. 2010), pp. 75–84. DOI: 10.1111/j.1365-2923.2009.03421.x.

[33] Rajinder Sodhi, Hrvoje Benko, and Andrew Wilson. "LightGuide: Projected Visualizations for Hand Movement Guidance." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. New York, NY, USA: Association for Computing Machinery, 2012, pp. 179–188. ISBN: 9781450310154. DOI: 10.1145/2207676.2207702.

[34] Maur\'\icio Sousa, João Vieira, Daniel Medeiros, Artur Arsenio, and Joaquim Jorge. "SleeveAR: Augmented Reality for Rehabilitation Using Realtime Feedback." In: *Proceedings of the 21st International Conference on Intelligent User Interfaces*. IUI '16. New York, NY, USA: ACM, 2016, pp. 175–185. ISBN: 978-1-4503-4137-0. DOI: 10.1145/2856767.2856773.

[35] Arash Tadayon, Troy McDaniel, and Sethuraman Panchanathan. "Functional Case Study Evaluation of the SmartGym: An Anticipatory System to Detect Body Compliance." In: *Proceedings of the 3rd International Workshop on Multimedia for Personal Health and Health Care*. HealthMedia'18. New York, NY, USA: Association for Computing Machinery, 2018, pp. 67–71. ISBN: 9781450359825. DOI: 10.1145/3264996.3265004.

[36] Richard Tang, Xing-Dong Yang, Scott Bateman, Joaquim Jorge, and Anthony Tang. "Physio@Home: Exploring Visual Guidance and Feedback Techniques for Physiotherapy Exercises." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. New York, NY, USA: Association for Computing Machinery, 2015, pp. 4123–4132. ISBN: 9781450331456. DOI: 10.1145/2702123.2702401.

[37] G Tao, P S Archambault, and M F Levin. "Evaluation of Kinect skeletal tracking in a virtual reality rehabilitation system for upper limb hemiparesis." In: *2013 International Conference on Virtual Rehabilitation (ICVR)*. Aug. 2013, pp. 164–165. DOI: 10.1109/ICVR.2013.6662084.

[38] Anton Umek, Sašo Tomažič, and Anton Kos. "Wearable Training System with Real-Time Biofeedback and Gesture User Interface." In: *Personal Ubiquitous Comput.* 19.7 (Oct. 2015), pp. 989–998. ISSN: 1617-4909. DOI: 10.1007/s00779-015-0886-4.

[39] Eduardo Velloso, Andreas Bulling, and Hans Gellersen. "MotionMA: Motion Modelling and Analysis by Demonstration." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. New York, NY, USA: ACM, 2013, pp. 1309–1318. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2466171.

[40] Robert Walter, Gilles Bailly, and Jörg Müller. "StrikeAPose: Revealing Mid-Air Gestures on Public Displays." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. Paris, France: Association for Computing Machinery,

2013, pp. 841–850. ISBN: 9781450318990. DOI: 10.1145/2470654.2470774.

[41] Wenchuan Wei, Yao Lu, Eric Rhoden, and Sujit Dey. “User performance evaluation and real-time guidance in cloud-based physical therapy monitoring and guidance system.” In: *Multimedia Tools and Applications* 78.7 (2019), pp. 9051–9081. ISSN: 1573-7721. DOI: 10.1007/s11042-017-5278-5.

[42] Ungyeon Yang and Gerard Jounghyun Kim. “Implementation and Evaluation of "Just Follow Me": An Immersive, VR-based, Motion-training System.” In: *Presence: Teleoper. Virtual Environ.* 11.3 (2002), pp. 304–323. ISSN: 1054-7460. DOI: 10.1162/105474602317473240.

P2

UNDERSTANDING PERSPECTIVES FOR SINGLE- AND MULTI-LIMB MOVEMENT GUIDANCE IN VIRTUAL 3D ENVIRONMENTS

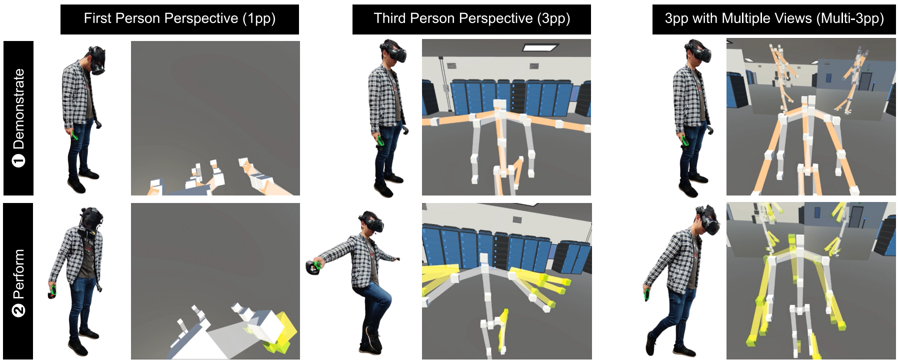


Figure P2.1: We evaluate three perspectives for motion guidance in VR: first-person, third-person, and multi third-person. The movement was first demonstrated by the system, before the users replicated the movement while seeing the steps of the motion.

ABSTRACT

Movement guidance in virtual reality has many applications ranging from physical therapy, assistive systems to sport learning. These movements range from simple single-limb to complex multi-limb movements. While VR supports many perspectives – e.g., first person and third person – it remains unclear how accurate these perspectives communicate different movements. In a user study (N=18), we investigated the influence of perspective, feedback, and movement properties on the accuracy of movement guidance. Participants had on average an angle error of 6.2° for single arm movements, 7.4° for synchronous two arm movements, and 10.3° for synchronous two arm and leg movements. Furthermore, the results show that the two variants of

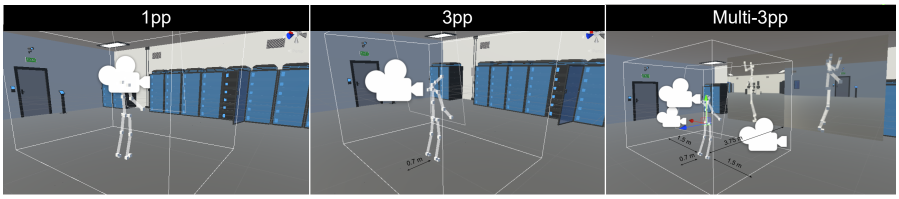


Figure P2.2: Illustration of the camera positions used by the different perspectives evaluated in our user study.

third-person perspectives outperform a first-person perspective for movement guidance (19.9% and 24.3% reduction in angle errors). Qualitative feedback confirms the quantitative data and shows users have a clear preference for third-person perspectives. Through our findings we provide guidance for designers and developers of future VR movement guidance systems.

P2.1 INTRODUCTION

Movement guidance plays a vital role in many domains, ranging from sports training or physical therapy to dancing support. Traditionally, users train with a coach, who observes their movements and offers guidance in the form of visual (e.g., demonstration of a movement), auditory (e.g., instructions for moving certain body parts) and tactile (e.g., physical guidance through a movement) information. While this approach has proven to be effective [15], it depends on the availability of the coach and the user at the same time and place, and is limited by the attention span of coach/user and high costs. Moreover, during the recent pandemic's time, traditional training with a coach becomes even more unlikely.

To overcome these limitations, research has proposed a variety of approaches. Among the earliest, is the use of video tutorials for movement guidance [4]. However, this approach is very limited as it is hard to accurately decode movement information from a prerecorded video, and the user receives no feedback on their performance.

With the advent of virtual reality (VR) and low cost sensing solutions, new interaction techniques became possible, e.g. the ability to show the user movements from different perspectives. Research has shown that VR is a more effective medium for movement instruction compared to video based approaches [11]. Furthermore, for posture guidance [11] and path guidance [21], a first person perspective was shown to outperform other perspectives. However, posture and path guidance overlook the time dimension, users can look around frequently and take their time while performing the movements without adversely affecting the accuracy. In contrast, most real-world movements are performed with time playing an important role. Therefore, it remains unclear how users perform using different perspectives for movement guidance under time constraints.

The primary research question we investigate in this paper is how the perspective influences the accuracy of timed movements in virtual 3d environments (see Figure P6.1). Therefore, we conducted a controlled user study with 18 participants. We varied the perspective (1pp, 3pp, and Multi-3pp) and movement complexity (one arm, two arms, and two arms + leg) to understand their influence on different movements. We also varied movement direction (backward, forward, and sideways) and speed (fast and slow) to cover a large set of typical movements. Each condition was performed without real-time feedback on the participants performance, with visual or with haptic feedback.

Our results show that for movement guidance, a third person perspective with multiple views outperforms a first person perspective (24% decrease in average joint angle error). Furthermore, by increasing the body parts involved in the movement (i.e., the movement complexity), the ability of users to replicate the movement correctly decreases. The angular error increases from 6.2° for single arm movements to 7.4° for synchronous two arm movements and to 10.3° for synchronous two arm and leg movements. We further collected qualitative feedback through a survey. Users found VR to be a viable alternative for movement guidance and expressed clear preferences to using a third person perspective over a first person perspective.

In summary, the main contributions of this paper are:

1. Findings from a controlled user study comparing three perspectives for single- and multi-limb movements in VR.

2. Qualitative results from a survey investigating subjective preferences for VR movement guidance systems.

3. A set of design recommendations based on our findings to help designers of VR movement guidance systems.

P2.2 RELATED WORK

To contextualize our research and contributions, we describe the current state of the field in the following.

P2.2.1 *Perspectives in Virtual 3D Environments*

Prior work has mainly used two types of perspectives for guidance in virtual reality: first-person and third-person perspective.

P2.2.1.1 *First-Person Perspective*

The first-person perspective is the same as our real-world view of our bodies. Guidance in this case consists of visual cues superimposed on our view of our bodies. Although this perspective has been shown to be more effective than other perspectives for posture guidance [11], it also leads to constant head rotation in order to perceive guidance cues [21]. We hypothesize that for movement guidance, these constant head rotations would lead to a decreased accuracy as users are under time-constraints while performing the movement.

P2.2.1.2 *Third-Person Perspective*

Commonly used in games, the third-person perspective shows an out-of-the-body view of the user. Two main types of third-person perspective were studied for guidance applications: mirror perspective (e.g., YouMove [2] and Physio @Home [17]) and a from behind view of a person as commonly found in games (e.g., the work by Yu et al. [21]). In our pilot tests, we found that the distance of visualization from the user influences the quality of guidance. The farther away a visualization was, the harder it was to perceive the movement. We therefore decided to use a third-person perspective from behind and above the user as it enabled placing the visualization close to the user. A mirror perspective would have to be placed farther away as the range of motion to the front is greater than to the back in the movements investigated. A view from behind also enabled executing the movements without mirroring them. We further used a skeleton visualization to reduce occlusions of the body that can make forward movements not visible.

P2.2.2 *Movement Guidance*

Prior work on movement guidance can be grouped into (1) posture guidance, (2) path guidance, and (3) movement guidance.

P2.2.2.1 *Posture Guidance*

Guidance of key frames in body movements is an important aspect of movement guidance and hence has been the subject of several research papers. OneBody [11] investigated the use of VR in comparison to video and Skype for remote posture guidance. Findings showed that using the first person perspective users could imitate target postures more accurately compared to Skype and prerecorded video. However, users also required the longest time to complete postures using a first person perspective. YouMove [2] was a system for posture- and movement guidance. Using an augmented mirror, users could see the target postures overlaid over their reflection. An evaluation showed that YouMove improved short-term retention compared to video demonstration. CameraReady [8] evaluated the use of different displays and visualizations for posture guidance. Larger displays led to lower errors and a 3d body visualization was rated to be more usable than a skeleton visualization.

P2.2.2.2 *Path Guidance*

A step closer to movement guidance, path guidance focuses on guiding users along a predefined path in three-dimensional space. The main difference to movement guidance is that there are no time constraints on the movement. LightGuide [16] introduced the use of projected visualizations on the body for hand guidance. Results showed that users are 85% more accurate using these projected visualizations compared to guidance from animated videos. In a series of user studies, Yu et al. [21] investigated the effect of different perspectives on path guidance in VR. Findings showed that a first person perspective outperforms other perspectives. However, a third person perspective led to significantly lower values for head rotation, indicating that with first person perspective, users had to keep moving their heads left and right constantly to perceive the path accurately. OctoPocus3D [5] investigated feedforward and feedback for executing gestures in three-dimensional space. Findings showed that concurrent feedback is useful at the beginning, but as users execute the gestures more frequently it becomes unnecessary.

P2.2.2.3 *Movement Guidance*

EGuide [6] investigated visual appearances and guidance techniques for mid-air arm movements. Findings showed that for continuous guidance, a realistic arm model resulted in higher accuracy compared to an abstract arm model. Hülsmann et al. [12] investigated showing users their own bodies, as well as showing users a superimposed body of the teacher from the front and side while performing squats. Results showed that users performed better with a superimposed visualization of skilled performance and that different views lead to different kinds of improvement. de Kok et al. [14] developed a closed loop system for multi-modal feedback while learning movements. Movements of users are automatically evaluated by the system and corrective instructions are given to the users in real-time. Han et al. [10] introduced AR-Arm, a movement guidance system for upper limb motions from the first-person perspective. Although all these approaches have demonstrated movement guidance in VR, an evaluation of the influence of different perspective and movement characteristics is still missing in the literature. In our work, we systematically evaluate the affect of varying the perspective used as well as the movement on the accuracy of VR movement guidance.

P2.3 CONCEPT

In the following, we describe and motivate the used concepts for the evaluated movement guidance.

P2.3.1 *Perspectives*

This paper evaluates three perspectives (see Figure P6.1) and compares their influence on single- and multi-limb movement guidance.

P2.3.1.1 *First-Person Perspective (1pp)*

First-person shows the user's own body as a stick figure. The advantage of this perspective is that the user does not need to translate the movement, since they are already shown in the correct location. However, checking the accuracy of multiple limbs requires head movement.

P2.3.1.2 *Third-Person Perspective (3pp)*

Third-person shows a stick figure 0.7 m in front of the user (see Figure P2.2b). This distance was chosen to ensure the whole stick figure is in view without requiring head movements. Hence, we expect this perspective to perform better for multi-limb movements, where the user can not view all body parts. In contrast to a human trainer, where the trainer movements are mirrored to allow for eye contact between student and trainer, we decided to have the stick figure facing in the same direction as the user to ease the interpretation of the movements.

P2.3.1.3 *Third-Person Perspective with Multiple Views (Multi-3pp)*

Multi third-person is similar to the third-person condition, but shows two additional third-person views 3.75 m behind the third person view. The two additional perspectives show the user from both sides to give additional information about movements (see Figure P2.2c). We expect these views to help with forward and backward movements that are difficult to interpret in a third-person perspective.

Although 1pp and 3pp could be combined into a single perspective (similar to the multiple views in Multi-3pp), we make the distinction between 1pp and 3pp to focus on the mere influence of each perspective on its own. An interesting direction for future work can be investigating the combination of 1pp and 3pp.

P2.3.2 *Phases of Movement Training*

The movement training consists of two phases: *demonstrate* and *perform*. The phases are inspired by interactions with human trainers (e.g., in a fitness course).

P2.3.2.1 *Demonstrate*

The first phase shows the movement to the user. The movement is performed with the correct timing to help the user to understand the speed of the movements. Although this phase is similar to a demonstration by a human trainer, it differs in the perspective. Instead of viewing the mirrored movement on another human, the system uses the capabilities of a virtual environment to show the movement either as an overlay on the user, as a non-mirrored third-person or from multiple perspectives.

P2.3.2.2 *Perform*

In the second phase the user performs the movement without demonstration. However, to guide the user's movements there are visible key frames along the movement path (see Figure P6.1). The guides are automatically extracted from the movement to ensure even spacing along the movement path. These visual guides disappear, when the user's body moves close enough (5 cm) to the position. In addition, we evaluated two types of feedback during this phase.

P2.3.3 *Feedback*

We evaluate movement guidance without and with two feedback modes in the perform phase. These modes were added to better understand the influence of visual and haptic feedback during multi-limb movements, since they might ease the adjustment of multiple body parts and hence lead to more accurate movements.

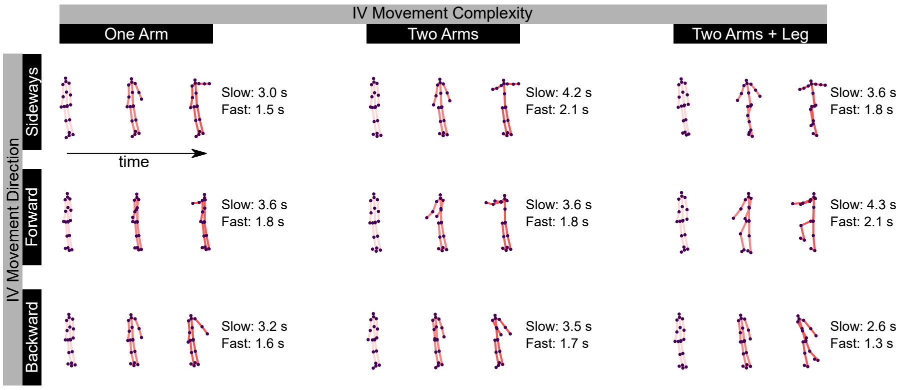


Figure P2.3: The nine different movements used in our evaluation. The levels of the two independent variables *Movement Complexity* and *Movement Direction* are illustrated.

P2.3.3.1 *None*

The baseline condition shows the the keyframes without additional feedback based on the user's movement.

P2.3.3.2 *Color Feedback*

The color condition shows keyframes and *changes the color* of the VR stick figure's body parts depending on how close these body parts are to their optimal path. If the distance between a body joint and the same joint in the optimal movement exceeds 15 cm, the joint is colored red.

P2.3.3.3 *Haptic Feedback*

The haptic condition shows key frames and gives *vibrotactile feedback* on each of the body parts depending on how close they are to their optimal path. The haptic stimulus was calibrated for each user and we used a linear mapping between the euclidean distance to the optimal path (distances beyond 15 cm are mapped to 100% and distances under 15 cm stopped the vibration).

P2.4 USER STUDY

Our user study investigates the influence of different perspectives, movement types, and feedback on the accuracy of movement guidance in VR. In particular, the quantitative part of our user study aims to answer the following hypotheses:

H1 Users are more accurate with 1pp for movements involving one arm.
Motivation: prior work on posture guidance showed that for upper limb postures, 1pp was more accurate than 3pp. However, since our study investigates movement guidance, we hypothesize that one arm movements will not require frequent head rotations and hence will be more accurate using 1pp.

H2 Users are more accurate with 1pp for forward movements.
Motivation: we based this hypothesis on the fact that users were more accurate with 1pp for visible postures and paths from prior work [11, 21].

H3 Users are more accurate with 3pp and Multi-3pp for movements requiring multiple body parts.
Motivation: we hypothesize that due to frequent head rotations necessary to perceive multi-limb movements accurately with 1pp, 3pp and Multi-3pp will be more accurate.

H4 Users are more accurate with Multi-3pp than 3pp.
Motivation: we hypothesize that the addition of side views in Multi-3pp will enable users to see errors in their movements more easily, as was shown in prior work [12] for other perspectives.

H5 Users perform movements requiring fewer body parts more accurately.
Motivation: we hypothesize that multi-limb movements require higher coordination efforts from users and hence result in higher movement errors.

H6 Users are more accurate with haptic feedback than color feedback and no feedback.
Motivation: haptic feedback can be instantaneously localized and does not require visual attention to the body part. Hence, we

hypothesize that haptic feedback will be more effective than color and no-feedback in correcting errors.

H7 Users perform slow movements more accurately than fast movements.
Motivation: we hypothesize that slow movements can be more easily replicated than faster movements.

P2.4.1 *Participants*

We recruited 18 (13 male, 5 female) participants aged between 21 and 27 years old (μ = 23.89, σ = 1.94). Three of our participants had previous experiences with VR. One participant had previously explored a museum in VR, and the remaining two used VR for gaming purposes. None of our participants had previous experience with movement guidance in VR. Participation in our experiment was voluntary, and no compensation was offered.

P2.4.2 *User Study Design*

In our user study, we varied the *perspective* (1pp, 3pp, and Multi-3pp), *movement complexity* (one arm, two arms, and two arms + leg), *movement direction* (forward, sideways, and backward), *movement speed* (slow and fast), and *feedback* (none, haptic, and color). This resulted in 162 ($3 \times 3 \times 3 \times 2 \times 3$) conditions. We used a balanced Latin-square to counterbalance the variable *perspective*. The order of the remaining variables was randomized. In total, we collected from each participant 162 movements.

P2.4.3 *Procedure*

After obtaining informed consent from the participants, we collected their demographic data. Then, we explained the task and provided a brief overview of the procedure. The task was to replicate a movement after observing it in VR.

Every trial started with the participant standing in a neutral pose with hands to the side. Upon pressing the trigger button of the Vive controller, a movement is visualized for the participant to observe. Pressing the trigger button again signals that the participant is ready to start. A guiding visualization is displayed and the participant can start moving. Upon completing a movement, the participant presses the trigger button once again to indicate that the movement is finished. When to press the trigger button was explained to the participants at the beginning, and 2-3 test movements were performed to get the participants familiar with our system that were not recorded. Participants were instructed to replicate the movements in the same speed in which they are displayed.

Upon completing all movements in a certain *perspective*, participants took a small break of 5–10 minutes. After completing all movements, we collected qualitative feedback by asking participants to fill out a survey with the following questions:

S1 What is your opinion on using a VR system to learn new movements?

S2 Which would you prefer: a VR system, a TV application or a real class for learning new movements? Why?

S3 Which perspective did you like the most in VR? Why?

S4 Which feedback did you like the most? Why?

S5 Did you find any aspects frustrating while using VR for motion guidance? Which?

S6 Are there further features you would like to see in a VR movement guidance application? Which?

The total duration of the experiment was approx. 60 minutes.

P2.4.4 *Apparatus*

We conducted the experiment on a i7 dual core 3.6 GHz, 16 GB RAM desktop PC with a NVIDIA GeForce GTX 970 graphics card. We used an HTC VIVE headset and Microsoft Kinect v2. Although not as accurate and precise as marker-based systems, the Microsoft Kinect v2 is accurate and depending on the joint, moderately precise [20]. The virtual environment was running on the same desktop computer and updated tracking information at 60 Hz.

Haptic feedback was generated using the built-in linear resonant actuators (LRAs) in the HTC Vive controllers. In addition to the controllers, haptic feedback was required for stimulation of the legs. We used two EAI C2 [3] linear actuators attached to the ankles. The actuators were set to 200 Hz and vibrated at full intensity with a maximum peak to peak displacement of 0.8 mm. They were placed directly under the outer side of the ankle (i.e., under the Lateral Malleolus bone), as vibrations on the bone were sometimes perceived as uncomfortable by the participants.

P2.4.5 *Dependent Variables*

We recorded the joint angle errors of the participants while performing movements. The joint angle error was computed frame by frame for all joints involved in the movements (i.e., the shoulders, elbows, hips, and knees) and averaged over joints and frames to produce a single value per movement. The following formula was used to calculate the joint angle denoted by θ:

$$\theta = \arccos\left(\frac{a \cdot b}{|a||b|}\right)$$

Where a and b are the vectors connecting the three joints, e.g., for the shoulder a is the vector connecting the shoulder to the spine and b is the vector connecting the shoulder to the elbow. We recorded the 3d positional accuracy (euclidean distance), but decided against using it for further analysis, as it was sensitive to participants' body sizes and full body translations, e.g., a participant stepping forward while performing a movement.

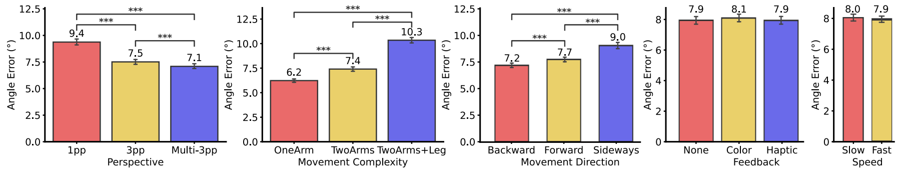


Figure P2.4: Joint angle errors for all independent variables. Error bars are the 95% confidence intervals. All significant effects are shown (* $\leq$ 0.05, ** $\leq$ 0.01, and *** $\leq$ 0.001).

P2.4.6 *Data Analysis*

We tested the data for normality using the Shapiro-Wilk test and found significant deviations. We therefore decided to use the Aligned Rank Transform (ART) [19] procedure to process our data. We then performed an ANOVA to compute the F-score and p-value of main and interaction effects as suggested by Wobbrock et al. [19]. As the ART procedure can inflate Type I errors for post-hoc pairwise comparisons, we used ART-C [7] for post-hoc testing with Bonferroni corrections.

P2.5 QUANTITATIVE RESULTS

We analyse the angle errors from our study and discuss the main (see Figure P2.4) and interaction effects (see Figure P2.5).

P2.5.1 *Main Effects*

The analysis showed a significant ($F_{192.49,2} = 2734$, $p < .001$) main effect of the variable *perspective* on the joint angle error. We found that 1pp ($\mu = 9.37$ °, $\sigma = 4.62$ °) resulted in the highest joint angle errors, followed by 3pp ($\mu = 7.51$ °, $\sigma = 3.51$ °), and Multi-3pp ($\mu = 7.09$ °, $\sigma = 3.51$ °). Post-hoc tests confirmed significant differences between 1pp and 3pp ($p < .001$), 1pp and Multi-3pp ($p < .001$), and 3pp and Multi-3pp ($p < .001$).

We found a statistically significant ($F_{737.45,2} = 2734$, $p < .001$) main effect of the variable *movement complexity* on the joint angle error of participants. Movements involving the use of one arm ($\mu = 6.23$ °, $\sigma = 2.90$ °) resulted in the lowest joint angle errors, followed by two arms (μ = 7.40 °, σ = 3.47 °), and finally two arms and a leg (μ = 10.35 °, σ = 4.42 °). Post-hoc tests confirmed significant differences between one arm and two arm ($p < .001$) movements, one arm and two arms plus leg ($p < .001$), and between two arms and two arms plus leg ($p < .001$).

Further, we found a significant ($F_{147.43,2} = 2734$, $p < .001$) main effect of the variable *movement direction* on the joint angle errors of participants. Backward (μ = 7.19 °, σ = 3.58 °) movements resulted in lowest joint angle errors, followed by forward (μ = 7.74 °, σ = 3.59 °) and sideway (μ = 9.05 °, σ = 4.63 °) movements. Post-hoc tests confirmed all pairwise differences as significant ($p < .001$).

We found no significant main effects for the variables *feedback* ($F_{1.18,2} = 2734$, $p > .05$) and *speed* ($F_{0.36,1} = 2734$, $p > .05$). Figure P2.4 summarizes the results.

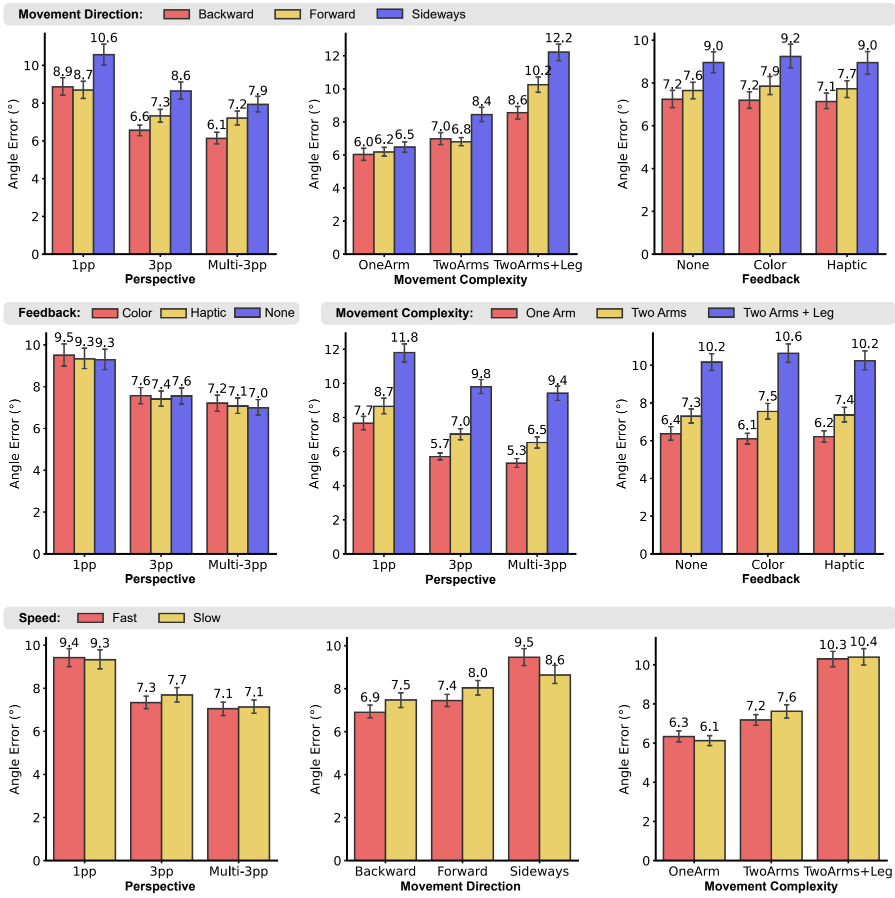


Figure P2.5: Joint angle errors for two-way interactions between the independent variables. Error bars are 95% confidence intervals.

P2.5.2 *Interaction Effects*

Figure P2.5 displays the two-way interactions.

P2.5.2.1 *Movement Direction * Perspective*

We found a significant ($F_{7.60,4}$ = 2734, p <.001) interaction effect between the variables *perspective* and *movement direction*. For 1pp, backward and forward movements were comparable, whereas for 3pp and Multi-3pp, backward movements were significantly more accurate than forward movements.

P2.5.2.2 *Movement Direction * Movement Complexity*

We found a significant interaction effect ($F_{37.53,4} = 2734$, p <.001) between the variables *movement complexity* and *movement direction*. Backward movements were significantly more accurate than forward movements only for movements with two arms and a leg. For movements with one arm and two arms, no significant difference was found between backward and forward directions.

P2.5.2.3 *Movement Direction * Feedback*

We did not find a significant ($F_{0.50,4} = 2734$, p >.05) interaction effect between the variables *feedback* and *movement direction*.

P2.5.2.4 *Feedback * Perspective*

Our analysis did not reveal a significant ($F_{0.42,4} = 2734$, p >.05) interaction effect between the variables *perspective* and *feedback*.

P2.5.2.5 *Movement Complexity * Perspective*

Our analysis did not reveal a significant ($F_{1.17,4} = 2734$, p >.05) interaction effect between the variables *perspective* and *movement complexity*.

P2.5.2.6 *Movement Complexity * Feedback*

We did not find a significant ($F_{1.02,4} = 2734$, p >.05) interaction effect between the variables *feedback* and *movement complexity*.

P2.5.2.7 *Speed * Perspective*

We found a significant ($F_{3.70,2} = 2734$, p <.05) interaction effect between the variables *perspective* and *speed*. For 1pp, fast movements had a higher joint angle error than slow movements. On the other hand, for 3pp and Multi-3pp, fast movements had a lower joint angle error. Post-hoc testing did not confirm these differences as significant.

P2.5.2.8 *Speed * Movement Direction*

Our analysis revealed a significant ($F_{36.97,2}$ = 2734, p <.001) interaction effect between the variables *movement direction* and *speed*. Fast movements were significantly more accurate than slow movements for backward and forward directions. For the movement direction sideways, slow movements were significantly more accurate than fast movements.

P2.5.2.9 *Speed * Movement Complexity*

We found a significant ($F_{4.87,2}$ = 2734, p <.01) interaction effect between the variables *movement complexity* and *speed*. One arm slow movements were more accurate than fast movements, while two arm fast movements were more accurate than slow movements. Post-hoc tests did not confirm these differences as significant.

P2.5.2.10 *Speed * Feedback*

We did not find a significant ($F_{0.83,2}$ = 2734, p >.05) interaction effect between the variables *feedback* and *speed*.

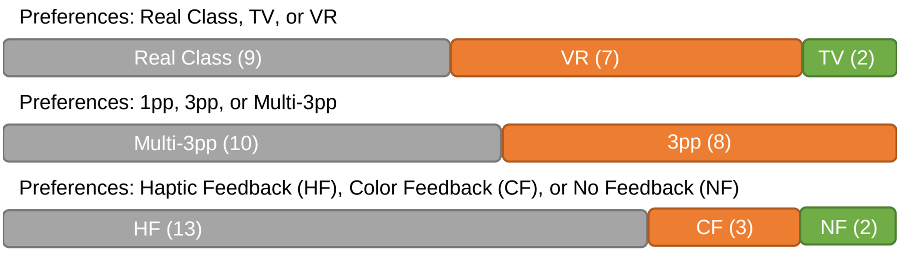


Figure P2.6: Users' qualitative preferences.

P2.6 QUALITATIVE RESULTS

In the following, we detail on the results of our survey.

P2.6.1 *Opinions on Using VR to Learn Movements*

The majority of participants (16) expressed a positive attitude towards using a VR system to learn new movements. They found it *"very interesting"* (P1, P4, P5, P10, P12), *"engaging and fun"* (P1, P10, P15), and it to be *"a good idea"* (P8, P9, P11, P13). Some participants expressed that the usefulness of the system depended on the perspective being used: *"pretty useful from the third person perspective"* (P7), *"it is kinda hard to watch the movement, especially in the first person point of view. With the third person's point of view it is easier to see the movement"* (P15), and that *"the third person perspective is easier to follow."* (P9). Two participants expressed negative attitudes towards learning new movements with a VR system. They found it *"quite tiring"* (P6) and it to be *"not very effective"* (P14).

P2.6.2 *Preferences: Real Class, TV, or VR*

Nine participants expressed preferences for learning new movements in a real class. P1 thought that *"an expert would be monitoring my actions and provide a more accurate feedback"*. Similarly, P7 thought that a real class provides *"quick and easier instruction from a person"* and P8 expressed that with a real class it is *"easier to follow the movement and someone to correct the movement if I did it wrongly"*. The remaining participants all expressed similar thoughts, with the presence of an expert to support them being the main reason why they would prefer a real class. Seven participants chose a VR system for learning new movements. P3 appreciated the independence associated with VR: *"I can learn the movements myself"*. P9 appreciated the flexibility: *"with VR I can do it at home and whenever I like"*. The remaining participants expressed similar thoughts, with independence being the main reason why they prefer a VR system. Lastly, two participants expressed preferences towards a TV system. The main reason was that with a TV, a headset is not required: *"no need for a heavy headset to wear on the head"* (P10).

P2.6.3 *Preferences: Perspectives in VR*

Ten participants preferred the use of Multi-3pp, while the remaining 8 participants all chose 3pp with no one choosing 1pp. The main reason users gave for not choosing 1pp was that 3pp and Multi-3pp were *"clearer"* (P1, P5, P13, P14) and allow users to *"observe the full movement"* (P4, P7), whereas 1pp caused *"neck pain"* (P1, P10) and required *"constant shifting from looking left to looking right"* (P1). Participants appreciated the ability to see themselves from *"different angles"* (P12) in Multi-3pp. Furthermore, P8 expressed *"if I am not sure from the 3rd person perspective, the other views makes it clear"*. On the other hand, P13 expressed that with 3pp *"no distraction compared to third person with multiple view"*. Similarly, P1 expressed that the multi-views can sometimes feel *"redundant"*, however, they are *"nice to have"*.

P2.6.4 *Preferences: Feedback*

13 participants preferred haptic feedback, 3 participants chose color feedback, and 2 participants preferred no feedback. Arguments for haptic feedback included: *"enabled me to respond quickly"* (P6), *"I can feel it directly"* (P18), *"don't need to see it, I can just feel it"* (P16), and *"I can feel the feedback instantly"* (P10). P15 further expressed that the haptic feedback felt more *"fun...it feels more like playing games instead of learning a new movement"*. The main argument for color feedback was the ability to *"see the feedback directly"* (P12). Participants that preferred no feedback expressed that *"I did not understand the feedback and what*

was it telling me" (P8) and *"other types of feedback are not very clear"* (P14).

P2.6.5 *Frustrating Aspects*

We asked participants if they found any aspects frustrating while using VR for movement guidance. Nine participants expressed that movement guidance with 1pp was frustrating. P18 expressed *"first person perspective is really tiring as I have to look around multiple times to see the movement"*. Similarly, P15 expressed *"the first person POV, it's hard to see the backside, i need to look around so much, pain to my neck"*. Three participants commented on the VR headset being *"quite heavy"* (P4, P16) and that it is *"not portable"* (P5).

P2.6.6 *Further Features in a VR Movement Guidance Application*

Further features that participants wanted to have in a VR movement guidance application were: mirrored perspective as it *"might be more natural to the users, it is also a more common perspective when following an instructor in a real class."* (P1), better tracking, adding audio to the experience, being able to choose scenery, having the option to change the skeleton to look like a real instructor, and adding more movements, e.g., jumping, walking, and side steps.

P2.7 DISCUSSION

In this section, we discuss quantitative and qualitative results of our user study. In general, we found that 3pp and Multi-3pp lead to significantly more accurate execution of movements compared to 1pp. This was also reflected in the qualitative results, where 10 participants chose Multi-3pp as their preferred perspective and the remaining participants choosing 3pp.

P2.7.1 *Quantitative Results*

We hypothesized at the beginning in **H1** and **H2** that users would be more accurate using 1pp for one arm movements and forward movements, respectively. However, our results showed that for all levels of movement complexity (one arm, two arms, two arms and a leg) as well as all levels of movement direction (forward, backward, and sideways), 3pp and Multi-3pp were more accurate than 1pp. Therefore, we cannot support **H1** & **H2**. An observation that we could make explaining this result is that regardless of the movement complexity and the direction, users had to nevertheless look around to make sure that there is no visual information that they missed. This led to higher errors using 1pp, even for one-arm movements and movements forward.

In **H3**, we hypothesized that users would be more accurate for multi-limb movements with 3pp and Multi-3pp. Our results confirm this and hence we can accept **H3**. In **H4**, we hypothesized that Multi-3pp would lead to lower errors in comparison to 3pp. Our results confirm that Multi-3pp resulted in significantly lower errors in comparison to 3pp and 1pp, and hence we can accept **H4**. Our findings further show that multi-limb movements result in higher errors compared to single-limb movements, and therefore we can accept **H5**.

In **H6**, we hypothesized that haptic feedback would lead to lower errors in comparison to color and no-feedback. However, our results show that performance of participants was comparable over all feedback types and no significant differences were found. Therefore, we cannot support **H6**. A possible reason for the lack of improvement of haptic and color feedback in comparison to no-feedback was provided by our participants, where they stated that the feedback is useful to find out if a deviation from the target movement is being made, but it does not inform the user in which direction the error is being made. Hence, participants were unsure how to correct their movements after being notified by the different feedback types.

Regarding the speed of movement, we hypothesized that fast movements would be harder to execute than slow (**H7**). Our results showed that users executed fast and slow movements comparably, and hence we cannot support **H7**.

P2.7.2 *Subjective Preferences*

In general, our participants expressed positive attitudes towards movement guidance in VR. However, 9 of our participants (50%) preferred a real class over movement guidance in VR, with the main reason being the presence of an expert that monitors and corrects movements. Therefore, future systems for movement guidance in VR should focus on supporting the interaction between an expert and the user, either using automated algorithms [13] for error correction or by supporting a two-way communication channel between expert and student in VR. This approach has the potential of combining the best of training in a real-class (presence of expert) and training in VR (independence).

In line with the quantitative results, all our participants expressed preference to either Multi-3pp (56%) or 3pp (44%). Hence, to improve the user experience of movement guidance systems in VR, a third-person perspective should be used.

Regarding the choice of feedback, haptic feedback was preferred by the majority of our participants (72%). Although the use of haptic feedback did not lead to a significant improvement in our quantitative results, it was preferred by participants over color and no-feedback, as it enabled them to respond quickly, did not require their visual attention, and felt more fun. To improve the user experience, future movement guidance systems should include haptic feedback and if possible encode the direction of correction required, e.g., using the push and pull metaphors [9], so that users are certain about what the feedback is communicating and the correction required.

P2.8 Design Recommendations

Based on our results, we derive four design recommendations for designers, developers, and researchers of motion guidance systems.

P2.8.1 *Third-Person Perspectives for Movements*

Both third-person perspectives (3pp and Multi-3pp) performed significantly better than the first-person perspective (1pp) for movement guidance. Third-person perspectives lead to an angle error reduction 19.9% or 24.3% compared to the first-person perspective.

P2.8.2 *Additional Views increase Accuracy*

We recommend adding multiple views for best accuracy, because Multi-3pp resulted in the least angle errors overall. The two additional views significantly reduced angle errors by 5.3% (-0.4°) compared to a third-person perspective without additional views.

P2.8.3 *Single-Limb Gestures for Precise Input*

New interaction possibilities that use movement gestures as an input modality are constantly being introduced by researchers, e.g., for interaction with public displays [18] or mid-air gestures [1]. The study shows that a lower movement complexity leads to significantly more accurate movements. We recommend to use single-limb movement gestures whenever precise input is required (-15.8% compared to two arms and -39.8% compared to two arms and leg).

P2.8.4 *Improve User Experience with Haptics*

Despite no significant effect on the movement errors, the qualitative feedback revealed 13 of 18 participants (72%) preferred haptic feedback over no feedback or color feedback. Therefore, we recommend adding haptic feedback to communicate errors to improve the user experience of motion guidance systems.

P2.9 CONCLUSION

In this paper, we investigated different perspectives, movement properties, and feedback on VR movement guidance. Our work extends prior work on posture [2, 8, 11], path [5, 16, 21], and movement guidance [6, 12, 14]. Our findings show that for timed movements, a third-person perspective should be preferred as it increases the accuracy of the user while replicating movements. It was also qualitatively preferred by our users. Furthermore, our results showed that the addition of multiple views led to a significant accuracy increase and that single-limb movements were more accurately replicated in comparison to multi-limb movements. Based on our quantitative and qualitative findings, we derive a set of design recommendations for VR movement guidance systems.

REFERENCES

[1] Christopher Ackad, Andrew Clayphan, Martin Tomitsch, and Judy Kay. "An In-the-Wild Study of Learning Mid-Air Gestures to Browse Hierarchical Information at a Large Interactive Public Display." In: *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. UbiComp '15. Osaka, Japan: Association for Computing Machinery, 2015, pp. 1227–1238. ISBN: 9781450335744. DOI: 10.1145/2750858.2807532.

[2] Fraser Anderson, Tovi Grossman, Justin Matejka, and George Fitzmaurice. "YouMove: Enhancing Movement Training with an Augmented Reality Mirror." In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST '13. New York, NY, USA: Association for Computing Machinery, 2013, pp. 311–320. ISBN: 9781450322683. DOI: 10.1145/2501988.2502045.

[3] Lorna Brown, Stephen Brewster, and Helen Purchase. "Multidimensional tactons for non-visual information presentation in mobile devices." In: vol. 159. Jan. 2006, pp. 231–238. DOI: 10.1145/1152215.1152265.

[4] Christopher Clarke, Doga Cavdir, Patrick Chiu, Laurent Denoue, and Don Kimber. "Reactive Video: Adaptive Video Playback Based on User Motion for Supporting Physical Activity." In:

Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology. New York, NY, USA: Association for Computing Machinery, 2020, pp. 196–208. ISBN: 9781450375146.

[5] William Delamare, Thomas Janssoone, Céline Coutrix, and Laurence Nigay. "Designing 3D Gesture Guidance: Visual Feedback and Feedforward Design Options." In: June 2016, pp. 152–159. DOI: 10.1145/2909132.2909260.

[6] Maximilian Dürr, Rebecca Weber, Ulrike Pfeil, and Harald Reiterer. "EGuide: Investigating Different Visual Appearances and Guidance Techniques for Egocentric Guidance Visualizations." In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '20. New York, NY, USA: Association for Computing Machinery, 2020, pp. 311–322. ISBN: 9781450361071. DOI: 10.1145/3374920.3374945.

[7] Lisa A. Elkin, Matthew Kay, James J. Higgins, and Jacob O. Wobbrock. "An Aligned Rank Transform Procedure for Multifactor Contrast Tests." In: *The 34th Annual ACM Symposium on User Interface Software and Technology*. UIST '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 754–768. ISBN: 9781450386357. DOI: 10.1145/3472749.3474784.

[8] Hesham Elsayed, Philipp Hoffmann, Sebastian Günther, Martin Schmitz, Martin Weigel, Max Mühlhäuser, and Florian Müller. "CameraReady: Assessing the Influence of Display Types and Visualizations on Posture Guidance." In: *Designing Interactive Systems Conference 2021*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1046–1055. ISBN: 9781450384766. DOI: 10.1145/3461778.3462026.

[9] Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. "TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. PETRA '18. Corfu, Greece: Association for Computing Machinery, 2018, pp. 273–280. ISBN: 9781450363907. DOI: 10.1145/3197768.3197785.

[10] Ping-Hsuan Han, Kuan-Wen Chen, Chen-Hsin Hsieh, Yu-Jie Huang, and Yi-Ping Hung. "AR-Arm: Augmented Visualization for Guiding Arm Movement in the First-Person Perspective." In: *Proceedings of the 7th Augmented Human International Conference 2016*. AH '16. Geneva, Switzerland: Association for Computing

Machinery, 2016. ISBN: 9781450336802. DOI: 10.1145/2875194.2875237.

[11] Thuong N. Hoang, Martin Reinoso, Frank Vetere, and Egemen Tanin. "Onebody: Remote Posture Guidance System Using First Person View in Virtual Environment." In: *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. NordiCHI '16. Gothenburg, Sweden: Association for Computing Machinery, 2016. ISBN: 9781450347631. DOI: 10.1145/2971485.2971521.

[12] Felix Hülsmann, Cornelia Frank, Irene Senna, Marc O Ernst, Thomas Schack, and Mario Botsch. "Superimposed Skilled Performance in a Virtual Mirror Improves Motor Performance and Cognitive Representation of a Full Body Motor Action." In: *Frontiers in Robotics and AI* 6 (2019), p. 43. ISSN: 2296-9144. DOI: 10.3389/frobt.2019.00043.

[13] Felix Hülsmann, Jan Göpfert, Barbara Hammer, Stefan Kopp, and Mario Botsch. "Classification of motor errors to provide real-time feedback for sports coaching in virtual reality — A case study in squats and Tai Chi pushes." In: *Computers & Graphics* 76 (Aug. 2018). DOI: 10.1016/j.cag.2018.08.003.

[14] Iwan de Kok, Julian Hough, Felix Hülsmann, Mario Botsch, David Schlangen, and Stefan Kopp. "A Multimodal System for Real-Time Action Instruction in Motor Skill Learning." In: *Proceedings of the 2015 ACM on International Conference on Multimodal Interaction*. ICMI '15. Seattle, Washington, USA: Association for Computing Machinery, 2015, pp. 355–362. ISBN: 9781450339124. DOI: 10.1145/2818346.2820746.

[15] Charles Shea and Rebecca Lewthwaite. "Motor skill learning and performance: A review of influential factors." In: *Medical education* 44 (Jan. 2010), pp. 75–84. DOI: 10.1111/j.1365-2923.2009.03421.x.

[16] Rajinder Sodhi, Hrvoje Benko, and Andrew Wilson. "LightGuide: Projected Visualizations for Hand Movement Guidance." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. New York, NY, USA: Association for Computing Machinery, 2012, pp. 179–188. ISBN: 9781450310154. DOI: 10.1145/2207676.2207702.

[17] Richard Tang, Xing-Dong Yang, Scott Bateman, Joaquim Jorge, and Anthony Tang. "Physio@Home: Exploring Visual Guidance and Feedback Techniques for Physiotherapy Exercises."

In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. New York, NY, USA: Association for Computing Machinery, 2015, pp. 4123–4132. ISBN: 9781450331456. DOI: 10.1145/2702123.2702401.

[18] Robert Walter, Gilles Bailly, and Jörg Müller. "StrikeAPose: Revealing Mid-Air Gestures on Public Displays." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. Paris, France: Association for Computing Machinery, 2013, pp. 841–850. ISBN: 9781450318990. DOI: 10.1145/2470654.2470774.

[19] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. "The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: Association for Computing Machinery, 2011, pp. 143–146. ISBN: 9781450302289. DOI: 10.1145/1978942.1978963.

[20] Kirk Woolford. "Defining Accuracy in the Use of Kinect v2 for Exercise Monitoring." In: MOCO '15. Vancouver, British Columbia, Canada: Association for Computing Machinery, 2015, pp. 112–119. ISBN: 9781450334570. DOI: 10.1145/2790994.2791002.

[21] Xingyao Yu, Katrin Angerbauer, Peter Mohr, Denis Kalkofen, and Michael Sedlmair. "Perspective Matters: Design Implications for Motion Guidance in Mixed Reality." In: *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 2020, pp. 577–587. DOI: 10.1109/ISMAR50242.2020.00085.

P3

VRSKETCHPEN: UNCONSTRAINED HAPTIC ASSISTANCE FOR SKETCHING IN VIRTUAL 3D ENVIRONMENTS

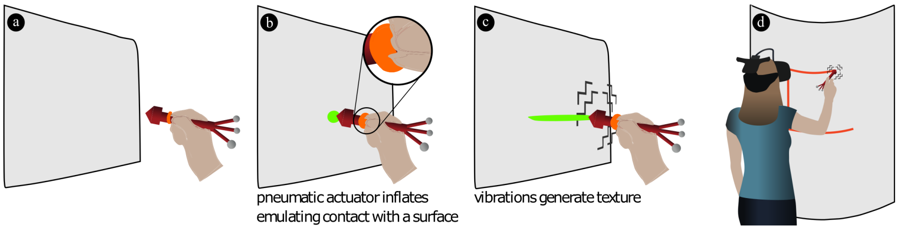


Figure P3.1: (a) VRSketchPen recreates the feeling of (b) contact pressure and (c) textures of surfaces, which allows users to have a more realistic experience when (d) drawing in VR. VRSketchPen also uses the unconstrained haptic feedback interaction technique, that allows users to draw in both flat and curved surfaces without snapping the stroke to a virtual canvas.

ABSTRACT

Accurate sketching in virtual 3D environments is challenging due to aspects like limited depth perception or the absence of physical support. To address this issue, we propose VRSketch-Pen – a pen that uses two haptic modalities to support virtual sketching without constraining user actions: (1) pneumatic force feedback to simulate the contact pressure of the pen against virtual surfaces and (2) vibrotactile feedback to mimic textures while moving the pen over virtual surfaces. To evaluate VRS-ketchPen, we conducted a lab experiment with 20 participants to compare (1) pneumatic, (2) vibrotactile and (3) a combination of both with (4) snapping and no assistance for flat and curved surfaces in a 3D virtual environment. Our findings show that usage of pneumatic, vibrotactile and their combination significantly improves 2D shape accuracy and leads to diminished depth errors for flat and curved surfaces. Qualitative results indicate that users find the addition of unconstraining haptic feedback to significantly improve convenience, confidence and user experience.

P3.1 INTRODUCTION

Recent advances in inexpensive, high-quality Virtual Reality (VR) headsets, such as HTC-VIVE and Oculus Rift, have promoted the interest of architects, artists, and designers to use immersive 3D sketching in their everyday activities [16, 42]. Most commercial systems, such as TiltBrush [26] and Quill [20], use 3D freehand drawing to create strokes by following the user's hand movements with a six degree of freedom (6 DOF) input device. Besides the flexibility and speed of this technique [75], users also have the advantage of being immersed inside the drawing and of sketching directly in 3D space [35]. This helps them create and visualize 3D shapes in a body-centric space. On the other hand, users need to project their shapes using perspective grids and scaffolding when drawing 3D shapes using pen and paper or a tablet.

Despite the stated advantages of immersive 3D sketching, one problem of sketching in 3D is lower accuracy compared to sketching with pen and paper [3, 77]. Some of the challenges that affect the user accuracy are the absence of physical support [3], higher cognitive [8] and sensorimotor demands [77], and the depth perception issues associated with stereo displays [6, 9, 60]. These challenges make correctly positioning a stroke in 3D space difficult. There have been different attempts to improve user accuracy while sketching in virtual environments, including the use of novel metaphors to create strokes [28, 36], beautification [5, 22], and surface snapping [2, 4, 5, 28, 42, 45]. However, these solutions constrain user actions, which can adversely influence the final sketch [48, 72].

To address the accuracy of sketching in virtual 3D environments, such as the absence of a physical surface and limited depth perception, we designed VRSketchPen – a tool for immersive 3D sketching that combines two types of haptic feedback in a new interaction technique called *unconstrained haptic assistance* (see Figure P3.1). The first type of feedback is pneumatic force feedback to simulate the contact pressure of the pen against virtual surfaces. The second one is a vibrotactile feedback to mimic textures while moving the pen over virtual surfaces. *Unconstrained haptic assistance* reduces the user's stroke-control errors without projecting the strokes to a virtual canvas by including the feeling of haptic textures. With VRSketchPen, we aim to enhance the user motor-control when sketching in VR, while maintaining the fluidity and expressiveness of the 3D freehand drawing interaction technique.

To evaluate VRSketchPen for sketching in a virtual 3D environment, we conducted an experiment with 20 participants where we compare pneumatic, vibrotactile and a combination of both with snapping and no assistance for flat and curved surfaces. We discovered that *unconstrained haptic assistance* made users draw more accurately in 3D than without assistance. Moreover, users could draw more accurately on curved surfaces than with snapping.

P3.2 RELATED WORK

Designing user interfaces to fix the inaccuracies of immersive 3D sketching compared to 2D sketching [3, 28, 77] has been an open area of research for decades. In this paper, we focus on user interfaces that emulate sketching on a physical surface to prevent the problems of sketching mid-air [3] and the depth perception problems of stereo displays [6, 9, 60]. This section refers to related work on surface-snapping and physical-object interfaces, as well as interfaces for rendering force feedback and haptic textures.

P3.2.1 *Surface-Snapping Interfaces*

Surface-snapping interfaces provide users with a virtual canvas where they can draw. These systems project strokes sketched by users on the virtual canvas to remove depth-related errors. Some user interfaces let users change the virtual canvas position manually [16, 28]. Others use strokes or gestures to move the drawing plane [42, 43, 52, 80]. The third set of user interfaces use predefined heuristics to automatically change the canvas position. For example, Multiplanes [5] uses the controller pose and previously drawn strokes. Finally, some interfaces use previously drawn strokes or shapes as canvases [2, 26, 28, 42, 53].

Although surface-snapping interfaces improve user accuracy, they can make the drawing less expressive [13]. They also constrain the user creativity [48, 72], as they limit the way users can create a stroke or make users re-position the drawing surface before sketching a new stroke. VRSketchPen on the other side allows users to experience unconstrained movements while maintaining expressiveness and fluidity in their interactions.

P3.2.2 *Physical-Object Interfaces*

In these user interfaces, users depend on a physical surface that passively provides haptic feedback, e.g. touch devices like mobile phones and tablets [2, 11, 16, 17, 34, 45–47, 65, 80], and large screens [15, 42, 43, 59]. User interfaces on these devices translate the position of the physical surface into the virtual environment by using virtual canvases. Altering the position of the virtual canvas can be achieved by moving the device or by using 3D navigation methods to change viewpoint. Afterwards, users sketch using the touch capabilities of the device. However, when using touch devices, users can not feel the shape of the sketched object or its texture. Another limitation with mobile devices and tablets is that users need to keep the device stable with one hand while sketching, which can be tiring [32, 45]. Other user interfaces use 3D printed shapes that users can trace over [37, 74]. Nevertheless, this approach requires users to carry specific objects for each shape they want to sketch.

P3.2.3 *Force-Feedback Interfaces*

Providing force sensations in user interfaces is currently accomplished using different technologies. For instance using pneumatic actuators [30, 62, 71], electrical muscle stimulation (EMS) [50, 51] and mechanical actuators [10, 29]. However, using mechanical actuators, such as exoskeletons [78], requires heavy components that lead to fatigue in a use case such as sketching.

In the context of 3D sketching, force feedback devices allow users to touch virtual objects like surfaces [23, 39, 53] or virtual canvases [24, 52]. For example, Mohanty et al. [52] use a force feedback pen to snap the tip to a virtual canvas. Force feedback devices also give users more control over their stroke [40, 41, 66]. For example, Drawing on Air [40] and Dynamic Dragging [41] use haptic feedback to help users create smooth transitions between curves. However, most of these user interfaces use a fixed force feedback device like the Touch [70] or the Phantom [69] that keeps users standing in the same place. Using VRSketchPen provides two types of haptic feedback, to feel both the shape of an object and its texture, while allowing users to walk inside the virtual environment by not fixing the system to a single position.

Many user interfaces for 3D sketching that use a force feedback device have not been evaluated. Only Mohanty et al. [52] and Keefe et al. [41] have done quantitative evaluations of the effect of haptic feedback on 3D sketching. Mohanty et al. [52] evaluated the effect of snapping on a plane using haptic feedback, and Keefe et al. [41] evaluated the effect of haptic feedback on the user stroke control. Finally, work that evaluates how haptic feedback emulates the sensation of painting with water-colors on physical objects [53] is outside the scope of this work, because we focus on 3D sketching in mid-air.

We extend prior work by evaluating the effect of different types of haptic feedback on 3D sketching.

P3.2.4 *Haptic Rendering of Textures*

Moving our fingers on a surface results in vibrations that help us experience textures. Such experiences are also possible when interacting using a tool [44]. A large body of work investigates how textures of different materials can be generated [14, 61, 68]. For example, by recording vibration data of different materials, movement of a pen on a flat surface can be experienced to have different textures [14]. Co-optimization of surface and styli can be applied to closely match the haptic perception of a digital tool with the perception of a traditional one [56]. Strohmeier et al. [67] apply haptic textures to mid-air interactions with different motion to vibration mappings, such as mapping changes in rotation to vibrations. Other works relied on actuating the tip of a brush for generating textures and impact force [53], and a controller with an actuated wheel for textures [76]. However, these devices are heavy and can lead to fatigue in a use-case like 3D sketching where users do not have a physical surface to rest their hand on.

P3.3 VRSKETCHPEN

We present VRSketchPen (Figure P3.2), a tool for immersive 3D sketching that uses a haptic feedback pen to help users sketch accurate shapes without constraining their actions. VRSketchPen consists of two parts: (1) a new haptic feedback pen that can emulate contact pressure and textures, and (2) a new interaction technique called *unconstrained haptic assistance*. With VRSketchPen we aim to help users sketch more accurately without sacrificing expressiveness by using haptic feedback to reduce control-errors when drawing in 3D [41, 73]. Especially those related to the lack of a physical surface [3], the high sensorimotor demands of controlling a 6-DOF device [77], and depth perception issues [6, 9, 60]. To achieve this, VRSketchPen's hardware implementation goes hand in hand with our proposed interaction technique *unconstrained haptic assistance*.

Unconstrained haptic assistance uses 3D freehand drawing combined with ungrounded haptic feedback to emulate the speed and expressiveness of sketching with pen and paper. In contrast to snapping, our interaction technique assists the users without altering their strokes. This allows users to express their ideas freely and does not limit user creativity like other CAD systems do [49]. Finally, unconstrained haptic assistance avoids breaking the design flow by removing the conscious engagement generated through constant interaction with the user interface, e.g. turning the snapping function on/off [54].

P3.3.1 *Design Considerations*

The design of VRSketchPen was informed by seven parameters:

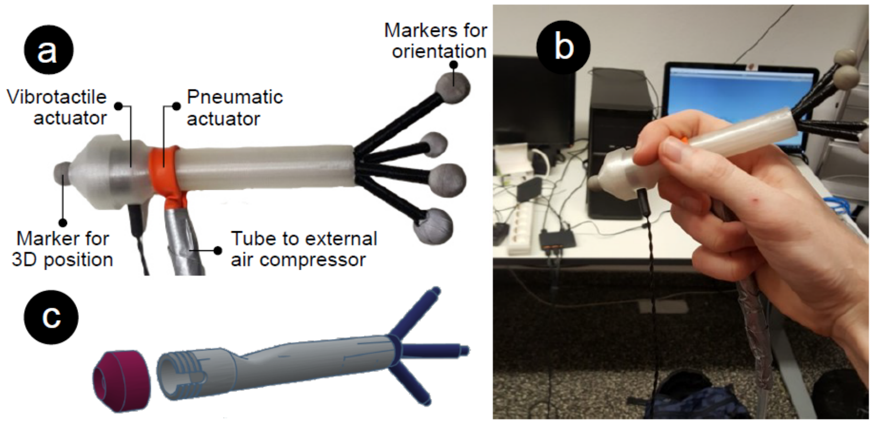


Figure P3.2: (a) VRSketchPen (b) used in the precision grip and (c) as a 3D model.

P3.3.1.1 *Familiarity*

Most people learn how to use a pen in their infancy [21]. Furthermore, the pen remains a widely used tool in the office and by artists. Finally, for interactions in a 3D environment, pens have better performance than controllers in today's VR and AR systems [55]. Therefore, we designed VRSketchPen as a pen-like device.

P3.3.1.2 *Grip type*

The design of our pen-like device encourages users to hold the pen using their fingers. Zhai et al. [81] found that using the finger muscles to grip the input device has better performance than using the wrist or elbows muscles. Users can hold the pen using the precision grip, where users grip the pen with their thumb and index finger (Figure P3.2b). The precision grip prevents errors when making a stroke using a pen on paper [21, 25, 64]. Moreover, the pen supports other grip types, for example, the three or four fingers grips used in Japanese calligraphy [19].

P3.3.1.3 *Size & shape*

We carefully choose the size and shape of our device to help users draw more accurately, as pen design affect the user 2D drawing [27].

Design of our pen was similar to Goonetilleke et al. [27], to prevent affecting comfort and accuracy, without increasing sketching time.

P3.3.1.4 *Weight*

Lightweight pens increase the user's dexterity, as the weight of a pen affects user interaction [27, 55]. For example, a lightweight pen prevents user fatigue when using the precision grip [55]. Finally, we aim for a balanced weight distribution to avoid decreasing the user performance [55].

P3.3.1.5 *Contact and Texture Feedback*

Similar to real-world interactions, it is important to receive feedback on when the pen contacts a virtual surface and feeling a feedback on the pen's movements. Visual feedback is not enough to communicate these cues [44]. Similar to [68], VRSketchPen emulates textures and contact force resulting from contact with a surface.

P3.3.1.6 *Avoiding Haptic Overstimulation*

Constant haptic stimulation fatigues the user [38]. To avoid this issue, our system only gives feedback when the user is attempting to sketch on the virtual surface (i.e., is close to it). If the pen is not in proximity to the system, no haptic signal is given.

P3.3.1.7 *Unconstrained Sketching*

3D environments enable the user to draw a wide variety of objects. While 2D surfaces can assist the user in sketching [5], snapping all strokes to a virtual surface limits the user's expressiveness. For example, a user might want to deviate from a predefined shape to draw an expressive fur on a 3D animal character, while staying close to the animal's body. In our work, we aim to assist the user drawing on virtual 2D surface without limiting expressiveness or constraining strokes to be on a surface.

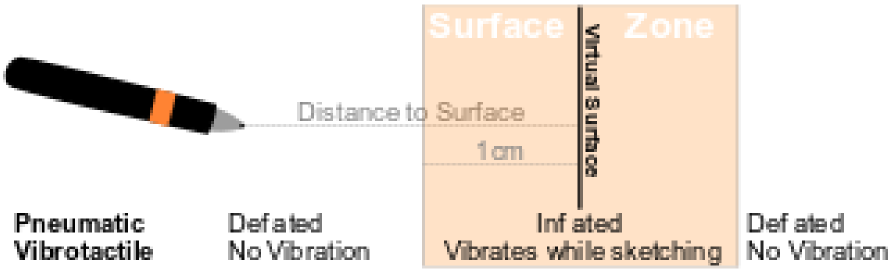


Figure P3.3: The *unconstrained haptic assistance* interaction technique combines vibrotactile and pneumatic feedback.

P3.3.2 *VRSketchPen Implementation*

P3.3.2.1 *Pen Design*

We designed a custom pen-like device (Figure P3.2a). The diameter of the pen-shank is 14 mm, and the length is 105 mm. The pen also has four legs to add the retro-reflective tracking markers, whose size is 9.5 mm. The frame of the pen was printed using PLA filament and weighs 20 g. For generating vibrations, we use a single lightweight vibrotactile actuator (17 g) fitted inside a compartment at the tip of the pen. In total, the pen weighs 37 g. Figure P3.2(c) shows the 3D model and the printed pen. The 3D model of the pen is also available in the paper's supplementary material.

P3.3.2.2 *Vibrotactile Actuator*

We use a high-fidelity vibrotactile actuator (EAI C2[1]) for rendering texture using localized high displacement vibrations (Figure P3.2a). The EAI C2 tactor is a linear resonant actuator that provides strong localized vibrations by using a moving contractor shielded by a passive housing. Signals to the tactor were sent using an EAI universal controller connected to a desktop computer. Vibration latency with our setup was 50 ms.

1 C-2 tactor from Engineering Acoustics, Inc. (www.eaiinfo.com/product/c2/, Retrieved: 25.08.2020)

P3.3.2.3 *Pneumatic Actuator*

For pressure feedback, we use a small balloon as an inflatable pneumatic actuator. It is attached at the location where the index finger contacts with the pen (Figure P3.2a). Our handheld prototype is connected to an external compressor and solenoid valve to keep VRSketchPen lightweight. The used air compressor (Einhell TH-AC 200/24 OF) is capable of providing up to 8 bar in pressure. Airflow from the compressor to the balloon is regulate by a solenoid valve. We used a normally closed (U.S. Solid JFSV00051) solenoid valve that is controlled using a micro-controller. Response time for the pneumatic actuator was 50 ms and inflates completely after 85 ms.

P3.3.2.4 *Tracking*

To ensure accurate representation of the haptic stimulation, we tracked the pen using a marker-based motion capture system (Optitrack V100:R2). The pen is fitted with retro-reflective markers for tracking.

P3.3.3 *Unconstrained Haptic Assistance*

Our proposed interaction technique is activated depending on the distance to a virtual surface (Figure P3.3). The haptic assistance is activated if the distance between the tip of the pen and the virtual surface is less than 1 cm (surface-zone). We identified this value in our informal tests before running the user study. The feedback is the same, no matter if the tip is in front or behind the surface.

While activated, the pneumatic actuator indicates contact to the surface. In this state, the user feels pressure from the pneumatic actuator and texture feedback through the vibrotactile actuator, while moving the pen parallel to the surface (i.e., sketching on it). For our vibrotactile textures we use a granularity of 2 pulses per cm, 50% maximum vibration amplitude of the EAI C2 tactor and a frequency of 120 Hz. We chose these values based on prior work exploring the parameter space for generating textures [68] and our pilot tests.

To avoid fatiguing the user, once the tip of the pen leaves the surface-zone, the pneumatic actuator deflates and the vibration feedback stops.

P3.4 EXPERIMENT

Our experiment aimed to evaluate the utility of VRSketchPen when sketching planar and non-planar strokes commonly used when designing 3D objects [63, 77]. We designed a task to evaluate VRSketchPen's utility, i.e. the combination of pneumatic force-feedback and vibrotactile textures, and how it improves user accuracy when sketching in both flat and curved surfaces.Based on prior work, we hypothesized the following outcomes:

H1 VRSketchPen reduces depth inaccuracies.

H2 VRSketchPen improves 2D sketching accuracy.

H3 VRSketchPen improves 3D sketching accuracy.

H4 VRSketchPen increases the sketching time, since participants require more time to process the haptic signals.

H5 VRSketchPen improves users' convenience, confidence and engagement ratings.

P3.4.1 *Methodology*

In this section, we describe our experiment design, the procedure we used, our participants, apparatus, and dependent variables.

P3.4.1.1 *Participants*

We recruited 20 participants (10 female) aged between 21 and 77 years (M = 30.72, SD = 13.71). Three of the participants had experience with sketching in VR, namely drawing on presentation slides in VR, from gaming and a previous research project. None of the participants had experience with snapping and haptic feedback for sketching before the experiment. Participation in our experiment was voluntary, and no compensation was offered.

P3.4.1.2 *Experiment Design*

Throughout the experiment we used two surface types (flat and curved), and five levels of assistance type (vibrotactile, pneumatic, vibrotactile and pneumatic, snapping and no assistance), resulting in ten (5×2) experimental conditions. We used a balanced Latin-square to counterbalance the variables *surface type* and *assistance type* in a within subjects design. For each combination of the levels of independent variables participants sketched three shape types (triangle, rectangle and circle) performing two repetitions for each shape. The order of the shapes was randomized. This resulted in a total of 60 strokes per participant.

P3.4.1.3 *Procedure*

After obtaining informed consent from the participants, we collected their demographic data. Then, we explained the task and provided a brief overview of the procedure. The task was to trace a shape (triangle, rectangle, or circle) in a single stroke.

Every trial started with the participant standing in front of a virtual surface displaying the shape to be drawn. Our participants were instructed not to move during our study, to prevent variables like participant's movement patterns influencing the results.

There was no formal training phase. As soon as the participant felt comfortable with the environment and location of the virtual surface, they were shown the first shape. After finishing sketching a shape, the participant manually switched to the next trial. Upon completing all shapes in a condition, which is the combination of one surface type and an assistance type, our participants filled out a short questionnaire with 3 5-point Likert-scale questions. We consider this time as resting-time. Afterwards, the experiment continued with the next condition. The total duration of the experiment was approximately 45 to 60 minutes.

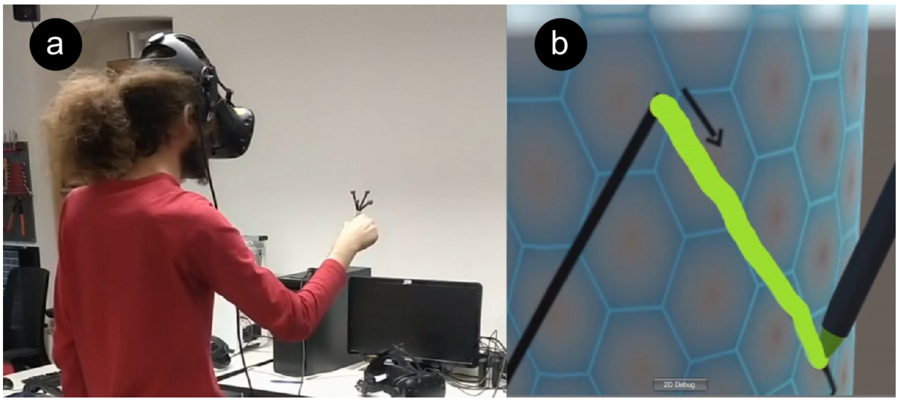


Figure P3.4: The setting of the experiment: (a) the physical setting, and (b) the participant view during the experiment.

P3.4.1.4 *Apparatus*

We conducted the experiment on a i7 dual core 3.6 GHz, 16 GB RAM desktop PC with a NVIDIA GeForce GTX 970 graphics card. We used an HTC VIVE headset [33] and an Optitrack V100:R2 motion capture system with six cameras (sub-millimeter accuracy) for tracking the pen at 100 Hz. The virtual environment was running on the same desktop computer and updated the position of the pen at 60 Hz. We provided participants with a 2.5m x 2.5m drawing area free of obstacles. VRSketchPen was used in four operating modes depending on the experiment condition:

1. *Vibration* VRSketchPen renders vibrotactile textures to emulate movement on a virtual surface.

2. *Pneumatic* VRSketchPen provides pneumatic force-feedback to simulate impact force with a virtual surface.

3. *Combined* VRSketchPen renders both vibrotactile texture and force-feedback.

4. *No* haptic feedback.

Virtual Environment: Unity version 2018.3.11f1 was used to create the virtual environment. It consisted of open space with no spatial reference except for a ground plane and the virtual surface that displays the current shape. The surface location was centered in the physical space available to our users, and its position remained constant throughout the experiment. The surface was either curved or flat, depending on the experiment condition (Figure P3.5). The curved surface was a cylinder with a radius of 25 cm. The flat surface extended through the entire scene with a size of 10 m x 10 m.

P3.4.1.5 *Shapes*

Participants drew three geometrical shapes that are commonly used when designing objects: a triangle, a square and a circle (Figure P3.5). These shapes are difficult to draw freehand without errors like waves in the strokes, non-matching corners, deviation from the drawing plane, and corrective movements [77]. For instance, even experienced designers have difficulties in precisely visualizing perspective transformations [63]. Based on their difficulty, they have been used to evaluate 3D sketching interfaces before [3, 18, 77].

The triangle base was 37 cm and its height 31 cm. The square had a side length of 37 cm. The circle had a 20 cm radius. Each shape was displayed in the middle of the surface, at a height comfortable for the participant. The position of the surface remained constant during the study.

P3.4.1.6 *Scoring*

For each drawn shape the 3D coordinates of the VRSketchPen and timestamps at the running frequency of the virtual scene (60 Hz) were logged. Similar to Arora et al. [3], the data was pre-processed using a median filter with a window size of 100ms to filter out high frequency noise. The data is then approximated using piecewise linear approximation and resampled to 100 equidistant points.

To test our hypothesis, we used the following dependent variables:

- **Depth Error:** the average distance in the z-direction (perpendicular to the surface) between the participants' drawn shape and the shape displayed on the surface.
- **2D Error:** the average two-dimensional error on the virtual surface between the participants' sketched shape and the shape displayed. It shows how well a user can control their arm movement without considering depth.

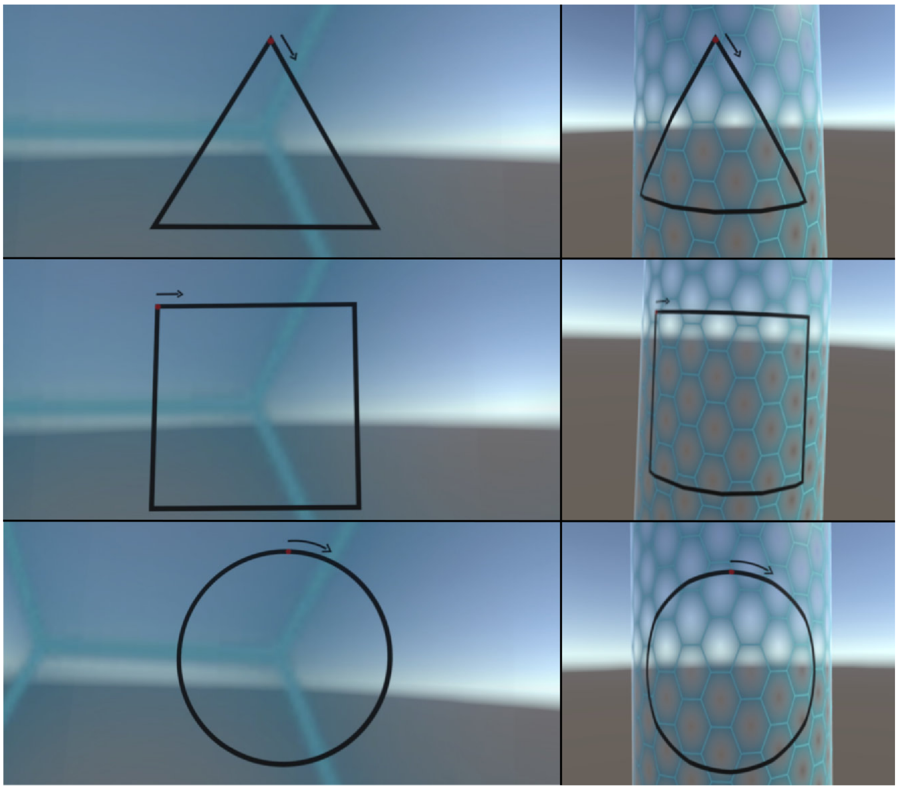


Figure P3.5: Participants sketched a triangle, a rectangle and a circle on flat (left) and curved (right) surfaces.

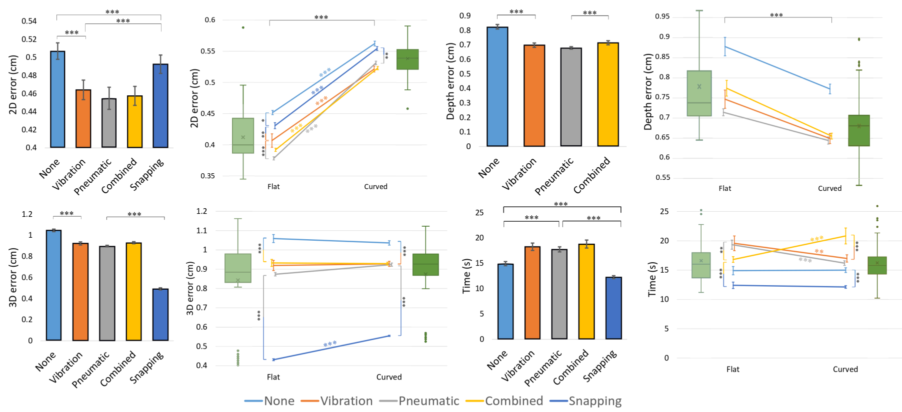


Figure P3.6: Average 2D, 3D, depth errors, and task completion time for each experimental condition.

- **3D Error:** the average three-dimensional error between the participants' drawn shape and the shape displayed on the surface.
- **Drawing Time:** the time between the first and last point in the sketch.
- **Convenience, confidence and engagement (5-point Likert scale):** the participants' subjective estimations of their perceived convenience, confidence and engagement.

P3.5 RESULTS

We evaluated the recorded data using a 2-way repeated measures ANOVA, followed by Bonferroni corrected pairwise t-tests where significant effects were present. We further report the eta-squared η^2 as an estimate of the effect size and use Cohen's suggestions to classify the effect size as small, medium or large [12]. For the Likert questionnaires, we performed an Aligned Rank Transformation as suggested by Wobbrock et al. [79]. We tested the data for normality with Shapiro Wilk's test and found no significant deviations. Where Mauchly's test indicated a violation of the assumption of sphericity, we used the Greenhouse Geisser method and report the ϵ.

P3.5.1 *2D Error*

The analysis showed a significant ($F_{4,32.51}$ = 98.87, ϵ=.43, p < .001) main effect of the *assistance type* on the 2D error with a medium (η^2=.09) effect size. We found that pneumatic (M = 0.45 cm, SD = 0.08 cm), the combined method (M = 0.46 cm, SD = 0.07 cm), and vibration feedback (M = 0.46 cm, SD = 0.07 cm) resulted in the lowest 2D error rates, followed by snapping (M = 0.49 cm, SD = 0.07 cm) and no assistance (M = 0.51 cm, SD = 0.06 cm). Post-hoc tests confirmed significant differences between no assistance and all other conditions (p < .001), vibration and snapping (p < .001), pneumatic and snapping (p < .001) and combined and snapping (p < .001).

Second, the analysis showed a significant ($F_{1,19}$ = 841.8, p <.001) main effect for the *surface type* on the 2D error with a large (η^2=.81) effect size between flat (M = 0.41 cm, SD = 0.04 cm) and curved (M = 0.54 cm, SD = 0.02 cm) surfaces.

Finally, we found statistically significant interaction effects for *assistance type * surface type* ($F_{4,24.05}$ = 5.95, ϵ=.32, p <.05) with a small (η^2=.01) effect size. We found that pneumatic, combined, and vibration methods performed significantly better than snapping (p < .01) and no assistance (p < .001) on both flat and curved surfaces using a pairwise t-test. However, we did not observe statistically significant differences among pneumatic, combined, and vibration methods (p > .05). Figure P3.6 depicts the 2D error for all conditions.

Conditions using VRSketchPen showed an improvement in terms of 2D error, hence, we accept **H1**.

P3.5.2 *Depth Error*

We found a statistically significant ($F_{3,40.62}$ = 108.68, ϵ=.71, p <.001) main effect of the *assistance type* on the depth error of participants with a large (η^2=.31) effect size. We found that the pneumatic feedback (M = 0.68 cm, SD = 0.05 cm) and a combined method (M = 0.71 cm, SD = 0.09 cm) resulted in the lowest depth errors, followed by vibration (M = 0.70 cm, SD = 0.10 cm) and no assistance (M = 0.83 cm, SD = 0.10 cm). Post-hoc tests confirmed significant differences be-

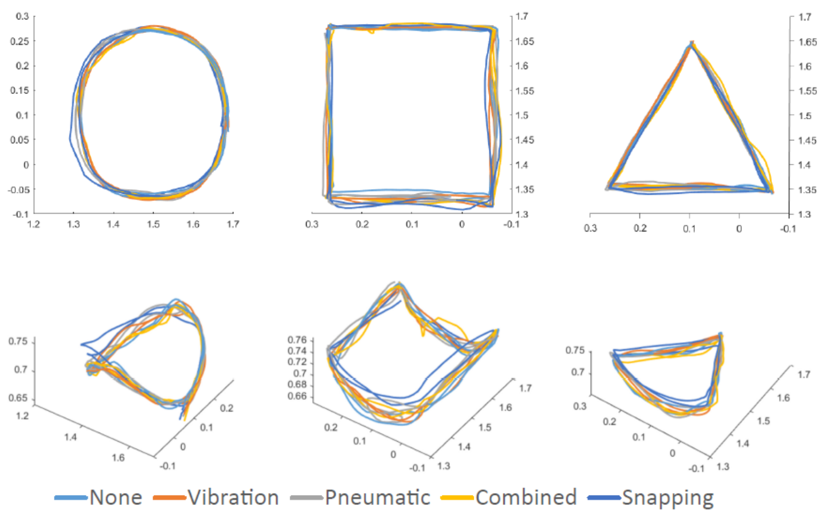


Figure P3.7: A circle, rectangle, and triangle sketched by one participant using five different assistance types.

tween combined and none (p < .001), vibration and none (p < .001), pneumatic and none (p < .001) and combined and pneumatic (p < 0.01).

Further, we found a significant ($F_{1,19}$ = 27.66, p <.001) main effect of the *surface type* on the depth error of participants with a large (η^2=.23) effect size between flat (M = 0.78 cm, SD = 0.11 cm) and curved (M = 0.68 cm, SD = 0.07 cm) surfaces.

We could not find significant ($F_{3,30.6}$ = 1.37, p >.05) interaction effects between the two factors. Figure P3.6 depicts the depth error for all conditions.

Compared to no assistance, VRSketchPen reduced depth errors, hence, we accept **H2**.

P3.5.3 *3D Error*

We found a significant ($F_{4,35.77}$ = 955.45, ϵ=.47, p <.001) main effect of the *assistance type* on the 3D error of participants with a large (η^2=.88) effect size. We found the lowest 3D error with snapping (M = 0.49 cm, SD = 0.07 cm), followed by pneumatic (M = 0.90 cm, SD = 0.05 cm), vibration (M = 0.92 cm, SD = 0.09 cm), combined (M = 0.93 cm, SD = 0.06 cm) and none (M = 1.05 cm, SD = 0.08 cm). Post-hoc tests confirmed significant differences between no assistance and all other conditions ($p < .001$), as well as between snapping and the haptic conditions ($p < .001$).

We could not find a significant main effect for the *surface type* ($F_{1,19}$ = 4.10, $p > 0.05$) between flat (M = 0.84 cm, SD = 0.23 cm) and curved (M = 0.87 cm, SD = 0.17 cm) surfaces.

Further, we found significant ($F_{4,30.65}$ = 10.05, ϵ=.40, $p < .001$) interaction effects between *assistance type* and *surface type* with a small (η^2=.02) effect size. We found that snapping had a significantly lower 3D error in comparison to pneumatic, combined, and vibration methods, as well as no assistance for both flat and curved surfaces ($p < .001$). We did not observe any significant differences between pneumatic, combined, and vibration methods for both types of surfaces ($p > .05$), but all three of them performed significantly ($p<.001$) better than no assistance. Figure P3.6 depicts the 3D error for all conditions.

Conditions using VRSketchPen did not result in an improvement compared to snapping, hence, we cannot support **H3**.

P3.5.4 *Drawing Time*

The analysis indicated a significant ($F_{4,21.23}$ = 104.62, ϵ=.28, $p <.001$) main effect of the *assistance type* on the drawing time of participants with a large (η^2=.31) effect size. We found that users were faster with snapping (M = 12.27 s, SD = 1.90 s), than none (M = 14.96 s, SD = 2.60 s), pneumatic (M = 17.77 s, SD = 3.21 s), vibration (M = 18.28 s, SD = 4.69 s) and combined (M = 18.82 s, SD = 5.05 s). Post-hoc tests confirmed significant differences between snapping and all other conditions ($p < .001$) and between none and all haptic conditions ($p < .001$).

The analysis could not confirm a significant ($F_{1,19}$ = 2.50, $p > .05$) main effect for the *surface type* between flat (M = 16.61 s, SD = 4.52 s) and curved (M = 16.23 s, SD = 4.31 s) surfaces.

Finally, we found significant interaction effects for assistance type * surface type ($F_{4,22.52}$ = 18.14, ϵ=.30, $p <.001$) with a medium (η^2=.08) effect size. We found that snapping had a significantly lower drawing time for both types of surfaces in comparison to other methods ($p < .001$). Additionally, we found that a combined method had sig-

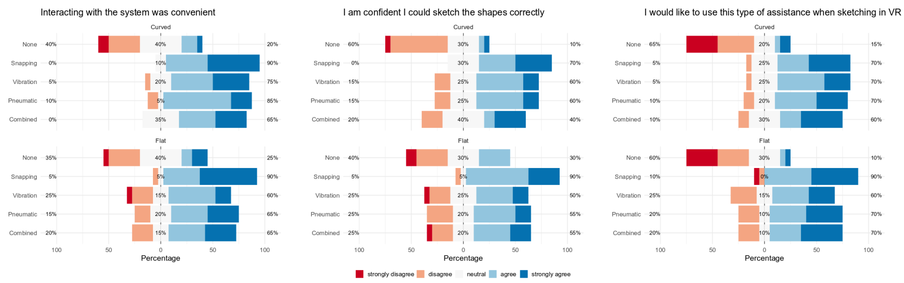


Figure P3.8: Participant answers to our questionnaire.

nificantly lower drawing time compared to vibration ($p < .001$) and pneumatic ($p < .01$), but on the curved surface, the combined method was significantly slower than vibration ($p < .001$) and pneumatic ($p < .001$) methods. Figure P3.6 depicts the drawing time for all conditions.

Compared to conditions using no haptic feedback, VRSketchPen results in an increased drawing time, hence, we accept **H4**.

P3.5.5 *Convenience*

Assistance type had a significant effect on the perceived convenience ($F_{4,76} = 14.94$, $p < .001$). Post-hoc tests showed that compared to no assistance, combined ($p < .001$), pressure ($p < .001$), vibration ($p < .001$) and snapping ($p < .001$) were rated more positively. In addition, snapping was rated more convenient than combined ($p < .05$), pressure ($p < .05$) and vibration ($p < .01$). *Surface type* ($F_{1,19} = 0.15$, $p > .05$) and the interaction between factors ($F_{4,76} = 1.23$, $p > .05$) was not significant.

P3.5.6 *Confidence*

Participants' confidence ratings were significantly affected by assistance type ($F_{4,76} = 15.70$, $p < .001$). Snapping was rated most positively compared with vibration ($p < .01$), pressure ($p < .05$), no assistance ($p < .001$), and combined ($p < .01$). Pressure ($p < .001$), vibration ($p < .001$) and combined ($p < .001$) resulted in significantly higher confidence ratings than no assistance. No significant effects were found for surface type ($F_{1,19} = 3.20$, $p = .09$) nor for the interaction between the variables ($F_{4,76} = 0.86$, $p > .05$).

P3.5.7 *Engagement*

We asked our participants if they would like to use this combination of surface and assistance type when sketching in VR. The type of assistance had a significant effect on participants' ratings ($F_{4,76}$ = 14.99, p < .001). The condition with no assistance was rated by our participants as least enjoyable in contrast to pressure (p < .001), vibration (p < .001), their combination (p < .001) and snapping (p < .001).

Convenience, confidence and engagement are improved using VRSketchPen, hence, we accept **H5**.

P3.6 DISCUSSION

In this section, we discuss quantitative and qualitative results of our experiment. In general, we found that the addition of haptic feedback in VRSketchPen helped participants sketch on virtual surfaces without the need to constrain user actions. Pneumatic feedback resulted in lowest 2D and depth errors. Snapping resulted in fastest execution time and performed best for 3D error. While different types of surfaces showed comparable results for 3D error and drawing time, differences were observed for 2D and depth errors.

P3.6.1 *VRSketchPen Accuracy*

In the following, measures related to accuracy are discussed.

P3.6.1.1 *2D Sketching Accuracy*

VRSketchPen's haptic assistance types (pneumatic, vibrotactile and a combination) improve 2D sketching accuracy by helping users control their arm movement in two dimensions. These results indicate that haptic assistance types in VRSketchPen are valuable additions to devices for sketching on virtual surfaces.

We further noted, that the snapping technique showed a lower 2D error than no assistance, indicating that when removing depth deviation in visual output, users can focus more on controlling their arm movement.

P3.6.1.2 *Depth Sketching Accuracy*

When using VRSketchPen, depth errors made by users were reduced in comparison to no assistance when drawing on flat and curved surfaces. We also identified that users made fewer errors with pneumatic assistance than with VRSketchPen's combination of pneumatic and vibration assistance (Figure P3.6). This indicates that for depth perception emulating contact force provides better cues than combining pneumatic with vibrotactile textures. A possible reason could be user specific preferences, e.g., P4 expressed *"I liked the balloon; the vibrations were too strong for me."*. Given that depth error with the snapping technique is always zero, we compare VRSketchPen to no assistance. These results complement previous work [3] and show that haptic feedback reduces depth perception errors when sketching on virtual surfaces.

P3.6.1.3 *3D sketching accuracy*

Our results show that VRSketchPen enriches the interaction with a virtual surface and provides motion assistance in 3D space that reduces users' 3D errors compared with no assistance. However, given no depth errors for the snapping technique, 3D error with VRSketchPen was still higher than snapping, however snapping sacrifices expressiveness by contstraining user actions, which is not the case for VRSketchPen. For example, compared with no assistance, VRSketchPen reduces depth-perception errors by 18%, and motor control problems by 11.8%. This makes our proposed interaction technique useful for design applications, where expressiveness and unconstrained user strokes are valuable [1].

P3.6.2 *Drawing Time*

When considering time participants took, we found that users were slower in their sketches when using VRSketchPen compared to snapping and no assistance. The combination of haptic modalities was faster on flat surfaces than curved surface. However, when using curved surfaces we observed that participants were faster using a single haptic modality than their combination. We suspect that differences in drawing time between assistance and surface types will become minimal with training [31].

P3.6.3 *Subjective Preferences*

Compared to no-assistance, users' perceived ratings of convenience, comfort and confidence were significantly higher when using VRSketchPen. Although snapping was subjectively perceived as more convenient and participants felt more confident using it, they, nevertheless, expressed a high willingness to use VRSketchPen for sketching in VR. We assume that this can be explained by the two following reasons: (1) preference of the snapping technique due to visual output removing depth inaccuracies and (2) novelty effect when using VRSketchPen.

P3.6.4 *Sketching on Flat and Curved Surfaces*

Sketching on flat surfaces reduces 2D error in comparison to curved surfaces. On the other hand, sketching on curved surfaces reduces depth error compared to flat surfaces. For 2D error, we assume that this difference is caused by the nature of the surface and participants' prior experience drawing in two dimension, e.g., using pen and paper. For depth, we suspect that participants concentrated more on the changing depth of the surface throughout the sketch, which resulted in lower overall depth errors.

With respect to the 3D error and drawing time, we did not observe differences between the two types of the surfaces. In comparison to previous work [3] that identified significant difference in sketching time between curved and flat surfaces. In our experiment we focused on the sketching accuracy, and so users were required to take their time while sketching which lead to slower drawing time, but therefore more precise.

P3.7 LIMITATIONS AND FUTURE WORK

The main limitation of our user study is that participants only drew geometrical 2D shapes, even if participants drew on curved surfaces. In the future, we will evaluate VRSketchPen in complex drawing scenarios, where our participants move and draw complex 3D shapes. Yet, we expect that our results extend to complex shapes, as our results show that haptic assistance help the user's motor control and prevents depth perception errors. We only evaluated one vibrotactile texture in our study. Future works should extend this by investigating and comparing various textures for sketching, since prior work has shown that vibrotactile parameters can change the perception of virtual surfaces [68]. Another limitation with VRSketchPen is that the hardware is not self-contained, and right now restricts the movement of the user to two meters. However, future versions of VRSketchPen can use tiny position trackers based on existing VR systems [58] and a small, mobile air compressor as in Squeezeback [57], to provide mobility. Finally, beautification of pen strokes or widgets inside the VE can further assist the user in drawing more accurately.

P3.8 CONCLUSION

In this paper, we presented VRSketchPen, a pen that combines two types of haptic feedback, extending previous work [41, 52], to produce a realistic feeling of experiencing a virtual surface. VRSketchPen enables a new interaction technique called *unconstrained haptic assistance* that helps users reduce motor and depth errors when drawing in 3D without constraining user actions. Our work extends the work by Barrera et al. [7] to include haptic feedback. VRSketchPen has better accuracy than no assistance, and in some aspects is comparable to snapping which is considered the state of the art for improving user accuracy. This makes VRSketchPen a viable option for sketching in VR. Especially when working on a new concept where an interface that does not constrain the user is needed. For example, future applications of VRSketchPen might include the use of haptic brushes in 3D sketching systems that not only change the visual aspect of a stroke, but also how they feel when the user draws with them. Involving other senses when drawing opens creative new possibilities for current 3D sketching systems.

REFERENCES

[1] Jorge Alcaide-Marzal, José Antonio Diego-Más, Sabina Asensio-Cuesta, and Betina Piqueras-Fiszman. "An exploratory study on the use of digital sculpting in conceptual product design." In: *Design Studies* 34.2 (2013), pp. 264–284.

[2] Rahul Arora, Rubaiat Habib Kazi, Tovi Grossman, George Fitzmaurice, and Karan Singh. "SymbiosisSketch: Combining 2D & 3D Sketching for Designing Detailed 3D Objects in Situ." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: ACM, 2018, 185:1–185:15. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173759.

[3] Rahul Arora, Rubaiat Habib Kazi, Fraser Anderson, Tovi Grossman, Karan Singh, and George Fitzmaurice. "Experimental Evaluation of Sketching on Surfaces in VR." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: ACM, 2017, pp. 5643–5654. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025474.

[4] Seok-Hyung Bae, Ravin Balakrishnan, and Karan Singh. "ILoveSketch: As-natural-as-possible Sketching System for Creating 3D Curve Models." In: *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology*. UIST '08. Monterey, CA, USA: ACM, 2008, pp. 151–160. ISBN: 978-1-59593-975-3. DOI: 10.1145/1449715.1449740.

[5] Mayra Donaji Barrera Machuca, Paul Asente, Wolfgang Stuerzlinger, Jingwan Lu, and Byungmoon Kim. "Multiplanes: Assisted Freehand VR Sketching." In: *Proceedings of the Symposium on Spatial User Interaction*. SUI '18. Berlin, Germany: ACM, 2018, pp. 36–47. ISBN: 978-1-4503-5708-1. DOI: 10.1145/3267782.3267786.

[6] Mayra Donaji Barrera Machuca and Wolfgang Stuerzlinger. "The Effect of Stereo Display Deficiencies on Virtual Hand Pointing." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '19)*. New York, NY: ACM Press, 2019, p. 14. ISBN: 9781450359702. DOI: 10.1145/3290605.3300437.

[7] Mayra Donaji Barrera Machuca, Wolfgang Stuerzlinger, and Paul Asente. "Smart3DGuides: Making Unconstrained Immersive 3D Drawing More Accurate." In: (2019), pp. 1–13. DOI: 10.1145/3359996.3364254.

[8] Mayra Donaji Barrera Machuca, Wolfgang Stuerzlinger, and Paul Asente. "The Effect of Spatial Ability on Immersive 3D Drawing." In: *Proceedings of the ACM Conference on Creativity & Cognition (C&C '19)*. 2019. DOI: 10.1145/3325480.3325489.

[9] Anil Ufuk Batmaz, Mayra Donaji Barrera Machuca, Duc Minh Pham, and Wolfgang Stuerzlinger. "Do Head-MountedDisplay Stereo Deficiencies Affect 3D Pointing Tasks in AR and VR?" In: *Proceedings of the IEEE Conference on Virtual Reality and 3D User Interfaces (VR'19)*. 2019.

[10] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. "NormalTouch and TextureTouch: High-Fidelity 3D Haptic Shape Rendering on Handheld Virtual Reality Controllers." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 717–728. ISBN: 9781450341899. DOI: 10.1145/2984511.2984526.

[11] Youngjun Cho, Andrea Bianchi, Nicolai Marquardt, and Nadia Bianchi-Berthouze. "RealPen: Providing Realism in Handwriting Tasks on Touch Surfaces Using Auditory-Tactile Feedback." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 195–205. ISBN: 9781450341899. DOI: 10.1145/2984511.2984550.

[12] Jacob Cohen. *Statistical Power Analysis for the Behavioral Sciences*. Routledge, July 1988. ISBN: 9780203771587. DOI: 10.4324/9780203771587.

[13] Douglas Cooper. "Imagination's hand: The role of gesture in design drawing." In: *Design Studies* 54 (2018), pp. 120–139. ISSN: 0142694X. DOI: 10.1016/j.destud.2017.11.001.

[14] H. Culbertson, J. Unwin, B. E. Goodman, and K. J. Kuchenbecker. "Generating haptic texture models from unconstrained tool-surface interactions." In: *2013 World Haptics Conference (WHC)*. Apr. 2013, pp. 295–300. DOI: 10.1109/WHC.2013.6548424.

[15] Bruno R. De Araùjo, Géry Casiez, and Joaquim A. Jorge. "Mockup Builder: Direct 3D Modeling on and Above the Surface in a Continuous Interaction Space." In: *Proceedings of Graphics Interface 2012*. GI '12. Toronto, Ontario, Canada: Canadian Information Processing Society, 2012, pp. 173–180. ISBN: 978-1-4503-1420-6.

[16] Tomás Dorta, Gokce Kinayoglu, and Michael Hoffmann. "Hyve-3D and the 3D Cursor : Architectural co-design with freedom in Virtual Reality." In: (2016). DOI: 10.1177/1478077116638921.

[17] Tobias Drey, Jan Gugenheimer, Julian Karlbauer, Maximilian Milo, and Enrico Rukzio. "VRSketchIn: Exploring the Design Space of Pen and Tablet Interaction for 3D Sketching in Virtual Reality." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–14. ISBN: 9781450367080. DOI: 10.1145/3313831.3376628.

[18] John J. Dudley, Hendrik Schuff, and Per Ola Kristensson. "Bare-Handed 3D Drawing in Augmented Reality." In: *Proceedings of the 2018 Designing Interactive Systems Conference*. DIS '18. Hong Kong, China: ACM, 2018, pp. 241–252. ISBN: 978-1-4503-5198-0. DOI: 10.1145/3196709.3196737.

[19] C.J. Earnshaw. *Sho Japanese Calligraphy: An In-Depth Introduction to the Art of Writing Characters*. Tuttle Publishing, 1989. ISBN: 9781462907823.

[20] Facebook. *Quill*. 2018.

[21] Tiago H. Falk, Cynthia Tam, Heidi Schwellnus, and Tom Chau. "Grip force variability and its effects on children's handwriting legibility, form, and strokes." In: *Journal of Biomechanical Engineering* 132.11 (2010). ISSN: 01480731. DOI: 10.1115/1.4002611.

[22] Michele Fiorentino, Giuseppe Monno, Pietro A. Renzulli, and Antonio E. Uva. "3D Sketch Stroke Segmentation and Fitting in Virtual Reality." In: *International Conference on the Computer Graphics and Vision*. 2003, pp. 188–191. DOI: 10.1.1.99.9190.

[23] Michele Fiorentino, Antonio E. Uva, and Giuseppe Monno. "The SenStylus: A novel rumble-feedback pen device for CAD application in virtual reality." In: *13th International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision 2005, WSCG'2005 - In Co-operation with EUROGRAPHICS, Full Papers* (2005), pp. 131–138.

[24] Tinsley A. Galyean and John F. Hughes. "Sculpting: An interactive volumetric modeling technique." In: *Proceedings of the 18th Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH 1991* 25 (1991), pp. 267–274. DOI: 10.1145/122718.122747.

[25] Arthur Gatouillat, Antoine Dumortier, Subashan Perera, Youakim Badr, Claudine Gehin, and Ervin Sejdić. "Analysis of the pen pressure and grip force signal during basic drawing tasks: The timing and speed changes impact drawing characteristics." In: *Computers in Biology and Medicine* 87.May (2017), pp. 124–131. ISSN: 18790534. DOI: 10.1016/j.compbiomed.2017.05.020.

[26] Google. *Tilt Brush*. 2016.

[27] Ravindra S. Goonetilleke, Errol R. Hoffmann, and Ameersing Luximon. "Effects of pen design on drawing and writing performance." In: *Applied Ergonomics* 40.2 (2009), pp. 292–301. ISSN: 00036870. DOI: 10.1016/j.apergo.2008.04.015.

[28] Tovi Grossman, Ravin Balakrishnan, Gordon Kurtenbach, George Fitzmaurice, Azam Khan, and Bill Buxton. "Creating principal 3D curves with digital tape drawing." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '02)*. New York, New York, USA: ACM Press, 2002, pp. 121–128. ISBN: 1581134533. DOI: 10.1145/503376.503398.

[29] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. "Dexmo: An Inexpensive and Lightweight Mechanical Exoskeleton for Motion Capture and Force Feedback in VR." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: ACM, 2016, pp. 1991–1995. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858487.

[30] Sebastian Günther, Mohit Makhija, Florian Müller, Dominik Schön, Max Mühlhäuser, and Markus Funk. "PneumAct: Pneumatic Kinesthetic Actuation of Body Joints in Virtual Reality Environments." In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. DIS '19. San Diego, CA, USA: ACM, 2019, pp. 227–240. ISBN: 978-1-4503-5850-7. DOI: 10.1145/3322276.3322302.

[31] Aakar Gupta, Antony Irudayaraj, Vimal Chandran, Goutham Palaniappan, Khai N. Truong, and Ravin Balakrishnan. "Haptic Learning of Semaphoric Finger Gestures." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 219–226. ISBN: 9781450341899. DOI: 10.1145/2984511.2984558.

[32] Juan David Hincapié-Ramos, Xiang Guo, Paymahn Moghadasian, and Pourang Irani. "Consumed Endurance: A Metric to Quantify Arm Fatigue of Mid-Air Interactions." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: Association for Computing Machinery, 2014, pp. 1063–1072. ISBN: 9781450324731. DOI: 10.1145/2556288.2557130.

[33] HTC. *VIVE*. 2016.

[34] Ke Huo, Vinayak, and Karthik Ramani. "Window-Shaping." In: *Proceedings of the International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17)*. 2017, pp. 37–45. ISBN: 9781450346764. DOI: 10.1145/3024969.3024995.

[35] Johann Habakuk Israel, E. Wiese, M. Mateescu, C. Zöllner, and R. Stark. "Investigating three-dimensional sketching for early conceptual design—Results from expert discussions and user studies." In: *Computers & Graphics* 33.4 (Aug. 2009), pp. 462–473. ISSN: 00978493. DOI: 10.1016/j.cag.2009.05.005.

[36] B. Jackson and D. F. Keefe. "Lift-Off: Using Reference Imagery and Freehand Sketching to Create 3D Models in VR." In: *IEEE Transactions on Visualization and Computer Graphics* 22.4 (Apr. 2016), pp. 1442–1451. ISSN: 1077-2626. DOI: 10.1109/TVCG.2016.2518099.

[37] Bret Jackson and Daniel F. Keefe. "Sketching Over Props: Understanding and Interpreting 3D Sketch Input Relative to Rapid Prototype Props." In: 2004.

[38] Chris Jansen, Antoon Wennemers, Wouter Vos, and Eric Groen. "FlyTact: A Tactile Display Improves a Helicopter Pilot's Landing Performance in Degraded Visual Environments." In: *Haptics: Perception, Devices and Scenarios*. Ed. by Manuel Ferre. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 867–875. ISBN: 978-3-540-69057-3.

[39] Sho Kamuro, Kouta Minamizawa, and Susumu Tachi. "3D Haptic modeling system using ungrounded pen-shaped kinesthetic display." In: *Proceedings - IEEE Virtual Reality* Figure 1 (2011), pp. 217–218. DOI: 10.1109/VR.2011.5759476.

[40] D. Keefe, R. Zeleznik, and D. Laidlaw. "Drawing on Air: Input Techniques for Controlled 3D Line Illustration." In: *IEEE Transactions on Visualization and Computer Graphics* 13.5 (Sept. 2007), pp. 1067–1081. ISSN: 1077-2626. DOI: 10.1109/TVCG.2007.1060.

[41] D. F. Keefe, R. C. Zeleznik, and D. H. Laidlaw. "Tech-note: Dynamic Dragging for Input of 3D Trajectories." In: *2008 IEEE Symposium on 3D User Interfaces*. 2008, pp. 51–54.

[42] Yongkwan Kim, Sang-Gyun An, Joon Hyub Lee, and Seok-Hyung Bae. "Agile 3D Sketching with Air Scaffolding." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '18)*. 2018, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3173812.

[43] Yongkwan Kim and Seok-Hyung Bae. "SketchingWithHands: 3D Sketching Handheld Products with First-Person Hand Posture." In: *Proceedings of the ACM Symposium on User Interface Software and Technology (UIST '16)*. New York, New York, USA: ACM Press, 2016, pp. 797–808. ISBN: 9781450341899. DOI: 10.1145/2984511.2984567.

[44] Roberta L. Klatzky, Susan J. Lederman, Cheryl Hamilton, Molly Grindley, and Robert H. Swendsen. "Feeling textures through a probe: Effects of probe and surface geometry and exploratory factors." In: *Perception & Psychophysics* 65.4 (May 2003), pp. 613–631. ISSN: 1532-5962. DOI: 10.3758/BF03194587.

[45] Kin Chung Kwan and Hongbo Fu. "Mobi3DSketch: 3D Sketching in Mobile AR." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: ACM, 2019, 176:1–176:11. ISBN: 978-1-4503-5970-2. DOI: 10.1145/3290605.3300406.

[46] Ki-Uk Kyung and Jun-Young Lee. "WUbi-Pen: Windows Graphical User Interface Interacting with Haptic Feedback Stylus." In: *ACM SIGGRAPH 2008 New Tech Demos*. SIGGRAPH '08. Los Angeles, California: Association for Computing Machinery, 2008. ISBN: 9781450378475. DOI: 10.1145/1401615.1401657.

[47] Johnny C. Lee, Paul H. Dietz, Darren Leigh, William S. Yerazunis, and Scott E. Hudson. "Haptic Pen: A Tactile Feedback Stylus for Touch Screens." In: *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology*. UIST '04. Santa Fe, NM, USA: Association for Computing Machinery, 2004, pp. 291–294. ISBN: 1581139578. DOI: 10.1145/1029632.1029682.

[48] Sangwon Lee and Jin Yan. "The impact of 3D CAD interfaces on user ideation: A comparative analysis using SketchUp and Silhouette Modeler." In: *Design Studies* 44 (2016), pp. 52–73. ISSN: 0142694X. DOI: 10.1016/j.destud.2016.02.001.

[49] Chor-kheng Lim. "An insight into the freedom of using a pen: Pen-based system and pen-and-paper." In: *Proceedings of the Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA '03)*. 2003, pp. 385–393.

[50] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. "Impacto: Simulating Physical Impact by Combining Tactile Stimulation with Electrical Muscle Stimulation." In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST '15. Charlotte, NC, USA: ACM, 2015, pp. 11–19. ISBN: 978-1-4503-3779-3. DOI: 10.1145/2807442.2807443.

[51] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. "Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: ACM, 2017, pp. 1471–1482. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025600.

[52] Ronak R. Mohanty, Ricardo M. Castillo, Eric D. Ragan, and Vinayak R. Krishnamurthy. "Investigating Force-Feedback in Mid-Air Sketching of Multi-Planar Three-Dimensional Curve-Soups." In: *Journal of Computing and Information Science in Engineering* 20.1 (Oct. 2019). 011010. ISSN: 1530-9827. DOI: 10.1115/1.4045142. eprint: https://asmedigitalcollection.asme.org/computingengineering/article-pdf/20/1/011010/6437380/jcise_20_1_011010.pdf.

[53] Mai Otsuki, Kenji Sugihara, Azusa Toda, Fumihisa Shibata, and Asako Kimura. "A brush device with visual and haptic feedback for virtual painting of 3D virtual objects." In: *Virtual Reality* (June 2017), pp. 1–15. DOI: 10.1007/s10055-017-0317-0.

[54] Jörg Petruschat. "Some Remarks on Drawing." In: *Form+zweck. How to Handle Hands?* 18 (2001), pp. 70–77.

[55] Duc-Minh Pham and Wolfgang Stuerzlinger. "Is the Pen Mightier than the Controller? A Comparison of Input Devices for Selection in Virtual and Augmented Reality." In: (2019), pp. 1–11. DOI: 10.1145/3359996.3364264.

[56] Michal Piovarči, Danny M. Kaufman, David I. W. Levin, and Piotr Didyk. "Fabrication-in-the-Loop Co-Optimization of Surfaces and Styli for Drawing Haptics." In: *ACM Trans. Graph.* 39.4 (July 2020). ISSN: 0730-0301. DOI: 10.1145/3386569.3392467.

[57] Henning Pohl, Peter Brandes, Hung Ngo Quang, and Michael Rohs. "Squeezeback: Pneumatic Compression for Notifications." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 5318–5330. ISBN: 9781450346559. DOI: 10.1145/3025453.3025526.

[58] Dario R. Quiñones, Gonçalo Lopes, Danbee Kim, Cédric Honnet, David Moratal, and Adam Kampff. "HIVE Tracker: A Tiny, Low-Cost, and Scalable Device for Sub-Millimetric 3D Positioning." In: *Proceedings of the 9th Augmented Human International Conference*. AH '18. Seoul, Republic of Korea: Association for Computing Machinery, 2018. ISBN: 9781450354158. DOI: 10.1145/3174910.3174935.

[59] Patrick Reipschläger and Raimund Dachselt. "Designar: Immersive 3D-modeling combining augmented reality with interactive displays." In: *ISS 2019 - Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces* (2019), pp. 29–41. DOI: 10.1145/3343055.3359718.

[60] Rebekka S. Renner, Boris M. Velichkovsky, and Jens R. Helmert. "The perception of egocentric distances in virtual environments - A review." In: *ACM Computing Surveys* 46.2 (Nov. 2013), pp. 1–40. ISSN: 03600300. DOI: 10.1145/2543581.2543590. arXiv: arXiv:1502.07526v1.

[61] J. M. Romano and K. J. Kuchenbecker. "Creating Realistic Virtual Textures from Contact Acceleration Data." In: *IEEE Transactions on Haptics* 5.2 (Apr. 2012), pp. 109–119. DOI: 10.1109/TOH.2011.38.

[62] Joseph M. Romano and Katherine J. Kuchenbecker. "The AirWand: Design and Characterization of a Large-Workspace Haptic Device." In: *Proceedings of the 2009 IEEE International Conference on Robotics and Automation*. ICRA'09. Kobe, Japan: IEEE Press, 2009, pp. 1010–1015. ISBN: 9781424427888.

[63] Ryan Schmidt, Azam Khan, Gord Kurtenbach, and Karan Singh. "On expert performance in 3D curve-drawing tasks." In: *Proceedings of the EUROGRAPHICS Symposium on Sketch-Based Interfaces and Modeling (SBIM '09)*. New York, New York, USA: ACM Press, 2009, pp. 133–140. ISBN: 9781605586021. DOI: 10.1145/1572741.1572765.

[64] Colleen M Schneck and Anne Henderson. "Descriptive Analysis of the Developmental Position for Pencil and." In: *American Journal of Occupational Therapy* 44.c (1990), pp. 893–900.

[65] Mark A Schroering, Cindy M Grimm, and Robert Pless. "A New Input Device for 3D Sketching." In: *Vision Interface* (2003), pp. 311–318.

[66] Scott Snibbe, Sean Anderson, Bill Verplank, Page Mill Road, Building C, and Palo Alto. "Springs and Constraints for 3D Drawing." In: *Artificial Intelligence* (1998).

[67] Paul Strohmeier, Sebastian Boring, and Kasper Hornbæk. "From Pulse Trains to "Coloring with Vibrations": Motion Mappings for Mid-Air Haptic Textures." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: ACM, 2018, 65:1–65:13. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173639.

[68] Paul Strohmeier and Kasper Hornbæk. "Generating Haptic Textures with a Vibrotactile Actuator." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: ACM, 2017, pp. 4994–5005. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025812.

[69] 3D Systems. *Phantom*. 2016.

[70] 3D Systems. *Touch*. 2017.

[71] Shan-Yuan Teng, Tzu-Sheng Kuo, Chi Wang, Chi-huan Chiang, Da-Yuan Huang, Liwei Chan, and Bing-Yu Chen. "PuPoP: Pop-up Prop on Palm for Virtual Reality." In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. UIST '18. Berlin, Germany: ACM, 2018, pp. 5–17. ISBN: 978-1-4503-5948-1. DOI: 10.1145/3242587.3242628.

[72] David Veisz, Essam Z. Namouz, Shraddha Joshi, and Joshua D. Summers. "Computer-aided design versus sketching: An exploratory case study." In: *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM* 26.3 (2012), pp. 317–335. ISSN: 08900604. DOI: 10.1017/S0890060412000170.

[73] Raquel Viciana-Abad, Arcadio Reyes Lecuona, and Matthieu Poyade. "The influence of passive haptic feedback and difference interaction metaphors on presence and task performance." In: *Presence: Teleoperators and Virtual Environments* 19.3 (2010), pp. 197–212. ISSN: 10547460. DOI: 10.1162/pres.19.3.197.

[74] Philipp Wacker, Adrian Wagner, Simon Voelker, and Jan Borchers. "Physical Guides: An Analysis of 3D Sketching Performance on Physical Objects in Augmented Reality." In: *Proceedings of the Symposium on Spatial User Interaction*. SUI '18. Berlin, Germany: ACM, 2018, pp. 25–35. ISBN: 978-1-4503-5708-1. DOI: 10.1145/3267782.3267788.

[75] Gerold Wesche and Hans-Peter Seidel. "FreeDrawer: A Free-form Sketching System on the Responsive Workbench." In: *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*. VRST '01. Baniff, Alberta, Canada: ACM, 2001, pp. 167–174. ISBN: 1-58113-427-4. DOI: 10.1145/505008.505041.

[76] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. "Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3173660.

[77] Eva Wiese, Johann Habakuk Israel, A. Meyer, and S. Bongartz. "Investigating the learnability of immersive free-hand sketching." In: *Proceedings of the EUROGRAPHICS Symposium on Sketch-Based Interfaces and Modeling (SBIM '10)*. October 2017. 2010, pp. 135–142. ISBN: 978-3-905674-25-5.

[78] Scott Winter and Mourad Bouzit. "Use of Magnetorheological Fluid in a Force Feedback Glove." In: *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society* 15 (Apr. 2007), pp. 2–8. DOI: 10.1109/TNSRE.2007.891401.

[79] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. "The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: ACM, 2011, pp. 143–146. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1978963.

[80] Min Xin, Ehud Sharlin, and Mario Costa Sousa. "Napkin sketch: Handheld Mixed Reality 3D Sketching." In: *Proceedings of the ACM Symposium on Virtual Reality Software and Technology (VRST '08)*. New York, New York, USA: ACM Press, 2008, p. 223. ISBN: 9781595939517. DOI: 10.1145/1450579.1450627.

[81] Shumin Zhai, Paul Milgram, and William Buxton. "Influence of muscle groups on performance of multiple degree-of-freedom input." In: *Conference on Human Factors in Computing Systems - Proceedings* (1996), pp. 308–315.

P4

VIBROMAP: UNDERSTANDING THE SPACING OF VIBROTACTILE ACTUATORS ACROSS THE BODY

ABSTRACT

In spite of the great potential of on-body vibrotactile displays for a variety of applications, research lacks an understanding of the spacing between vibrotactile actuators. Through two experiments, we systematically investigate vibrotactile perception on the wrist, forearm, upper arm, back, torso, thigh, and leg, each in transverse and longitudinal body orientation. In the first experiment, we address the maximum distance between vibration motors that still preserves the ability to generate phantom sensations. In the second experiment, we investigate the perceptual accuracy of localizing vibrations in order to establish the minimum distance between vibration motors. Based on the results, we derive VibroMap, a spatial map of the functional range of inter-motor distances across the body. VibroMap supports hardware and interaction designers with design guidelines for constructing body-worn vibrotactile displays.

P4.1 INTRODUCTION

Vibrotactile displays on the body are increasingly used in situations where interaction with visual or audio displays is not possible or recommended, e.g., while driving, holding conversations, riding a bike, and countless other forms of physical activities [5, 7, 44, 59]. Prior research in HCI studied haptic feedback for many applications, ranging from navigation [16], motion coaching [50, 55], passive motor skill learning [53], driving [21, 28], and human-robot interaction [1].

Depending on the use-case, haptic feedback is proposed on many different body locations, e.g., upper arm [3, 4, 58], forearm [37, 38, 45, 47, 51, 70], wrist [7, 14, 30, 31, 35], stomach [28], thigh [56], legs [9], and feet [61].

Although a multitude of systems and application scenarios using vibrotactile actuators are proposed, the HCI community still lacks a systematic understanding of the required spacing of vibrotactile actuators. This is crucial to the effectiveness of vibrotactile feedback and can have a huge effect on the haptic perception, as the amount of mechanoreceptors and the thickness of the human skin varies across the body [26].

This paper aims to systematically study the accuracy of vibrotactile perception and the illusion of phantom sensations on different body parts (see Figure P6.1). Phantom sensations are a tactile illusion where the perceived location of a vibration is controlled by two or more neighbouring tactors [2]. Phantom sensations have been commonly used in HCI to generate high resolution tactile sensations using a low resolution tactile display. From these findings, we derive *VibroMap*, a first attempt to map vibrotactile perception across different body parts from an HCI perceptive.

In particular, this paper contributes the findings of two controlled experiments:

- A first experiment on *phantom sensations* at different body locations. Our findings detail on the maximum distance of two physical tactors that still allows for continuous vibrotactile feedback to allow for an efficient tactor placement.

- A second experiment on the *perceived accuracy* of vibrotactile stimulation on different body parts. These findings help to understand the minimum distance between two tactors without a loss of precision in the haptic perception.

These findings are combined together in the form of *VibroMap*. VibroMap is a map of the ideal tactor spacing across the human body (see Figure P4.6). It provides an understanding on the *minimum and maximum distance* of tactors across body locations. HCI researchers and practitioners can use this map as a design guideline to gain insights into the perception on different body parts in order to design efficient future haptic devices and user studies.

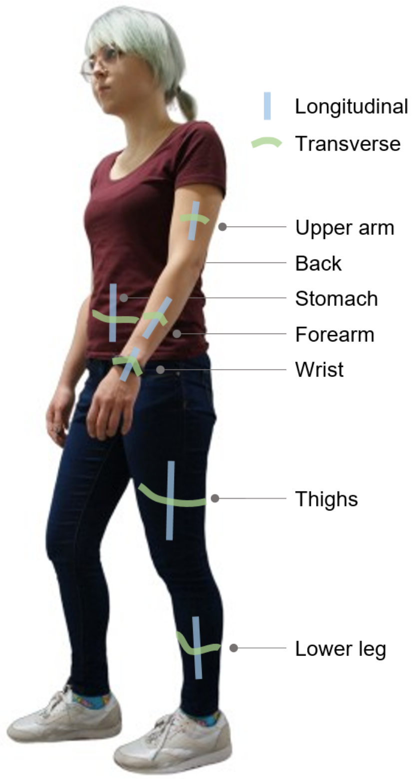


Figure P4.1: Locations studied in our experiments

P4.2 RELATED WORK

Our work aims to systematically investigate the spacing of vibrotactile actuators on the body. Therefore, we discuss in this section prior work using vibrations as an interaction modality, the human body's ability to resolve spatial tactile stimulation and work leveraging phantom sensations to generate continuous vibrotactile stimulation.

P4.2.1 *On-body Vibrotactile Interfaces*

On-body computing opens up a wide variety of opportunities for interaction, e.g., leveraging the skin as a platform for interaction [20, 63, 64], using electrical muscle stimulation to move users' limbs [36] and providing feedback for prosthetic limbs [34]. Vibrotactile interfaces on the body for output are particularly attractive as they are not restricted to body locations that are visible, which leads to their use across a diverse range of body locations, e.g., on the hand [17–19, 33, 42], wrist [7, 30, 31, 35], forearm [37, 38, 45, 47, 51, 70], upperarm [3, 4, 58], back [23, 41, 60], stomach [28], thigh [56] and lower leg [9]. Their usage spans a wide range of interaction scenarios, such as speech communication [46, 67, 70], affective communication [43], progress monitoring [7], learning gestures [19], spatial guidance [18, 33], motion guidance [51, 56] and navigation [13, 15, 24].

Table P4.1: Body locations for vibrotactile feedback in related work ↕ indicates a longitudinal arrangement, ⟳ indicates a transverse arrangement, ⊞ indicates a grid and ○ indicates a single actuator.

	Wrist	Forearm	Upperarm	Back	Stomach	Thigh	Legs
Srikulwong and O'Neill [57]				⟳	⟳		
Meier et al. [40]	⊞			⟳	⟳		
Konishi et al. [27]		↕	↕	⊞	⊞	↕	↕
Israr and Poupyrev [23]							
Tam et al. [59]	⟳						
Cauchard et al. [7]	○						
Leong et al. [34]			⟳			⟳	
Lee et al. [30]	⊞						
Lee and Starner [31]	⊞						
Liao et al. [35]	⊞						
Zhao et al. [70]		⊞					
Luzhnica and Veas [38]		⊞					
Luzhnica et al. [37]	⟳	↕	⟳				
Pfeiffer et al. [45]		○					
Schönauer et al. [51]		⊞					
Reinschluessel et al. [47]		⟳					
Stratmann et al. [58]			⟳				
Bark et al. [4]		⟳	⟳				
Alvina et al. [3]			⊞		⊞	⊞	
Spelmezan et al. [56]				⊞	⊞	⊞	
Chen et al. [9]	⟳	⟳					○
Wong et al. [67]		↕					
Dobbelstein et al. [13]	⟳						
Karuei et al. [25]	○		○		○	○	
Cholewiak and Collins [12]		↕					
Cholewiak et al. [11]				⟳	⟳		
Schneider et al. [49]				⊞			
Krüger et al. [28]				⟳	⟳		
Spelmezan [55]						↕	
Ertan et al. [16]				⊞			
Aggravi et al. [1]		⟳					
Ho et al. [21]				○	○		
Elvitigala et al. [14]	⊞						

While a large body of work explored vibrotactile interfaces (see Table P4.1) that are limited to a particular body location, prior work has also explored vibrotactile interfaces spanning across body locations. In OmniVib [3], recognition rate of vibrotactile notifications across the palm, upperarm, waist and thigh using a mobile phone form factor are investigated. Karuei et al. [25] investigated the influence of movement and visual load on the detection rate and reaction time of vibrations at different body locations. Spelmezan et al. [56] investigated full-body vibrotactile patterns for physical activities. Meier et al. [40] investigated vibrotactile feedback on several body locations for pedestrian navigation. In this work, we aim to gain a systematic understanding of the effect of inter-actuator distance across body locations. Thus, we contribute VibroMap, a map of the minimum and maximum inter-actuator distances for vibrotactile actuators across body locations.

P4.2.2 *Spatial Acuity of the Human Body*

Spatial acuity of the human body's sense of touch is investigated in previous research [54, 62, 65]. Results of earlier studies by Weber and Ross [62] with a metal compass show that spatial acuity varies across body regions, with the tongue being most sensitive followed by the fingers, toes and forehead; and that spatial acuity increases when the stimulus is oriented along the transverse rather than the longitudinal body axis. Weinstein [65] extended upon this by investigating two-point discrimination thresholds, i.e., the distance at which two stimuli applied to the skin are detected as distinct; and localization errors across a larger number of body locations. The findings of these studies show that spatial acuity of touch varies across the body. Sensitivity to touch stimulation has been shown to be higher at the limbs, e.g. the fingertips and lower going towards the body center, e.g. forearm, upper arm and back [54].

In contrast to touch stimulation, vibration propagates for larger distances on the skin, which makes localization of vibrations harder [12]. For designs using closely-spaced tactors, vibrotactile localization accuracy on the skin is important. If vibrotactile actuators are placed too close to each other that their signals cannot be distinguished, information will be lost. Prior work investigated vibrotactile localization accuracy on body locations, such as the arm [12] and the torso [11].

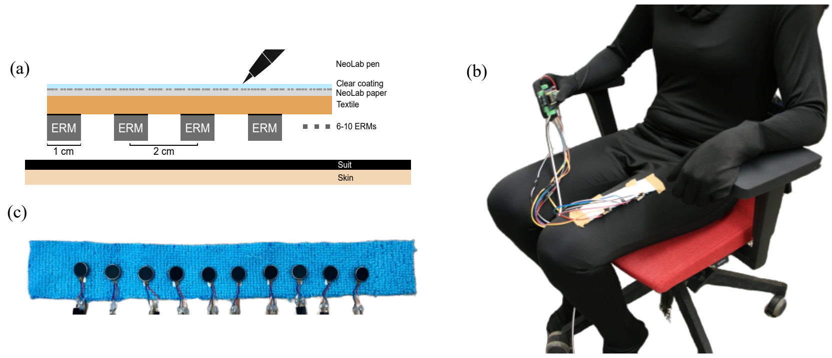


Figure P4.2: (a) cross-section of vibrotactile strip with input, (b) experimental setup and (c) vibrotactile strips used in our experiments

These studies however measure discrete identification of a vibration location in a set of candidate locations, e.g., 6, 8, or 12 locations on the torso [11]. In this work, we aim to provide a map of *continuous* vibrotactile localization accuracy across body locations.

P4.2.3 *Vibrotactile Phantom Sensations*

Phantom sensations refer to one of many tactile illusions [29], where the perceived location of a vibration is controlled by varying intensity (funneling) or time delay (saltation) between two (1D phantom sensations) or more (2D phantom sensations) neighbouring vibrotactile actuators [2, 42]. Phantom sensations are extremely useful for HCI applications as they enable rendering high resolution spatial vibrotactile stimuli using a low resolution grid of tactors [8, 22, 23, 48]. Mango [49], an authoring tool for creating vibrotactile patterns, uses direct manipulation of phantom sensations for designing and rendering expressive 2D patterns. In Tactile Brush [23], an algorithm is proposed and validated that uses phantom sensations and apparent motion to generate high resolution 2D vibrotactile strokes. While prior work investigated the control parameters for rendering phantom sensations, such as interpolation models, a systematic understanding of the effect of inter-tactor distance across the body needs to be investigated. As this has a direct influence on the design of vibrotactile displays. With VibroMap we investigate maximum inter-tactor distance across body locations while preserving the ability to generate phantom sensations.

P4.3 EXPERIMENTS

To better understand the maximum and minimum spacing between vibration motors, we conducted two controlled experiments to measure vibrotactile perception across body parts. The maximum distance is defined to be the biggest distance, where generating phantom sensations is possible. The minimum distance is defined to be the distance, where distinguishing between 2 vibrotactile actuators is possible. We conducted 2 psychophysical experiments to measure these values at different body locations. This section details on the participants, apparatus, locations and analysis both studies have in common.

P4.3.1 *Participants*

We recruited 24 voluntary participants between 21 and 34 years old (12f, 12m; mean age 25.9 y; median age 27 y). None of the participants had experience with haptic feedback on the body beyond every day use of smartphones.

P4.3.2 *Apparatus*

To study the perception of vibrations with different spacings, we built a textile stip (microfiber polyester cloth) with eccentric rotating mass (ERM) vibration motors (see Figure P4.2). The tactors have a diameter of 10 mm and were placed with a distance of 2 cm between each other. There are two versions of the strips, differing only in their length and the amount of tactors: one with 10 tactors and one with 6 tactors attached. The strip with 6 tactors was used on the wrist to account for the smaller area. The tactors are powered with 3 V, which leads to a maximum rotation speed of 12.000 rpm (200 Hz) and a maximum current draw of 60 mA. The experiments were controlled and logged on a computer that sends the tactor intensities over Serial connection to an ESP32 microcontroller. The ESP32 sends these commands over I^2C to a custom PCB to control the individual tactors.

Clothing influences the perception of vibrations, e.g., it can dampen the vibration. We standardized the clothing worn in the experiments to control for these effects by asking participants to wear a morphsuit (Polyester 91%, Elastane 9%). The strip was attached on top of the suit and centered on the location using an adhesive bandage.

In one experiment, participants were asked to mark the location of the vibration. For precise measurement of the input, we used a Neo smartpen [1] as an input device. The pen localizes its tip position on NeoLab paper attached on the top of the textile strip. Location of touch events on the paper were transmitted to the computer over Bluetooth. A clear coating on top of the NeoLab paper prevented abrasion and visible marks of prior inputs. A cross-section of the complete strip is shown in Figure P4.2a.

P4.3.3 *Design*

We evaluate participants' perception of vibrotactile stimuli on 7 body locations: the *wrist*, *forearm*, *upper arm*, *stomach*, *back*, *thigh* and *lower leg*. All locations are evaluated in two orientations: arranged along the *transverse* and *longitudinal* body axis. Both experiments follow a within-subject design with body location and orientation as independent variables. In experiment 2, we excluded the back location, since all body locations need to be reachable by the participants' hands.

To keep experiment time short and avoid excessive switching of locations, we used a 6x6 balanced latin square for counterbalancing body location (without wrist) and alternate starting or ending with the wrist condition between participants. Switching to the 6 tactor strip used for the wrist increased experiment time due to plugging and unplugging of motor connections to the board. By starting or ending with the wrist condition this change had to be done only once during the experiment. We expect this not to have an influence on our results.

P4.3.4 *Procedure*

Participants were welcomed into the lab and given a brief explanation of the purpose of the experiment and the procedure. Once participants agreed to take part in the experiments, participants were asked to

1 https://www.neosmartpen.com/en/neosmartpen-m1/

fill a short demographic questionnaire and to wear the morphsuit. For each condition the experiment started by placing the vibrotactile strip on the body. A calibration procedure was performed to find the voltage at each tactor where a stimulus becomes perceptible for the user. The driving voltage was increased gradually using the keyboard until a vibration became perceptible by the user. To ensure a quicker tactor response we used a 5ms overdrive cycle at 70% maximum voltage. This procedure was performed for all tactors on the strip. During the experiment all vibrations were performed at double the voltage from the calibration procedure, we ensured that vibrations were clearly perceived by participants. After successful completion of the calibration procedure, the participant proceeded with the task.

P4.3.5 *Data Analysis*

We analyzed the recorded data using a two-way repeated measures ANOVA with *body part* and *orientation* as the two independent factors. For the Likert questionnaires, we performed an Aligned Rank Transformation as proposed in [66]. We tested the data for normality with Shapiro Wilk's test and found no significant deviations. Where Mauchly's test indicates a violation of the assumption of sphericity, we corrected the tests using the Greenhouse-Geisser method and report the ϵ. When significant effects are revealed, we use Bonferroni corrected pairwise t-tests for post-hoc analysis. We further report the eta-squared η^2 as an estimate of the effect size. As an estimate of the influence of the individual factors, we report the estimated marginal mean (EMM) as proposed in [52].

P4.4 EXPERIMENT 1: MAXIMUM DISTANCE FOR PHANTOM SENSATIONS

In experiment 1 we investigated the *maximum* threshold distance between vibration motors, where participants could still experience phantom sensations. Using a larger distance between tactors results in losing the ability to generate continuous vibrotactile stimuli between the motors. We therefore used the lower 95% confidence interval as the *maximum distance*.

P4.4.1 *Research Questions*

We aim to answer the following research questions with our experiment:

RQ 1 How do 2-point thresholds differ between touch and vibration?

RQ 2 How does stimulus orientation affect 2-point thresholds for vibration?

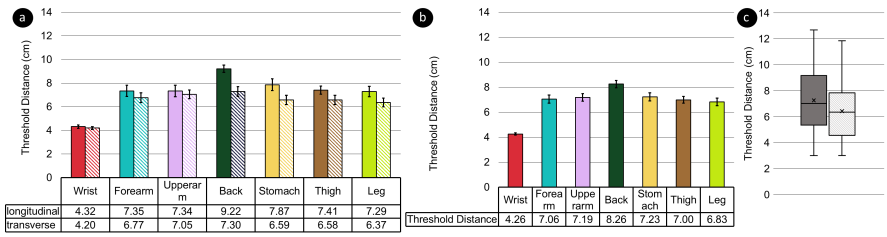
P4.4.2 *Task*

In line with related work [23, 32], we used a one-interval two-alternative forced-choice paradigm using a one-up one-down adaptive staircase procedure to determine thresholds for phantom sensations. Participants start by feeling the first and last tactor (18 cm apart) on the strip vibrating simultaneously. The participants are asked if they feel vibration at a single position or more than one position. For every response of feeling distinct vibration points the distance is decreased until the participants respond with feeling a single vibration point, at this point a reversal occurs and distance is increased. We used a constant step size of 2 cm. After 6 reversals a measurement of *threshold distance* was taken to be the average of the reversals.

For every body location and orientation we conducted 2 series of trials, resulting in a total of 28 trials per participant. After completing a body location, participants answered questions regarding their experiences on a 7 point Likert scale.

P4.4.3 *Dependent Variables*

In addition to the questionnaire, we used *threshold distance* as a dependent variable. Threshold distance is the maximum distance where the participants still perceive two neighbouring vibrations at a single location.



	Wrist	Forearm	Upperar m	Back	Stomach	Thigh	Leg
longitudinal	4.32	7.35	7.34	9.22	7.87	7.41	7.29
transverse	4.20	6.77	7.05	7.30	6.59	6.58	6.37

	Wrist	Forea rm	Uppe rarm	Back	Stom ach	Thigh	Leg
Threshold Distance	4.26	7.06	7.19	8.26	7.23	7.00	6.83

Figure P4.3: Average threshold distance of phantom sensations for each body location and orientation (a), body location (b), and orientation (c). Error bars are the standard errors. Data tables are displayed below each plot.

P4.4.4 *Results*

This section presents the results for *threshold distance* using the tested body locations (see Figure P4.3(b)), orientations (see Figure P4.3(c)) and their combination (see Figure P4.3(a)). Analysis procedures are described in section P4.3.5.

P4.4.4.1 *Body Location*

A 2-way repeated measures ANOVA showed a significant main effect of body location on threshold distance ($F_{3.89,89.39}$ = 22.48, p < .001, ϵ = .648 , η^2 = 0.252). Post-hoc tests revealed significant differences between wrist and all other body locations (p < .001), forearm and back (p < 0.05), back and thigh (p < 0.05) and back and leg (p < 0.01).

We found a larger threshold distance going from wrist to all other body locations, from thigh to back, as well as a larger threshold distance of the back location compared to the forearm. All of these differences were significant. In connection to *RQ1*, these results demonstrate that the relative 2-point thresholds follow a similar pattern to touch, i.e increasing thresholds going to less sensitive body locations, however vibration thresholds show a larger absolute value [65]. An overview of the results can be found in Figure P4.3(b).

P4.4.4.2 *Orientation*

A 2-way repeated measures ANOVA showed a significant main effect of the orientation of vibrotactile stimulation ($F_{1,23}$ = 15.27, p < .001, η^2

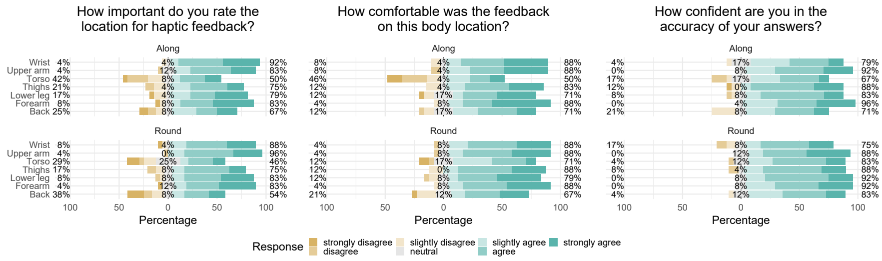


Figure P4.4: Participant's questionnaire answers about vibrations on different body locations and orientations on a 7-point Likert-scale.

= 0.035). Post-hoc tests confirmed the significantly lower threshold distance using the *transverse* orientation in comparison to the *longitudinal* orientation ($p < .001$).

Regarding *RQ2* (How does stimulus orientation affect 2-point thresholds for vibration?), our tests show that a longitudinal orientation always results in a significantly larger threshold distance in comparison to the transverse orientation. An overview of the results can be found in Figure P4.3(c).

P4.4.4.3 *Body Location x Orientation*

A 2-way repeated measures ANOVA revealed no significant interaction effects between body location and orientation ($F_{6,138} = 1.60$, $p > .05$). An overview of the results can be found in Figure P4.3(a).

P4.4.4.4 *Questionnaire*

Participants were asked questions relating to the importance, comfort and confidence experienced using the different locations and orientations. The questions and participants'answers are depicted in Figure P4.4.

Importance. We asked participants to rate how important they find the different body locations for haptic feedback. Analysis of participants' answers showed a significant effect for body location ($F_{6,138} = 4.82$, $p < .001$) and no significant effects for orientation ($F_{1,23} = 0.00$, $p > .05$) as well as no interaction between body location and orientation ($F_{6,138} = 1.40$, $p > .05$). Post-hoc tests reveal significantly higher ratings of *wrist* ($p < .01$), *forearm* ($p < .01$) and *upper arm* ($p < .05$) in comparison to the *stomach* location. Similarly, we found significantly higher ratings of the *wrist* ($p < .05$) and *forearm* ($p < .05$) in comparison to the *back* location.

Comfort. We further asked participants how comfortable they found the different body locations. Our analysis showed both location ($F_{6,138} = 6.17$, $p < .001$) and orientation ($F_{1,23} = 6.30$, $p < .05$) as well as their interaction ($F_{6,138} = 2.34$, $p < .05$) to be significant. For the body location, post-hoc tests showed that participants found the forearm ($p < .001$), leg ($p < 0.01$), thigh ($p < .01$), *upper arm* ($p < .001$) and *wrist* ($p < .001$) more comfortable than the *stomach*. Regarding the orientation, our participants found the *transverse* orientation to be significantly more comfortable than a *longitudinal* orientation ($p < .05$).

Confidence. Participants were lastly asked to rate how confident they were with their answers. Our analysis showed that body location ($F_{6,138} = 3.45$, $p < .01$) as well as orientation ($F_{1,23} = 7.76$, $p < .05$) have a significant effect on participants' ratings. We could not find any interaction effects between the two factors ($F_{6,138} = 1.24$, $p > .05$). For the body location, post-hoc tests revealed significantly higher ratings for *forearm* ($p < .05$) in comparison with the *stomach* location. For the different orientations, participants' were more confident using the *transverse* orientation ($p < .05$) in comparison to the *longitudinal* orientation.

P4.5 EXPERIMENT2: MINIMUM TACTOR DISTANCE

Experiment 2 investigates the minimum distance to use when placing vibrotactile actuators on the body. We use the upper 95% confidence interval as the localization error for a vibrotactile actuator. The minimum distance between 2 actuators, that does not lead to confusion is then the upper 95% confidence interval multiplied by a factor of 2 to account for the localization errors of both actuators.

P4.5.1 *Research Questions*

In this experiment, our goal is to answer these research questions:

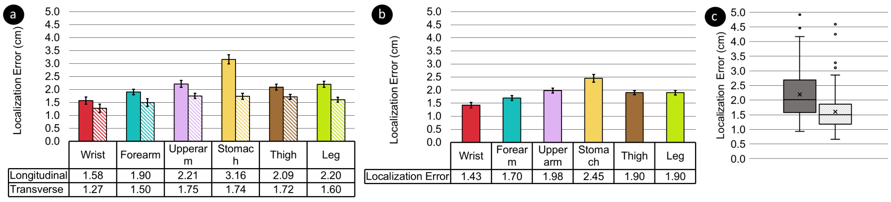


Figure P4.5: Average localization error for body location and orientation (a), body location (b) and orientation (c). Error bars are the standard errors. Data tables are displayed below each plot.

- *RQ3* Are localization errors for vibration different than touch?
- *RQ4* How does stimulus orientation affect localization error?

P4.5.2 *Task*

Participant's task was to indicate using the digital pen the location of vibration. The input was collected from the participants' after experiencing the vibration, so that the pen touching the surface does not influence the participants' perception of the vibrations. Participants were instructed to perform a light press on the paper which was also controlled visually by the experimenter. A light press avoids (1) markings being made by the pen despite the tape coating and (2) that the participant feels where the pen is located in comparison to the vibration locations previously felt. Every tactor on the vibrotactile strip is vibrated twice, resulting in 20 trials (12 at the wrist) per body location and orientation for a total number of 224 trials per participant.

P4.5.3 *Dependent Variables*

We measured *localization error* as our only dependent variable. Localization error is the *absolute* distance between where the participant feels the vibration and the location of vibrotactile actuator.

P4.5.4 *Results*

This section details on the results for *localization error* using the tested body locations (see Figure P4.5(b)), orientations (see Figure P4.5(c)) and their combination (see Figure P4.5(a)). Analysis procedures are described in section P4.3.5.

P4.5.4.1 *Body Location*

A 2-way repeated measures ANOVA reveals a significant effect of body location on localization error ($F_{3.60,82.70} = 10.79$, $p < .001$, $\epsilon = .719$, $\eta^2 = 0.159$). Post-hoc tests showed significant differences between wrist and upper arm ($p < .01$), wrist and stomach ($p < .001$), wrist and thigh ($p < .05$), wrist and leg ($p < .05$), forearm and stomach ($p < .001$), upper arm and stomach ($p < .05$), stomach and thigh ($p < .01$) and stomach and leg ($p < .01$). Similar to touch, body locations which have been shown to be more sensitive to touch stimulation resulted in lower localization error with vibrotactile stimulation. Significant differences supporting this have been found between wrist and all other locations except forearm, between forearm and stomach, upper arm and stomach, thigh and stomach and between leg and stomach. For *RQ3*, we can infer that localization errors follow a similar trend, but demonstrate larger absolute error values. [10, 65] The results are illustrated in Figure P4.5(b).

P4.5.4.2 *Orientation*

A 2-way repeated measures ANOVA showed this effect to be significant ($F_{1,23} = 117.71$, $p < .001$, $\eta^2 = 0.147$). Post-hoc tests confirmed the significantly lower localization error using the *transverse* orientation in comparison to the *longitudinal* orientation ($p < .001$).

Participants were significantly more accurate in localizing vibrations with a transverse orientation in comparison to a longitudinal orientation. With regards to *RQ4*, we can infer that localization errors are reduced using the transverse body axis. The results are illustrated in Figure P4.5(c)

P4.5.4.3 *Body Location x Orientation*

A 2-way repeated measures ANOVA revealed a significant interaction effect between body location and orientation ($F_{5,115}$ = 8.27, $p < .001$, η^2 = 0.060). Post-hoc tests confirmed significant differences between wrist transverse and all other body locations in longitudinal orientation ($p < .05$), stomach longitudinal and all 13 other combinations of body location and orientation ($p < .001$), leg longitudinal and leg transverse ($p < .01$), forearm transverse and each of upper arm longitudinal ($p < .01$) and leg longitudinal ($p < .01$), and wrist longitudinal with upper arm ($p < .05$) and leg ($p < .05$) in longitudinal orientation. Significant differences found between orientations at the same body location for leg and stomach indicate a more prominent difference at these locations. The results are illustrated in Figure P4.5(a)

		Wrist		Forearm		Upperarm		Back		Stomach		Thigh		Leg	
		Longitudinal	Transverse	Logitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse
Localization Error	Mean	1.58 cm	1.27 cm	1.90 cm	1.50 cm	2.21 cm	1.75 cm	-	-	3.16 cm	1.74 cm	2.09 cm	1.72 cm	2.20 cm	1.60 cm
	95% CI	[1.32 , 1.83]	[1.02 , 1.53]	[1.65 , 2.16]	[1.24 , 1.75]	[1.96 , 2.47]	[1.50 , 2.0]	-	-	[2.91 , 3.41]	[1.48 , 1.99]	[1.84 , 2.35]	[1.46 , 1.97]	[1.95 , 2.46]	[1.35 , 1.86]
Threshold Distance	Mean	4.32 cm	4.20 cm	7.35 cm	6.77 cm	7.34 cm	7.05 cm	9.22	7.30	7.87 cm	6.59 cm	7.41 cm	6.58 cm	7.29 cm	6.37 cm
	95% CI	[3.55 , 5.10]	[3.43 , 4.98]	[6.57 , 8.12]	[6.00 , 7.54]	[6.56 , 8.11]	[6.27 , 7.82]	[8.44 , 9.99]	[6.52 , 8.07]	[7.09 , 8.64]	[5.82 , 7.36]	[6.64 , 8.18]	[5.81 , 7.36]	[6.52 , 8.07]	[5.59 , 7.14]

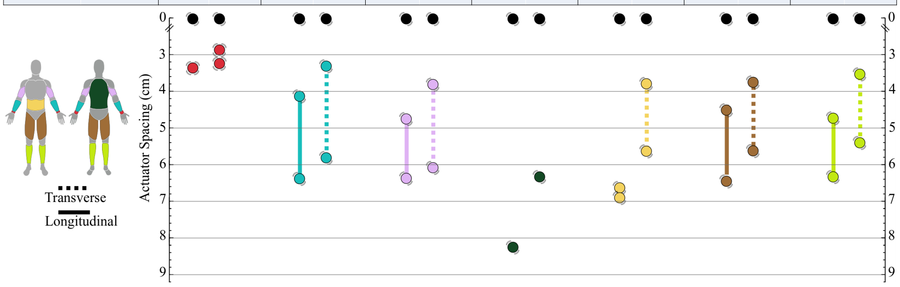


Figure P4.6: VibroMap shows the ideal tactor spacing for different body parts. It combines the minimum and maximum distances from both experiments.

P4.6 DISCUSSION AND IMPLICATIONS

In this section, we summarize the main findings of our experiments and discuss their implications on vibrotactile interfaces.

P4.6.1 *Summary*

In general, locations towards the body extremities showed higher sensitivity to vibrotactile stimulation, and hence smaller localization error between vibration actuators. This is evident by the increasing minimum distance going from wrist, forearm and upper arm to stomach and similarly from thigh and leg to stomach. Considering the maximum distance between vibrotactile actuators where the generation of phantom sensations is still possible, a similar trend is observed. Locations at the limbs show a higher sensitivity to vibrotactile stimulation and therefore a smaller maximum distance. This is evident by the decreasing maximum distance possible going from back and stomach to other body locations. With regards to orientation, participants showed higher sensitivity when using a transverse orientation, this resulted in lower minimum and maximum values over body parts in comparison to a longitudinal arrangement of vibrotactile actuators. These findings are in line with experiments on touch sensitivity, however the absolute values for vibrotactile stimulation differ considerably, as shown in Figure P4.7. Qualtitatively, our participants rated *wrist* to be significantly more important and more comfortable than *stomach*. However, in comparison to other body locations *wrist* was not rated significantly higher and was rated comparably to *forearm* and *upper arm*.

P4.6.2 *Design Implications for Vibrotactile On-Body Interfaces*

The results of our experiments provide valuable information on the required spacing between vibrotactile actuators at various body locations. In the following, we discuss implications for the design of on-body vibrotactile interfaces based on our results.

P4.6.2.1 *Favour Distal Over Proximal Placement*

An important question faced by designers of wearable devices is where to place these devices on the body [69]. For vibrotactile devices our results show that distally (going away from the torso) placing vibration motors should be preferred over a proximal (going towards the torso) placement. Participants perceived vibrotactile stimulation on the wrist, forearm and upperarm to be significantly more important than on the stomach. Participants further rated the wrist and forearm to be of higher importance than the back.

With regards to comfort, our participants rated the wrist, forearm, upper arm, leg and thigh as a more comfortable location for vibrotactile feedback than the stomach.

In line with the participants' ratings, results of localization error show a clear trend and significant differences. Distal locations such as the wrist have shown a higher localization accuracy compared to proximal locations (e.g. the stomach). The body locations in ascending order of localization error are: wrist, forearm, leg, thigh, upper arm and stomach.

P4.6.2.2 *Favour Transverse Over Longitudinal*

If given the choice between a transverse and a longitudinal arrangement of vibrotactile actuators on the same body part, our results show that a transverse orientation should be favoured for delivering accurately localized vibrotactile stimulation. Since for each body part, a transverse arrangement resulted in higher accuracy in comparison to a longitudinal arrangement. However, a transverse orientation (e.g on the forearm) is not necessarily more accurate than a longitudinal orientation (e.g on the wrist) of another body location.

Using a transverse orientation consistently resulted in significantly lower localization errors across body locations. Our participants further reported higher confidence ratings when using a transverse arrangement of vibrotactile actuators. We expect this to be of particular relevance for applications such as navigation and motion coaching where directions encoded spatially need to be accurately distinguished.

P4.6.2.3 *Design for the Correct Mechanoreceptor*

Results of both our experiments show considerable deviation of localization and two-point thresholds for vibrotactile stimulation in comparison to touch stimulation. These differences could arise due to the mechanoreceptors in the skin targeted by touch (Merkel disc) and vibration (Pacinian corpuscle) that are different in the size of their receptive fields. They could also be due to the nature of stimulation, where vibrations cause displacements that propagate for larger distances on the skin [12].

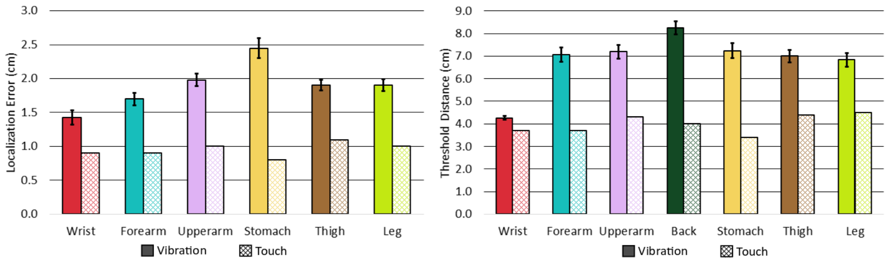


Figure P4.7: Comparison of localization and two-point distance thresholds for vibrations and touch as reported by [65]. Error bars are the standard errors.

In experiment 1, thresholds for phantom sensations were consistently larger than reported values for two-point discrimination of touch stimulation [39]. For instance, two-point thresholds for simultaneous touch stimulation on the forearm and thigh are $\approx$ 2 cm in comparison to 7 cm for simultaneous vibrotactile stimulation.

Additionally, the localization error was always larger for vibrations than touch stimulation across all tested body locations [65]. For example, a touch has a localization error of 1 cm on the forearm and thigh in comparison to $\approx$ 2 cm for vibrotactile stimulation. Figure P4.7 compares two-point thresholds and localization for touch and vibrations.

These findings necessitate that designers abstain from using values on the human body's spatial acuity to touch stimulation when designing vibrotactile interfaces. Relying on information on touch acuity results in degraded recognition rates for spatial patterns due to a denser than required placement of vibrotactile actuators. Instead designers should base their decisions regarding spacing of vibrotactile actuators on information obtained specifically for vibrotactile stimulation.

P4.7 LIMITATIONS AND FUTURE WORK

In this section, we mention limitations relating to our approach for deriving VibroMap and outline directions for future work.

Although we systematically investigated the perception of vibrations on major parts of the human body, a few locations such as the hand, head and shoulder were excluded. We excluded these body locations, as due to their complex geometries and properties such as hair on the head, they required significant changes to our experimental setup. These locations are promising for vibrotactile interfaces and should be systematically evaluated in future work. Moreover, we also investigated a single intensity level, varying intensity can lead to changes in threshold distances.

A second limitation that has to be mentioned is the granularity of VibroMap. We used a coarse-grained representation of the human body that assumes no variance in vibrotactile perception within body parts. Although this is in line with related work on spatial acuity of the human body [39], we plan to investigate in future work how vibrotactile perception varies on the human body in a more fine-grained manner.

Lastly, there are many different vibrotactile actuators available. In our experiments, we chose to use eccentric rotating mass (ERM) vibrotactile actuators as they are most commonly used in HCI research (e.g., [3, 68]). They are also cheap and widely accessible due to their use in phones. However, ERM actuators are controlled only by varying input voltage with no precise control over the frequency of the vibration. Future work should investigate the effect of using other types of vibrotactile actuators (e.g. LRA and piezos), the influence of the vibration frequency and important factors beside frequency, e.g rythm [6] on the spacing of vibrotactile actuators.

P4.8 CONCLUSION

A systematic exploration of the spacing required for vibrotactile interfaces on the body is required in the HCI community given the amount of research using vibrations as a modality for interaction. We conducted two controlled experiments in which we explored the minimum and maximum spacing necessary for correctly discriminating between vibrotactile actuators and ensuring the ability to generate phantom sensations. Based on the results, we discussed implications for the design of vibrotactile interfaces to be worn on the body.

REFERENCES

[1] M. Aggravi, G. Salvietti, and D. Prattichizzo. "Haptic wrist guidance using vibrations for Human-Robot teams." In: *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. Aug. 2016, pp. 113–118. DOI: 10.1109/ROMAN.2016.7745098.

[2] D. S. Alles. "Information Transmission by Phantom Sensations." In: *IEEE Transactions on Man-Machine Systems* 11.1 (Mar. 1970), pp. 85–91. ISSN: 0536-1540. DOI: 10.1109/TMMS.1970.299967.

[3] Jessalyn Alvina, Shengdong Zhao, Simon T. Perrault, Maryam Azh, Thijs Roumen, and Morten Fjeld. "OmniVib: Towards Cross-body Spatiotemporal Vibrotactile Notifications for Mobile Phones." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 2487–2496. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702341.

[4] K. Bark, E. Hyman, F. Tan, E. Cha, S. A. Jax, L. J. Buxbaum, and K. J. Kuchenbecker. "Effects of Vibrotactile Feedback on Human Learning of Arm Motions." In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 23.1 (Jan. 2015), pp. 51–63. ISSN: 1534-4320. DOI: 10.1109/TNSRE.2014.2327229.

[5] Dominik Bial, Dagmar Kern, Florian Alt, and Albrecht Schmidt. "Enhancing Outdoor Navigation Systems Through Vibrotactile Feedback." In: *CHI '11 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '11. Vancouver, BC, Canada: ACM, 2011, pp. 1273–1278. ISBN: 978-1-4503-0268-5. DOI: 10.1145/1979742.1979760.

[6] Stephen Brewster and Lorna M. Brown. "Tactons: Structured Tactile Messages for Non-Visual Information Display." In: *Proceedings of the Fifth Conference on Australasian User Interface - Volume 28*. AUIC '04. Dunedin, New Zealand: Australian Computer Society, Inc., 2004, pp. 15–23.

[7] Jessica R. Cauchard, Janette L. Cheng, Thomas Pietrzak, and James A. Landay. "ActiVibe: Design and Evaluation of Vibrations for Progress Monitoring." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: ACM, 2016, pp. 3261–3271. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858046.

[8] J. Cha, L. Rahal, and A. El Saddik. "A pilot study on simulating continuous sensation with two vibrating motors." In: *2008 IEEE International Workshop on Haptic Audio visual Environments and Games*. Oct. 2008, pp. 143–147. DOI: 10.1109/HAVE.2008.4685314.

[9] Qin Chen, Simon T. Perrault, Quentin Roy, and Lonce Wyse. "Effect of Temporality, Physical Activity and Cognitive Load on Spatiotemporal Vibrotactile Pattern Recognition." In: *Proceedings of the 2018 International Conference on Advanced Visual Interfaces*. AVI '18. Castiglione della Pescaia, Grosseto, Italy: ACM, 2018, 25:1–25:9. ISBN: 978-1-4503-5616-9. DOI: 10.1145/3206505.3206511.

[10] Roger Cholewiak. "The perception of tactile distance: Influences of body site, space, and time." In: *Perception* 28 (Feb. 1999), pp. 851–75. DOI: 10.1121/1.2023365.

[11] Roger Cholewiak, J Christopher Brill, and Anja Schwab. "Vibrotactile localization on the abdomen: Effects of place and space." In: *Perception & psychophysics* 66 (Sept. 2004), pp. 970–87. DOI: 10.3758/BF03194989.

[12] Roger W. Cholewiak and Amy A. Collins. "Vibrotactile localization on the arm: Effects of place, space, and age." In: *Perception & Psychophysics* 65.7 (Oct. 2003), pp. 1058–1077. ISSN: 1532-5962. DOI: 10.3758/BF03194834.

[13] David Dobbelstein, Philipp Henzler, and Enrico Rukzio. "Unconstrained Pedestrian Navigation Based on Vibro-tactile Feedback Around the Wristband of a Smartwatch." In: *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA '16. San Jose, California, USA: ACM, 2016, pp. 2439–2445. ISBN: 978-1-4503-4082-3. DOI: 10.1145/2851581.2892292.

[14] Don Samitha Elvitigala, Denys J. C. Matthies, Vipula Dissanayaka, Chamod Weerasinghe, and Suranga Nanayakkara. "2bit-TactileHand: Evaluating Tactons for On-Body Vibrotactile Displays on the Hand and Wrist." In: *Proceedings of the 10th Augmented Human International Conference 2019*. AH2019. Reims, France: ACM, 2019, 3:1–3:8. ISBN: 978-1-4503-6547-5. DOI: 10.1145/3311823.3311832.

[15] Jan B. F. Van Erp, Hendrik A. H. C. Van Veen, Chris Jansen, and Trevor Dobbins. "Waypoint Navigation with a Vibrotactile Waist

Belt." In: *ACM Trans. Appl. Percept.* 2.2 (Apr. 2005), pp. 106–117. ISSN: 1544-3558. DOI: 10.1145/1060581.1060585.

[16] S. Ertan, C. Lee, A. Willets, H. Tan, and A. Pentland. "A wearable haptic navigation guidance system." In: *Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215)*. Oct. 1998, pp. 164–165. DOI: 10.1109/ISWC.1998.729547.

[17] Sebastian Günther, Sven Kratz, Daniel Avrahami, and Max Mühlhäuser. "Exploring Audio, Visual, and Tactile Cues for Synchronous Remote Assistance." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. PETRA '18. Corfu, Greece: ACM, 2018, pp. 339–344. ISBN: 978-1-4503-6390-7. DOI: 10.1145/3197768.3201568.

[18] Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. "TactileGlove: Assistive Spatial Guidance in 3D Space Through Vibrotactile Navigation." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. PETRA '18. Corfu, Greece: ACM, 2018, pp. 273–280. ISBN: 978-1-4503-6390-7. DOI: 10.1145/3197768.3197785.

[19] Aakar Gupta, Antony Irudayaraj, Vimal Chandran, Goutham Palaniappan, Khai N. Truong, and Ravin Balakrishnan. "Haptic Learning of Semaphoric Finger Gestures." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: ACM, 2016, pp. 219–226. ISBN: 978-1-4503-4189-9. DOI: 10.1145/2984511.2984558.

[20] Chris Harrison, Shilpa Ramamurthy, and Scott E. Hudson. "On-body Interaction: Armed and Dangerous." In: *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*. TEI '12. Kingston, Ontario, Canada: ACM, 2012, pp. 69–76. ISBN: 978-1-4503-1174-8. DOI: 10.1145/2148131.2148148.

[21] Cristy Ho, Hong Z. Tan, and Charles Spence. "Using spatial vibrotactile cues to direct visual attention in driving scenes." In: *Transportation Research Part F: Traffic Psychology and Behaviour* 8.6 (2005), pp. 397–412. ISSN: 1369-8478. DOI: https://doi.org/10.1016/j.trf.2005.05.002.

[22] Gi-Hun Yang, Moon-sub Jin, Yeonsub Jin, and Sungchul Kang. "T-mobile: Vibrotactile display pad with spatial and directional information for hand-held device." In: *2010 IEEE/RSJ Interna-*

tional Conference on Intelligent Robots and Systems. Oct. 2010, pp. 5245–5250. DOI: 10.1109/IROS.2010.5651759.

[23] Ali Israr and Ivan Poupyrev. “Tactile Brush: Drawing on Skin with a Tactile Grid Display.” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’11. Vancouver, BC, Canada: ACM, 2011, pp. 2019–2028. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1979235.

[24] Lynette Jones. “Tactile communication systems: optimizing the display of information.” In: *Progress in brain research* 192 (Dec. 2011), pp. 113–28. DOI: 10.1016/B978-0-444-53355-5.00008-7.

[25] Idin Karuei, Karon E. MacLean, Zoltan Foley-Fisher, Russell MacKenzie, Sebastian Koch, and Mohamed El-Zohairy. “Detecting Vibrations Across the Body in Mobile Contexts.” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’11. Vancouver, BC, Canada: ACM, 2011, pp. 3267–3276. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1979426.

[26] Paul AJ Kolarsick, Maria Ann Kolarsick, and Carolyn Goodwin. “Anatomy and physiology of the skin.” In: *Journal of the Dermatology Nurses’ Association* 3.4 (2011), pp. 203–213.

[27] Yukari Konishi, Nobuhisa Hanamitsu, Kouta Minamizawa, Ayahiko Sato, and Tetsuya Mizuguchi. “Synesthesia Suit: The Full Body Immersive Experience.” In: *ACM SIGGRAPH 2016 Posters*. SIGGRAPH ’16. Anaheim, California: ACM, 2016, 71:1–71:1. ISBN: 978-1-4503-4371-8. DOI: 10.1145/2945078.2945149.

[28] Matti Krüger, Heiko Wersing, and Christiane B. Wiebel-Herboth. “Approach for Enhancing the Perception and Prediction of Traffic Dynamics with a Tactile Interface.” In: *Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI ’18. Toronto, ON, Canada: ACM, 2018, pp. 164–169. ISBN: 978-1-4503-5947-4. DOI: 10.1145/3239092.3265961.

[29] S. J. Lederman and L. A. Jones. “Tactile and Haptic Illusions.” In: *IEEE Transactions on Haptics* 4.4 (2011), pp. 273–294.

[30] Jaeyeon Lee, Jaehyun Han, and Geehyuk Lee. “Investigating the Information Transfer Efficiency of a 3x3 Watch-back Tactile Display.” In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI ’15. Seoul, Republic of Korea: ACM, 2015, pp. 1229–1232. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702530.

[31] Seungyon "Claire" Lee and Thad Starner. "BuzzWear: Alert Perception in Wearable Tactile Displays on the Wrist." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '10. Atlanta, Georgia, USA: ACM, 2010, pp. 433–442. ISBN: 978-1-60558-929-9. DOI: 10.1145/1753326.1753392.

[32] Marjorie R. Leek. "Adaptive procedures in psychophysical research." In: *Perception & Psychophysics* 63.8 (Nov. 2001), pp. 1279–1292. ISSN: 1532-5962. DOI: 10.3758/BF03194543.

[33] Ville Lehtinen, Antti Oulasvirta, Antti Salovaara, and Petteri Nurmi. "Dynamic Tactile Guidance for Visual Search Tasks." In: *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology*. UIST '12. Cambridge, Massachusetts, USA: ACM, 2012, pp. 445–452. ISBN: 978-1-4503-1580-7. DOI: 10.1145/2380116.2380173.

[34] Joanne Leong, Patrick Parzer, Florian Perteneder, Teo Babic, Christian Rendl, Anita Vogl, Hubert Egger, Alex Olwal, and Michael Haller. "proCover: Sensory Augmentation of Prosthetic Limbs Using Smart Textile Covers." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: ACM, 2016, pp. 335–346. ISBN: 978-1-4503-4189-9. DOI: 10.1145/2984511.2984572.

[35] Yi-Chi Liao, Yi-Ling Chen, Jo-Yu Lo, Rong-Hao Liang, Liwei Chan, and Bing-Yu Chen. "EdgeVib: Effective Alphanumeric Character Output Using a Wrist-Worn Tactile Display." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: ACM, 2016, pp. 595–601. ISBN: 978-1-4503-4189-9. DOI: 10.1145/2984511.2984522.

[36] Pedro Lopes, Alexandra Ion, Willi Müller, Daniel Hoffmann, Patrik Jonell, and Patrick Baudisch. "Proprioceptive Interaction." In: *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA '15. Seoul, Republic of Korea: ACM, 2015, pp. 175–175. ISBN: 978-1-4503-3146-3. DOI: 10.1145/2702613.2732490.

[37] Granit Luzhnica, Sebastian Stein, Eduardo Veas, Viktoria Pammer, John Williamson, and Roderick Murray Smith. "Personalising Vibrotactile Displays Through Perceptual Sensitivity Adjustment." In: *Proceedings of the 2017 ACM International Symposium on Wearable Computers*. ISWC '17. Maui, Hawaii: ACM, 2017, pp. 66–73. ISBN: 978-1-4503-5188-1. DOI: 10.1145/3123021.3123029.

[38] Granit Luzhnica and Eduardo Veas. "Optimising Encoding for Vibrotactile Skin Reading." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: ACM, 2019, 235:1–235:14. ISBN: 978-1-4503-5970-2. DOI: 10.1145/3290605.3300465.

[39] Flavia Mancini, Armando Bauleo, Jonathan Cole, Fausta Lui, Carlo Porro, Patrick Haggard, and Gian Iannetti. "Whole-Body Mapping of Spatial Acuity for Pain and Touch." In: *Annals of Neurology* 75 (June 2014). DOI: 10.1002/ana.24179.

[40] Anita Meier, Denys J. C. Matthies, Bodo Urban, and Reto Wettach. "Exploring Vibrotactile Feedback on the Body and Foot for the Purpose of Pedestrian Navigation." In: *Proceedings of the 2Nd International Workshop on Sensor-based Activity Recognition and Interaction*. iWOAR '15. Rostock, Germany: ACM, 2015, 11:1–11:11. ISBN: 978-1-4503-3454-9. DOI: 10.1145/2790044.2790051.

[41] Scott Novich and David Eagleman. "Using space and time to encode vibrotactile information: toward an estimate of the skin's achievable throughput." In: *Experimental brain research* 233 (June 2015). DOI: 10.1007/s00221-015-4346-1.

[42] Gunhyuk Park and Seungmoon Choi. "Tactile Information Transmission by 2D Stationary Phantom Sensations." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: ACM, 2018, 258:1–258:12. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173832.

[43] Young-Woo Park, Chang-Young Lim, and Tek-Jin Nam. "CheekTouch: An Affective Interaction Technique While Speaking on the Mobile Phone." In: *CHI '10 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '10. Atlanta, Georgia, USA: ACM, 2010, pp. 3241–3246. ISBN: 978-1-60558-930-5. DOI: 10.1145/1753846.1753965.

[44] S. M. Petermeijer, J. C. F. de Winter, and K. J. Bengler. "Vibrotactile Displays: A Survey With a View on Highly Automated Driving." In: *IEEE Transactions on Intelligent Transportation Systems* 17.4 (Apr. 2016), pp. 897–907. ISSN: 1524-9050. DOI: 10.1109/TITS.2015.2494873.

[45] Max Pfeiffer, Stefan Schneegass, Florian Alt, and Michael Rohs. "Let Me Grab This: A Comparison of EMS and Vibration for Haptic Feedback in Free-hand Interaction." In: *Proceedings of the 5th Augmented Human International Conference*. AH '14. Kobe,

Japan: ACM, 2014, 48:1–48:8. ISBN: 978-1-4503-2761-9. DOI: 10.1145/2582051.2582099.

[46] Charlotte Reed, Hong Tan, Zach Perez, E Wilson, Frederico Severgnini, Jaehong Jung, Juan Martinze, Yang Jiao, Ali Israr, Frances Lau, Keith Klumb, Robert Turcott, and Freddy Abnousi. "A Phonemic-Based Tactile Display for Speech Communication." In: *IEEE transactions on haptics* PP (July 2018). DOI: 10.1109/TOH.2018.2861010.

[47] Anke Verena Reinschluessel, Sarah Christin Cebulla, Marc Herrlich, Tanja Döring, and Rainer Malaka. "Vibro-Band: Supporting Needle Placement for Physicians with Vibrations." In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI EA '18. Montreal QC, Canada: ACM, 2018, LBW039:1–LBW039:6. ISBN: 978-1-4503-5621-3. DOI: 10.1145/3170427.3188549.

[48] D. Ryu, G. Yang, and S. Kang. "T-hive : Vibrotactile interface presenting spatial information on handle surface." In: *2009 IEEE International Conference on Robotics and Automation*. May 2009, pp. 683–688. DOI: 10.1109/ROBOT.2009.5152740.

[49] Oliver S. Schneider, Ali Israr, and Karon E. MacLean. "Tactile Animation by Direct Manipulation of Grid Displays." In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST '15. Charlotte, NC, USA: ACM, 2015, pp. 21–30. ISBN: 978-1-4503-3779-3. DOI: 10.1145/2807442.2807470.

[50] Christian Schönauer, Kenichiro Fukushi, Alex Olwal, Hannes Kaufmann, and Ramesh Raskar. "Multimodal Motion Guidance: Techniques for Adaptive and Dynamic Feedback." In: *Proceedings of the 14th ACM International Conference on Multimodal Interaction*. ICMI '12. Santa Monica, California, USA: ACM, 2012, pp. 133–140. ISBN: 978-1-4503-1467-1. DOI: 10.1145/2388676.2388706.

[51] Christian Schönauer, Kenichiro Fukushi, Alex Olwal, Hannes Kaufmann, and Ramesh Raskar. "Multimodal Motion Guidance: Techniques for Adaptive and Dynamic Feedback." In: *Proceedings of the 14th ACM International Conference on Multimodal Interaction*. ICMI '12. Santa Monica, California, USA: ACM, 2012, pp. 133–140. ISBN: 978-1-4503-1467-1. DOI: 10.1145/2388676.2388706.

[52] S. R. Searle, F. M. Speed, and G. A. Milliken. "Population Marginal Means in the Linear Model: An Alternative to Least Squares Means." In: *The American Statistician* 34.4 (1980), pp. 216–221. DOI: 10.1080/00031305.1980.10483031. eprint: https://www.tandfonline.com/doi/pdf/10.1080/00031305.1980.10483031.

[53] Caitlyn E. Seim, David Quigley, and Thad E. Starner. "Passive Haptic Learning of Typing Skills Facilitated by Wearable Computers." In: *CHI '14 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '14. Toronto, Ontario, Canada: ACM, 2014, pp. 2203–2208. ISBN: 978-1-4503-2474-8. DOI: 10.1145/2559206.2581329.

[54] Kannathu Shibin and Asir Samuel. "The Discrimination of Two-point Touch Sense for the Upper Extremity in Indian Adults." In: *International Journal of Health and Rehabilitation Sciences* 2 (Jan. 2013), pp. 38–43.

[55] Daniel Spelmezan. "An Investigation into the Use of Tactile Instructions in Snowboarding." In: *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services*. MobileHCI '12. San Francisco, California, USA: ACM, 2012, pp. 417–426. ISBN: 978-1-4503-1105-2. DOI: 10.1145/2371574.2371639.

[56] Daniel Spelmezan, Mareike Jacobs, Anke Hilgers, and Jan Borchers. "Tactile Motion Instructions for Physical Activities." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: ACM, 2009, pp. 2243–2252. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1519044.

[57] Mayuree Srikulwong and Eamonn O'Neill. "A Comparative Study of Tactile Representation Techniques for Landmarks on a Wearable Device." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: ACM, 2011, pp. 2029–2038. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1979236.

[58] Tim Claudius Stratmann, Andreas Löcken, Uwe Gruenefeld, Wilko Heuten, and Susanne Boll. "Exploring Vibrotactile and Peripheral Cues for Spatial Attention Guidance." In: *Proceedings of the 7th ACM International Symposium on Pervasive Displays*. PerDis '18. Munich, Germany: ACM, 2018, 9:1–9:8. ISBN: 978-1-4503-5765-4. DOI: 10.1145/3205873.3205874.

[59] Diane Tam, Karon E. MacLean, Joanna McGrenere, and Katherine J. Kuchenbecker. "The Design and Field Observation of a Haptic Notification System for Timing Awareness During Oral Presentations." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. Paris, France: ACM, 2013, pp. 1689–1698. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2466223.

[60] Hong Tan, Rob Gray, and J. Young. "A Haptic Back Display for Attentional and Directional Cueing." In: *Haptics-e* 3 (July 2003).

[61] P. Vyas, F. Al Taha, J. R. Blum, A. Weill-Duflos, and J. R. Cooperstock. "Ten Little Fingers, Ten Little Toes: Can Toes Match Fingers for Haptic Discrimination?" In: *IEEE Transactions on Haptics* 13.1 (2020), pp. 130–136.

[62] Ernst Heinrich Weber and Helen Elizabeth Ross. *The sense of touch*. Academic Press for [the] Experimental Psychology Society, 1978.

[63] Martin Weigel, Tong Lu, Gilles Bailly, Antti Oulasvirta, Carmel Majidi, and Jürgen Steimle. "iSkin: Flexible, Stretchable and Visually Customizable On-Body Touch Sensors for Mobile Computing." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 2991–3000. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702391.

[64] Martin Weigel, Vikram Mehta, and Jürgen Steimle. "More Than Touch: Understanding How People Use Skin As an Input Surface for Mobile Computing." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: ACM, 2014, pp. 179–188. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557239.

[65] S. Weinstein. "Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality." In: *The skin senses. Proceedings of the First International Symposium March*, (1968), pp. 195–222.

[66] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. "The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: ACM, 2011, pp. 143–146. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1978963.

[67] E. Y. Wong, A. Israr, and M. K. O'Malley. "Discrimination of consonant articulation location by tactile stimulation of the forearm." In: *2010 IEEE Haptics Symposium*. Mar. 2010, pp. 47–54. DOI: 10.1109/HAPTIC.2010.5444681.

[68] Koji Yatani, Nikola Banovic, and Khai Truong. "SpaceSense: Representing Geographical Information to Visually Impaired People Using Spatial Tactile Feedback." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. Austin, Texas, USA: ACM, 2012, pp. 415–424. ISBN: 978-1-4503-1015-4. DOI: 10.1145/2207676.2207734.

[69] Clint Zeagler. "Where to Wear It: Functional, Technical, and Social Considerations in On-body Location for Wearable Technology 20 Years of Designing for Wearability." In: *Proceedings of the 2017 ACM International Symposium on Wearable Computers*. ISWC '17. Maui, Hawaii: ACM, 2017, pp. 150–157. ISBN: 978-1-4503-5188-1. DOI: 10.1145/3123021.3123042.

[70] Siyan Zhao, Ali Israr, Frances Lau, and Freddy Abnousi. "Coding Tactile Symbols for Phonemic Communication." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: ACM, 2018, 392:1–392:13. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173966.

P5

UNDERSTANDING STATIONARY AND MOVING DIRECT SKIN VIBROTACTILE STIMULATION ON THE PALM

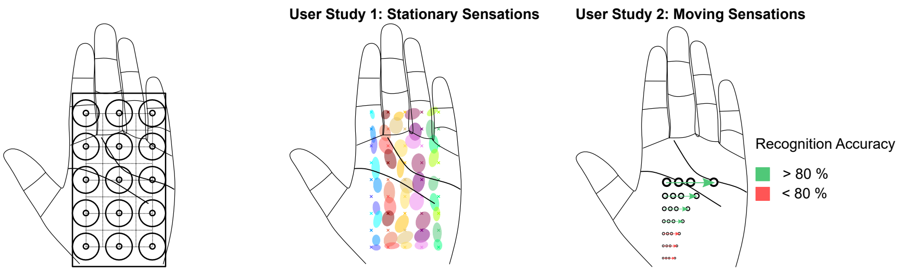


Figure P5.1: We investigate stationary and moving tactile sensations on the palm that inform the design of haptic interfaces.

ABSTRACT

Palm-based tactile displays have the potential to evolve from single motor interfaces (e.g., smartphones) to high-resolution tactile displays (e.g., back-of-device haptic interfaces) enabling richer multi-modal experiences with more information. However, we lack a systematic understanding of vibrotactile perception on the palm and the influence of various factors on the core design decisions of tactile displays (number of actuators, resolution, and intensity). In a first experiment (N=16), we investigated the effect of these factors on the users' ability to localize *stationary* sensations. In a second experiment (N=20), we explored the influence of resolution on recognition rate for *moving* tactile sensations. Findings show that for *stationary* sensations a 9 actuator display offers a good trade-off and a 3×3 resolution can be accurately localized. For *moving* sensations, a 2×4 resolution

led to the highest recognition accuracy, while 5×10 enables higher resolution output with a reasonable accuracy.

P5.1 INTRODUCTION

From navigation [60] and skin reading [29] to movement guidance [15, 32] and haptic learning [16, 30], research proposed palm-based vibrotactile displays as a promising output modality for a diverse set of use-cases. These interfaces are especially applicable in situations where multi-modal interaction is beneficial, where interaction with video and audio displays is infeasible or not recommended – e.g., while driving or riding a bike – or where subtle interaction is required – e.g., while holding a conversation. Research has started to explore how to encode information via vibrotactile patterns, that are either *stationary* at a fixed location or *moving* over time between various spatial locations.

One of the most promising locations for applying vibrotactile patterns is the palm due to high sensitivity and the frequency with which we use our hands to interact with the environment. Fundamental to the design of palm-based tactile displays is their resolution. Research has investigated the spatial acuity (2-point discrimination and point localization) [31] of the human body to touch at various locations, including the palm. However, prior work has shown that vibrotactile sensations have a different spatial acuity than touch [12]. This difference occurs because vibrations (1) activate the Pacinian corpuscle mechanoreceptors [42] with larger receptive fields and (2) propagate larger distances on the skin [9], making them harder to localize. Thus, given that vibration is a commonly used modality in haptics research, we currently lack information on the perception of *stationary* and *moving* tactile sensations. This information is necessary for the design and usage of palm-based tactile displays.

In this paper, we contribute important insights on *stationary* and *moving* vibrotactile sensations on the palm. In a first experiment, we investigated the influence of the layout and number of actuators, intensity, and resolution on the localization error and perception of real and phantom *stationary sensations*. Based on the results, we determined that a 3×3 resolution can be accurately localized on the palm. Nine vibration motors with a bigger (approximately 2:1 ratio) spacing along the length of the palm than the width should be used. We further observed that increasing the number of actuators to 15 resulted in a significant increase in correct perception of phantom sensations at a single location.

In a second experiment, we investigated *moving* sensations. In particular, we explored the influence of the resolution of the display and direction of movement on the recognition accuracy and reaction time of users. We observed that a 2×4 resolution can be used for *accurate* interactions with *moving* sensations (recognition accuracy > 95%). While a 5×10 resolution can be used where more *expressive* tactile sensations are required (recognition accuracy > 85%). Based on the findings of our two experiments, we contribute a set of design guidelines for vibrotactile output on the palm.

Taken together, the main contributions of this paper are:

1. Findings from a controlled user study investigating perception of *stationary* tactile sensations.

2. Findings from a controlled user study investigating perception of *moving* tactile sensations.

3. A set of design guidelines based on our findings to improve future vibrotactile displays on the palm.

P5.2 RELATED WORK

This work relates to prior research in measuring the spatial acuity of the palm, leveraging vibrotactile illusions, and work on *stationary* and *moving* tactile sensations on the palm.

P5.2.1 *Spatial Acuity of the Palm*

Various aspects of vibrotactile perception have been investigated on the body, for example temporal aspects of perceiving vibrations as distinct [37], the effect of the number of actuators on perceived intensity [8], and parameters effecting perception of patterns on the body [10]. In the following, work related to vibrotactile spatial acuity of the palm is discussed. Research [54, 55] has shown that the spatial acuity of the sense of touch varies across the body, with the palm being among the most sensitive body parts, superseded only by the fingertips [31]. Ever since the seminal work of Weber [53] on touch, spatial acuity has been measured by two-point discrimination thresholds. These refer to the minimum distance required between two simultaneous stimuli for them to be perceived as distinct. However, this wealth of knowledge cannot be used to inform the core design decisions of vibrotactile displays (e.g., spacing of actuators), as prior work has shown that spatial acuity of the body to vibrotactile stimulation is fundamentally different than touch [12]. This is mainly due to vibrations activating mechanoreceptors with a larger receptive field (Pacinian corpuscle) [42] and the fact that vibrations propagate for larger distances on the skin [9].

To overcome this, recent research has investigated vibrotactile perception on major body locations, e.g., forearm, upper arm, thigh, stomach, back, and leg [12]. Findings show that the spatial acuity of the body to vibrotactile stimulation follows a similar trend to touch regarding the sensitivity of body locations, however, with considerably different absolute values. To the best of our knowledge, a systematic investigation of vibrotactile perception on the palm remains unexplored. The palm is a prime location for vibrotactile feedback due to high sensitivity and the frequency with which we use our hands to interact with the environment. Therefore, this work is concerned with measuring vibrotactile perception on the palm—localization error of *stationary* vibrations and recognition rate of *moving* sensations across resolutions—to inform the main decisions associated with the design and usage of palm-based tactile displays. Although several factors affect vibrotactile perception, e.g. body site, choice of actuator, and actuator mounting conditions, prior work has identified that the main factors that affect localization at a particular body site to be the number and spacing of actuators [49].

P5.2.2 *Vibrotactile Illusions*

Tactile illusions have proven to be useful in HCI applications due to their ability to generate sensations where no physical actuator is present, thus rendering high resolution spatial vibrotactile stimuli using a low resolution grid of actuators. The three most common tactile illusions are *phantom sensations* [1, 35], *cutaneous rabbit* [13, 33, 39, 50], and *apparent tactile motion* [5, 22, 48]. Although all of these illusions can generate robust sensations, only *phantom sensations* have the ability to produce *stationary* and *moving* sensations. Therefore, in this work we use phantom sensations to increase the resolution of palm-based vibrotactile displays.

Also known as the funneling illusion, phantom sensations refer to the illusion where the perceived location of a vibration is controlled by varying intensity between two (1D phantom sensations) or more (2D phantom sensations) neighbouring vibrotactile actuators [1, 35]. Tactile interfaces have leveraged phantom sensations to generate expressive patterns. Mango [44], an authoring tool for creating vibrotactile patterns, uses direct manipulation of phantom sensations for designing and rendering 2D patterns. In Tactile Brush [20], an algorithm is proposed and validated that uses phantom sensations and apparent tactile motion to generate high resolution 2D vibrotactile strokes.

P5.2.3 *Stationary Sensations on the Palm*

There is a vast literature on work that has leveraged vibrotactile sensations on the body, e.g., on the hand [14–16, 26, 35], wrist [6, 24, 25, 27], forearm [28, 29, 38, 41, 45, 62], upperarm [2, 3, 51], back [20, 34, 52], stomach [23], thigh [50] and leg [7]. This section outlines the most relevant related work that focuses on *stationary* sensations on the palm.

P5.2.3.1 *Layout & Number of Actuators*

Palm-based tactile displays have taken many shapes, e.g.: spherical handles [43], square/diamond arrangements [40], and grids [2, 35, 60, 61]. The number of actuators ranged from one [59] to 30 [4] with inter-actuator spacing varying depending on the display. In our work, we systematically investigate the influence of the layout and number of actuators on the perception of *stationary* sensations.

P5.2.3.2 *Resolution*

Typically, prior work used a resolution that is defined by the number of real actuators on the palm [2, 40, 61]. However, approaches also exist that extend the resolution by leveraging phantom sensations [35, 43]. It is unclear, what the maximum resolution is, where accurate localization of *stationary* sensations is still possible. In our work, we systematically investigate the interdependency between localization accuracy and resolution and the extent to which phantom sensations can overcome the limits of physical resolution.

P5.2.4 *Moving Sensations on the Palm*

In addition to *stationary* sensations, many approaches in the literature were introduced that focus on evaluating the utility of *moving* tactile sensations [2, 19, 36, 47, 56–58].

Prior work has used many different resolutions for generating *moving* sensations on the palm, ranging between grids of four [47] to 12 actuators [19, 56–58]. Recognition rates of *moving* sensations vary from 70-80% [2, 56, 58] up to above 90% [2, 19, 57], depending on the number of patterns, actuators, and inter-actuator spacing. While most work focuses on discriminating between a set of distinct patterns [2, 19, 47, 56–58], some approaches were aimed at providing a display for continuous sensations [36].

In this paper, we aim to systematically investigate the influence of resolution on the vibrotactile perception (recognition rate) of users. This information is missing in the literature and is critical for the usage and design of palm-based vibrotactile displays.

P5.3 USER STUDY 1: STATIONARY TACTILE SENSATIONS

Spatial acuity of touch is different from that of vibrations [12]. To get a better understanding of how we perceive vibrotactile *stationary* sensations on the palm, this user study aimed to answer the following research questions:

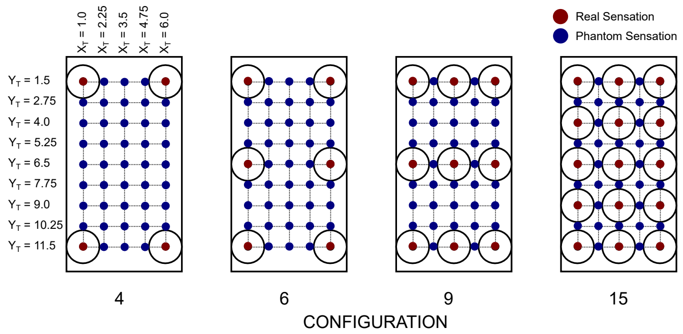


Figure P5.2: Independent variables of user study 1: CONFIGURATION, target X (X_T), and target Y (Y_T).

RQ1 How does the choice of configuration (number and layout of actuators) influence the localization accuracy and perception of vibrations? Prior work used many different configurations. It is unclear, how the choice of configuration effects the localization accuracy and perception of vibrations on the palm.

RQ2 How does the intensity of vibration affect the localization accuracy and perception of vibrations? We hypothesized that higher intensity vibrations increase localization error due to a wider area of propagation on the skin.

RQ3 The number of actuators and phantom sensations can increase the tactile resolution. How does the choice of resolution influence the localization accuracy? Prior work has utilized one resolution per configuration. It is unclear, how the choice of resolution influences the localization accuracy.

In this section, we describe our study design, the procedure, our participants, apparatus, dependent variables, and data analysis methods.

P5.3.1 *User Study Design*

Throughout the user study we varied the following four independent variables:

CONFIGURATION: The number of vibration motors in the palm-based tactile display. CONFIGURATION has 4 levels: 4, 6, 9, and 15 vibration motors. Figure P5.2 illustrates the placement of the vibration motors in the grid. We chose grids as they are most frequently used [2, 35, 60, 61] and because they enable the use of 2D phantom sensations [35]. The number of actuators was systematically varied by adding rows and columns.

INTENSITY: The intensity of the vibrations with 2 levels: 0.5 ($0.5 \cdot Amplitude_{max}$ of the EAI C2 tactor) and 1.0 (vibrations with maximum amplitude of the EAI C2 tactor). All vibrations were performed at a fixed frequency (200 Hz [35]) and lasted one second.

X_T: The stimulus position of the tactile sensation on the x-axis. X_T has 5 levels translating to 5 columns as shown in Figure P5.2. We chose 5 columns along the width of the palm based on prior work [35].

Y_T: The stimulus position of the tactile sensation on the y-axis. Y_T has 9 levels translating to 9 rows as shown in Figure P5.2. We chose 9 rows based on related work [35] and to keep the same spacing as the x-axis. Depending on the CONFIGUARTION, X_T, and Y_T, the stimulus was either a real or phantom sensation. For generating phantom sensations, we used the same approach as Park and Choi [35] as described in the next section.

The user study contained a total of 360 ($4 \times 2 \times 5 \times 9$) conditions and followed a within subjects study design. We used an 8×8 balanced latin square to counterbalance the variables CONFIGURATION and INTENSITY. For each combination of these independent variables, participants experienced 45 vibration locations (5×9). The order of these locations was randomized and each location was repeated only once, resulting in a total of 360 trials per participant.

P5.3.2 *Generation of Phantom Sensations*

To generate 1D and 2D phantom sensations we used an algorithm [35] that controls the intensities of four actuators arranged in a grid to interpolate between them. The vibration intensity of an actuator i is calculated using the following equation.

$$Intensity_i = Intensity_{target}(1 - \frac{d_i^x}{D^x})(1 - \frac{d_i^y}{D^y})$$

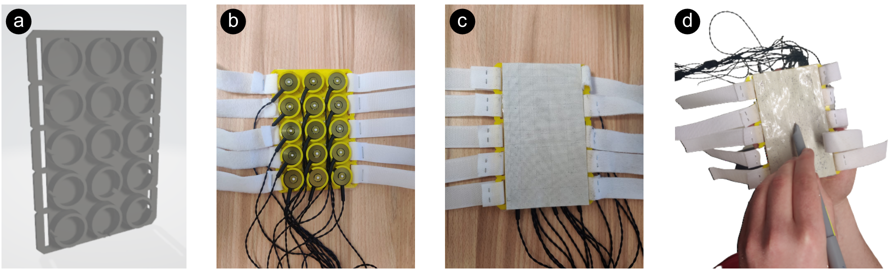


Figure P5.3: Apparatus used in user study 1: (a) 3D model of vibrotactile grid, (b&c) the grid from both sides, and (d) the smartpen used for input on the digital paper.

where d_i^x and d_i^y are the horizontal and vertical distances from the target point to actuator i, respectively. $Intensity_{target}$ is the target intensity of the phantom sensation. The algorithm is used to calculate the intensities of all four actuators involved in the generation of a 2D phantom sensation. In case of 1D phantom sensations, the actuators not involved in the generation of the sensation are inactive as $d^x = D^x$ or $d^y = D^y$.

P5.3.3 *Apparatus*

The prototype consisted of three parts: vibrotactile actuators, 3D printed case with smartpen paper attached to the backside, and a smartpen. We printed our prototype grids with a Prusa i3 MK3S+ using thermoplastic polyurethane (TPU) filament. The grids contained holders for attaching EAI C2 vibration motors [17]. Furthermore, the EAI C2 tactor featured a small contact spot (7.6 mm diameter) enclosed within a larger rigid cylindrical housing (30.5 mm diameter) that prevented the spread of vibration [49]. For input, we used a Neo Smartpen M1. A clear coating on top of the NeoLab paper prevented abrasion and visible marks of prior inputs. Five bands of Velcro tape on the sides of our prototypes allowed attachment on participants' palms while ensuring that all vibration motors are in contact with the skin. Figure P5.3 shows a prototype used in our experiment.

The prototype was connected to an i7 dual core 3.6 GHz 16 GB RAM desktop PC, which ran the software used in our user study. The software consisted of a C# project that received data from the smartpen over Bluetooth and controlled the vibration motors over USB.

P5.3.4 *Procedure*

After obtaining informed consent from the participants, we collected their demographic data. Then, we explained the task and provided a brief overview of the procedure. The task was to indicate the location of the vibration using the digital pen.

At the beginning, we asked participants to wear noise cancelling headphones playing white noise to prevent the sound of vibrations influencing their answers. Each trial started with the participant in a seated position with their hands resting on the armrest of the chair and their palm side up. All participants were right-handed and hence wore the grid on their left palm and held the pen in their right hand. After experiencing a vibration, the experimenter asked the participant if the vibration was at one location or more than one location. The experimenter explained to the participants that they should indicate after the number of perceived points after each trial before starting the experiment. Communication about the number of perceived points was accomplished using hand gestures so that participants were not required to remove the headphones after each trial. All stimuli were targeted at one location using real and phantom sensations. Participants were instructed to indicate a location in the middle if they perceived more than one vibration. Participants were further instructed to wait until the vibration was over before using the pen.

Participants took a break (approximately five minutes long) every 90 vibrations. This resulted in four breaks and a total duration of about 60 minutes for conducting the user study.

P5.3.5 *Dependent Variables*

The following dependent variables were measured:

EUCLIDEAN DISTANCE: The euclidean distance between the perceived and target location of the vibration.

X DEVIATION: The deviation on the x-axis between the target and perceived location.

Y DEVIATION: The deviation on the y-axis between target and perceived location.

ACCURACY: The accuracy of localizing target location. A response is considered correct when the closest point is the target location.

NUMBER OF PERCEIVED POINTS: The number of vibrations perceived by the user (binary: either one point or two or more points)

P5.3.6 *Participants*

We recruited 16 right-handed participants (12 male and 4 female) aged between 20 and 32 years old ($\mu = 23.19$, $\sigma = 2.88$). None of the participants had prior experience with vibrotactile feedback beyond the everyday use of smartphones and game controllers and no sensory processing disorders were reported by our participants.

P5.3.7 *Data Analysis*

After visually confirming that the data follows a normal distribution, we used four-way repeated measures (RM) ANOVAs with the factors CONFIGURATION, INTENSITY, X_T, and Y_T to compute the F-score and p-value of main and interaction effects. Where Mauchly's test indicated a violation of the assumption of sphericity, we used the Greenhouse Geisser method. We further report the generalized eta-squared η_g^2 as an estimate of the effect size and use Cohen's suggestions to classify the effect size as small, medium or large [11]. If significant effects were found, we used pairwise t-tests with Tukey adjustment for post-hoc analysis. Furthermore, we report the estimated marginal mean (EMM) with 95% confidence intervals as proposed by Searle et al. [46].

P5.4 USER STUDY 1: RESULTS

In the following, we report the results of our first user study as detailed in the prior section. We label key observations with **[MF-#]** for main effects and **[IF-#]** for interaction effects. The recorded location data is visualized in Figure P5.4.

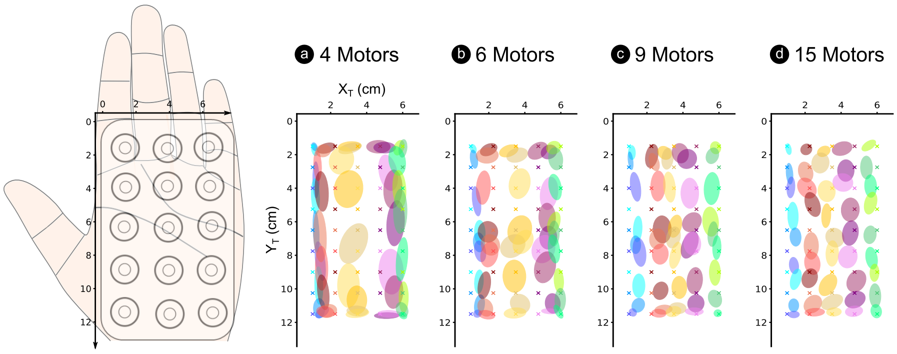


Figure P5.4: Error ellipses for (a) 4 MOTOR, (b) 6 MOTOR, (c) 9 MOTOR, and (d) 15 MOTOR CONFIGURATIONS based on the mean and covariance of point clouds at the different locations defined by X_T and Y_T ($\sigma = .5$).

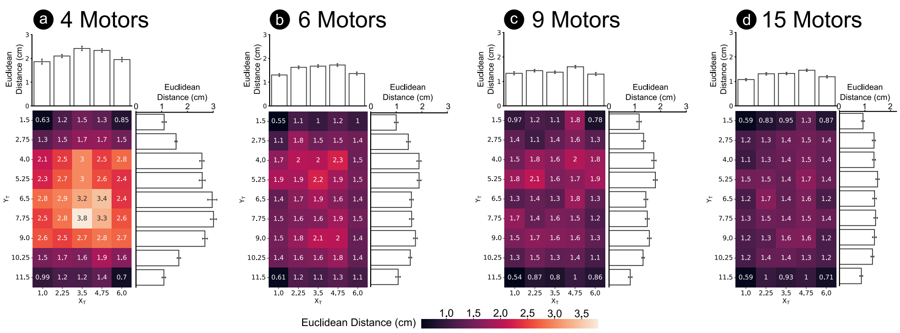


Figure P5.5: Illustration of the influence of the factors CONFIGURATION (a = 4 MOTOR, b = 6 MOTOR, c = 9 MOTOR, and d = 15 MOTOR), X_T, $Y_T$and the interactions CONFIGURATION:X_T and CONFIGURATION:Y_T on the euclidean distance. Error bars are the standard error.

P5.4.1 *Euclidean Distance*

To get an understanding of the influence of the factors on the general localization accuracy of users, we measured the euclidean distance between target locations (X_T and Y_T) and perceived locations. Figure P5.5 shows the results. Our analysis revealed no significant four-way and three-way interaction effects. We found two significant two-way interactions. In the following, we report the main effects and significant interaction effects.

P5.4.1.1 CONFIGURATION

[MF-1] The analysis showed a significant ($F_{1.54,23.09} = 45.53$, $p < .001$) main effect of the factor CONFIGURATION on the euclidean distance with a medium (η^2=.10) effect size. We found that the 15 MOTORS CONFIGURATION (EMM = 1.28cm [1.16cm, 1.40cm]) resulted in the lowest errors, followed by the 9 MOTORS CONFIGURATION (EMM = 1.41cm [1.30cm, 1.52cm]), the 6 MOTORS CONFIGURATION (EMM = 1.54cm [1.45cm, 1.63cm]), and finally the 4 MOTORS CONFIGURATION (EMM = 2.12cm [1.93cm, 2.31cm]). Post-hoc tests confirmed significant differences between the 4 MOTORS CONFIGURATION and all other CONFIGURATIONS ($p < .001$) and between the 6 MOTORS and 15 MOTORS CONFIGURATIONS ($p < .001$).

P5.4.1.2 INTENSITY

We could not find a significant main effect for the factor INTENSITY ($F_{1,15} = 1.16$, $p > 0.05$) on the euclidean distance between 0.5 INTENSITY (EMM = 1.60cm [1.50cm, 1.71cm]) and 1.0 INTENSITY (EMM = 1.57cm [1.49cm, 1.65cm]).

P5.4.1.3 X_T

[MF-2] Our analysis revealed a significant ($F_{2.95,44.23} = 11.13$, $p < .001$) main effect of the factor X_T on the euclidean distance with a small (η^2=.02) effect size. The euclidean distance was lowest for X_T at the edges of the vibration grid, X_T= 1.0 (EMM = 1.40cm [1.25cm, 1.54cm]), X_T= 6.0 (EMM = 1.45cm [1.29cm, 1.62cm]) and higher for locations in the middle: X_T= 2.25 (EMM = 1.62cm [1.53cm, 1.70cm]), X_T= 3.5 (EMM = 1.70cm [1.57cm, 1.82cm]), and X_T= 4.75 (EMM = 1.77cm [1.68cm, 1.87cm]).

P5.4.1.4 Y_T

[MF-3] The analysis revealed a significant ($F_{4.42,66.26}$ = 41.98, $p < .001$) main effect of the factor Y_T on the euclidean distance with a medium (η^2=.12) effect size. Similar to X_T, the lowest euclidean distances were at the top and bottom edges of the vibration grid: Y_T= 1.5 (EMM = 1.06cm [0.88cm, 1.23cm]) and Y_T= 11.5 (EMM = 0.97cm [0.83cm, 1.12cm]). Rows in the middle showed higher euclidean distances: Y_T= 2.75 (EMM = 1.43cm [1.33cm, 1.54cm]), Y_T= 4.0 (EMM = 1.88cm [1.75cm, 2.01cm]), Y_T= 5.25 (EMM = 1.94cm [1.80cm, 2.08cm]), Y_T= 6.5 (EMM = 1.84cm [1.66cm, 2.01cm]), Y_T= 7.75 (EMM = 1.88cm [1.71cm, 2.04cm]), Y_T= 9.0 (EMM = 1.83cm [1.70cm, 1.96cm]), and Y_T= 10.25 (EMM = 1.46cm [1.35cm, 1.57cm]).

P5.4.1.5 CONFIGURATION : X_T

[IF-1] The analysis showed a significant ($F_{5.74,86.07}$ = 2.30, $p < .05$) interaction effect between the factors CONFIGURATION and X_T with a small effect size (η^2=.01). The euclidean error depended on the combination of CONFIGURATION and X_T, with CONFIGURATIONS using a lower number of actuators (4 and 6) showing significant differences ($p < .05$) as X_T changes, and CONFIGURATIONS using a higher number of actuators (9 and 15) showing comparable performance ($p > .05$) across changing X_T.

P5.4.1.6 CONFIGURATION : Y_T

[IF-2] The analysis revealed a significant ($F_{24,360}$ = 9.12, $p < .001$) interaction effect between the factors CONFIGURATION and Y_T with a medium effect size (η^2=.06). The euclidean distance was significantly lower at the top and bottom edges of the grid for all CONFIGURATIONS. However, for CONFIGURATIONS using a lower number of actuators (4, 6, and 9), significant differences ($p < .05$) were observed in the range

$1.5 < Y_T < 11.5$, whereas the CONFIGURATION with the highest number of actuators (15) showed comparable performance ($p > .05$).

P5.4.2 *X Deviation*

To get a better understanding of the influence of the factors on users' ability to localize sensations along the width of the palm, we analyzed the deviations in the x-axis between the target and perceived locations.

P5.4.2.1 CONFIGURATION

[MF-4] The analysis revealed a significant ($F_{2,30.05} = 21.06$, $p < .001$) main effect of the factor CONFIGURATION on the recorded X deviation with a small (η^2=.02) effect size. We found that the 9 MOTORS CONFIGURATION (EMM = 0.64cm [0.58cm, 0.71cm]) resulted in the lowest errors, followed by the 15 MOTORS CONFIGURATION (EMM = 0.66cm [0.58cm, 0.74cm]), the 6 MOTORS CONFIGURATION (EMM = 0.77cm [0.70cm, 0.83cm]), and finally the 4 MOTORS CONFIGURATION (EMM = 0.86cm [0.78cm, 0.94cm]). Post-hoc tests confirmed significantly decreasing X deviation going from a lower number of actuators (4,6) to a higher number of actuators (9,15) ($p < .001$). X deviation was comparable for the CONFIGURATION pairs (4,6) and (9,15).

P5.4.2.2 INTENSITY

The analysis showed no significant ($F_{1,15} = 0.26$, $p > .05$) main effect of the factor INTENSITY on the X deviation. 0.5 INTENSITY (EMM = 0.73cm [0.66cm, 0.79cm]) showed comparable X deviation to 1.0 INTENSITY (EMM = 0.74cm [0.67cm, 0.80cm]).

P5.4.2.3 X_T

[MF-6] The analysis revealed a significant ($F_{2.84,42.61} = 23.51$, $p < .001$) main effect of the factor X_T on the X deviation with a medium (η^2=.10) effect size. The X deviation was lowest for X_T at the left X_T= 1.0 (EMM = 0.48cm [0.36cm, 0.60cm]) and right X_T= 6.0 (EMM = 0.50cm [0.37cm, 0.64cm]) edges of the vibration grid. Locations in the middle showed higher X deviation: X_T= 2.25 (EMM = 0.83cm [0.78cm, 0.88cm]), X_T= 3.5 (EMM = 0.84cm [0.71cm, 0.98cm]), and X_T= 4.75 (EMM = 1.00cm [0.93cm, 1.07cm]). Post-hoc confirmed signficantly rising X deviation going from the edges (X_T= 1.0, X_T= 6.0) towards the middle (X_T= 2.25, X_T= 3.5, X_T= 4.75) ($p < .001$).

P5.4.2.4 Y_T

We could not find a significant ($F_{4.67,70.09}$ = 1.71, $p > .05$) main effect of the factor Y_T on the recorded X deviation. Comparable values for X deviation were observed across all levels: Y_T= 1.5 (EMM = 0.68cm [0.62cm, 0.75cm]), Y_T= 2.75 (EMM = 0.70cm [0.64cm, 0.75cm]), Y_T= 4.0 (EMM = 0.75cm [0.68cm, 0.82cm]), Y_T= 5.25 (EMM = 0.75cm [0.69cm, 0.82cm]), Y_T= 6.5 (EMM = 0.79cm [0.69cm, 0.89cm]), Y_T= 7.75 (EMM = 0.74cm [0.65cm, 0.83cm]), Y_T= 9.0 (EMM = 0.73cm [0.65cm, 0.81cm]), Y_T= 10.25 (EMM = 0.74cm [0.65cm, 0.83cm]), and Y_T= 11.5 (EMM = 0.70cm [0.62cm, 0.79cm]).

P5.4.3 *Y Deviation*

To get a better understanding of the influence of the factors on users' ability to localize sensations along the length of the palm, we analyzed deviations in the y-axis between target and perceived locations.

P5.4.3.1 CONFIGURATION

[MF-7] The analysis showed a significant ($F_{1.66,24.87}$ = 37.23, $p < .001$) main effect of the factor CONFIGURATION on the Y deviation with a medium (η^2=.09) effect size. The 4 MOTOR CONFIGURATION resulted in the highest Y deviation (EMM = 1.75cm [1.56cm, 1.93cm]), followed by the 6 MOTOR CONFIGURATION (EMM = 1.15cm [1.07cm, 1.24cm]), the 9 MOTOR CONFIGURATION (EMM = 1.11cm [1.01cm, 1.21cm]), and finally the 15 MOTOR CONFIGURATION (EMM = 0.94cm [0.84cm, 1.04cm]). Post-hoc tests confirmed significant differences between the 4 MOTOR CONFIGURATION and all other CONFIGURATIONS ($p < .001$), between 6 and 15 ($p < .001$), and between 9 and 15 ($p < .05$).

P5.4.3.2 Intensity

We could not find a significant main effect for the factor INTENSITY ($F_{1,15}$ = 3.85, p > 0.05) on the Y deviation between 0.5 INTENSITY (EMM = 1.27cm [1.19cm, 1.34cm]) and 1.0 INTENSITY (EMM = 1.21cm [1.15cm, 1.27cm]).

P5.4.3.3 X_T

We could not find a significant main effect for the factor X_T ($F_{3.05,45.81}$ = 1.22, p > 0.05) on the Y deviation. We observed comparable Y deviation for X_T= 1.0 (EMM = 1.19cm [1.09cm, 1.29cm]), X_T= 2.25 (EMM = 1.21cm [1.13cm, 1.29cm]), X_T= 3.5 (EMM = 1.27cm [1.20cm, 1.34cm]), X_T= 4.75 (EMM = 1.27cm [1.20cm, 1.35cm]), and X_T= 6.0 (EMM = 1.24cm [1.13cm, 1.36cm]).

P5.4.3.4 Y_T

[MF-8] The analysis showed a significant ($F_{4.22,63.30}$ = 44.96, p < .001) main effect of the factor Y_T on the Y deviation with a large (η^2=.16) effect size. Y deviation was lowest at the top Y_T= 1.5 (EMM = 0.62cm [0.43cm, 0.81cm]) and the bottom Y_T= 11.5 (EMM = 0.48cm [0.33cm, 0.62cm]) rows of the grid. Rows in the middle showed higher Y deviation values: Y_T= 2.75 (EMM = 1.11cm [0.98cm, 1.23cm]), Y_T= 4.0 (EMM = 1.58cm [1.45cm, 1.72cm]), Y_T= 5.25 (EMM = 1.63cm [1.49cm, 1.77cm]), Y_T= 6.5 (EMM = 1.48cm [1.30cm, 1.66cm]), Y_T= 7.75 (EMM = 1.57cm [1.42cm, 1.72cm]), Y_T= 9.0 (EMM = 1.54cm [1.42cm, 1.67cm]), and Y_T= 10.25 (EMM = 1.12cm [1.02cm, 1.23cm]). Post-hoc tests confirmed significantly rising Y deviation from the top and bottom (Y_T= 1.5, Y_T= 11.5), to the next two rows (Y_T= 2.25, Y_T= 10.25) (p < .01), and between Y_T= 2.25, Y_T= 10.25 and all other rows in the middle (p < .05).

P5.4.4 *Accuracy*

We analyzed the accuracy of localizing the target positions. To get a better overview, we further filtered the data to measure the accuracy of reducing from 5 columns to 3 and 2 equally spaced columns. Similarly,

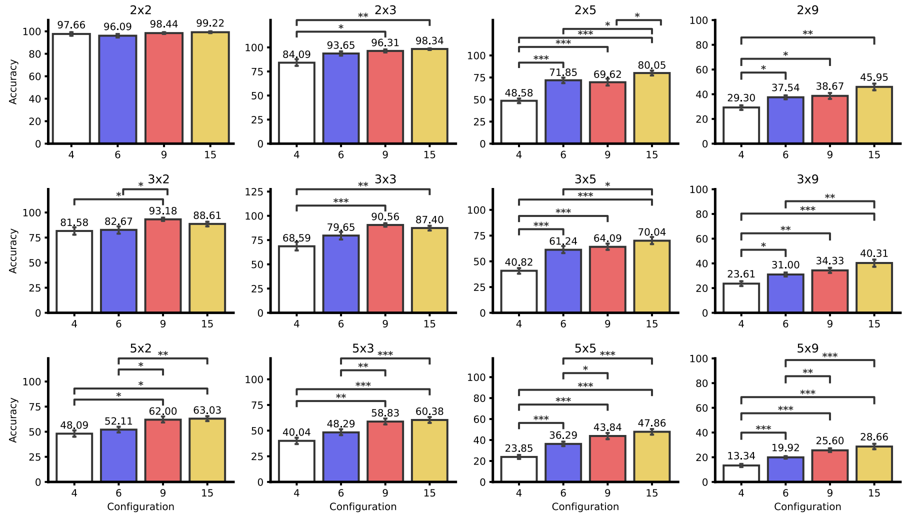


Figure P5.6: Localization accuracy of stationary sensations on the palm across different resolutions. Error bars are the standard errors. Results from post-hoc pairwise comparisons are shown (* $\leq$ 0.05, ** $\leq$ 0.01, *** $\leq$ 0.001)

Resolution (X*Y)	F	df	p	η^2_g	CONFIGURATION (EMM [lower CL, upper CL]) 4	6	9	15
2x2	1.00	2.54, 38.12	.393	.041	97.7% [94.0%, 100%]	96.1% [92.1%, 100%]	98.4% [96.2%, 100%]	99.2% [97.6%, 100%]
2x3	9.08	1.58, 23.70	.002	.273	84.1% [76.6%, 91.6%]	93.6% [88.6%, 98.7%]	96.3% [93.1%, 99.6%]	98.3% [96.4%, 100%]
2x5	33.46	2.32, 34.80	.001	.455	48.6% [42.7%, 54.5%]	71.8% [64.8%, 78.9%]	69.6% [61.2%, 78.0%]	80.0% [73.6%, 86.5%]
2x9	11.09	2.64, 39.55	.001	.322	29.3% [25.3%, 33.3%]	37.5% [34.1%, 40.9%]	38.7% [33.9%, 43.5%]	46.0% [39.8%, 52.1%]
3x2	3.78	2.36, 35.41	.026	.137	81.6% [73.5%, 89.7%]	82.7% [74.7%, 90.7%]	93.2% [89.5%, 96.9%]	88.6% [83.7%, 93.5%]
3x3	11.47	2.23, 33.43	.001	.296	68.6% [59.1%, 78.1%]	79.6% [71.2%, 88.1%]	90.6% [86.6%, 94.6%]	87.4% [82.1%, 92.7%]
3x5	31.50	2.68, 40.16	.001	.441	40.8% [35.1%, 46.5%]	61.2% [53.7%, 68.8%]	64.1% [57.4%, 70.7%]	70.0% [62.8%, 77.3%]
3x9	14.63	2.37, 35.61	.001	.332	23.6% [19.6%, 27.6%]	31.0% [27.3%, 34.7%]	34.3% [29.8%, 38.8%]	40.3% [34.1%, 46.5%]
5x2	9.12	2.39, 35.78	.001	.237	48.1% [41.5%, 54.7%]	52.1% [45.7%, 58.5%]	62.0% [55.5%, 68.5%]	63.0% [57.5%, 68.6%]
5x3	17.74	2.09, 31.35	.001	.335	40.0% [33.2%, 46.9%]	48.3% [42.0%, 54.6%]	58.8% [52.5%, 65.2%]	60.4% [54.2%, 66.5%]
5x5	31.79	2.40, 36.05	.001	.463	23.9% [19.8%, 27.9%]	36.3% [31.7%, 40.8%]	43.8% [37.2%, 50.5%]	47.9% [41.9%, 53.9%]
5x9	32.82	2.02, 30.35	.001	.481	13.3% [10.7%, 16.0%]	19.9% [17.9%, 22.0%]	25.6% [22.1%, 29.1%]	28.7% [24.0%, 33.3%]

Table P5.1: Results of RM-ANOVAs for the factor CONFIGURATION on the dependent variable accuracy.

reducing from 9 rows to 5, 3, and 2 equally spaced rows. For each resolution, we conducted a RM-ANOVA with the factors CONFIGURATION and INTENSITY. The factor INTENSITY did not have a significant effect on the accuracy of any of the resolutions. Table P5.1 summarizes the results of the RM-ANOVAs for the factor CONFIGURATION. Figure P5.6 visualizes the accuracy across varying resolution and the post-hoc tests.

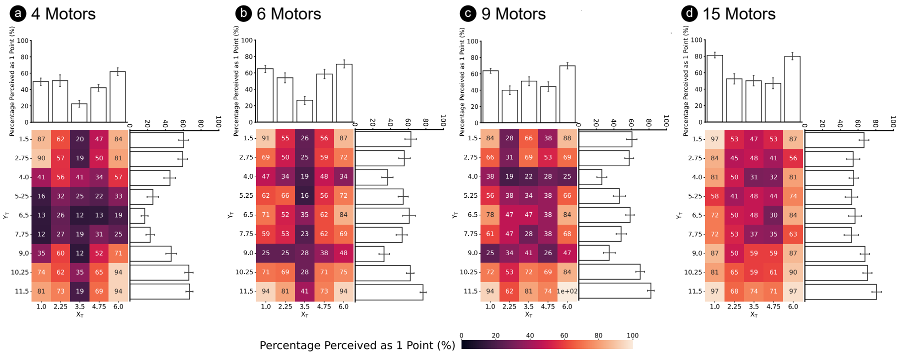


Figure P5.7: Probability of perceiving a single point for the factors CONFIGURATION (a = 4 MOTOR, b = 6 MOTOR, c = 9 MOTOR, and d = 15 MOTOR), X_T, and Y_T. Error bars are the standard errors.

P5.4.5 *Number of Perceived Points*

We analyzed the binary dependent variable number of perceived points. Therefore, we used a logistic mixed model, estimated with ML and BOBYQA optimizer, with the fixed effects CONFIGURATION, INTENSITY, X_T, and $Y_T$while including the participant as a random effect. The explanatory power [21] of the model was substantial $R^2 =$ 0.31 and the part related to the fixed effects alone -marginal R^2- was 0.18. We computed the 95% confidence intervals and p-values using the Wald approximation. Figure P5.7 visualizes the results.

P5.4.5.1 CONFIGURATION

[MF-9] The analysis revealed a significant ($\chi^2(3) = 100.47$, p < .001) main effect of the factor CONFIGURATION on the number of perceived points. The 15 MOTOR CONFIGURATION resulted in the highest probability (EMM = 65.7% [56.3%, 74.1%]) of perceiving vibration at a single location, followed by the 6 MOTOR CONFIGURATION (EMM = 56.8% [46.9%, 66.2%]), the 9 MOTOR CONFIGURATION (EMM = 55.2% [45.3%, 64.7%]), and finally the 4 MOTOR CONFIGURATION (EMM = 44.5% [35.1%, 54.5%]). Post-hoc pairwise contrasts confirmed all differences to be significant (p < .001) except between the 6 and 9 MOTOR CONFIGURATIONS.

P5.4.5.2 INTENSITY

[MF-10] The analysis showed a significant ($\chi^2(1) = 14.75$, $p < .001$) main effect of the factor INTENSITY on the number of perceived points between 0.5 INTENSITY (EMM = 58.6% [48.9%, 67.6%]) and 1.0 INTENSITY (EMM = 52.8% [43.1%, 62.3%]).

P5.4.5.3 X_T

[MF-11] The analysis showed a significant ($\chi^2(4) = 372.676$, $p < .001$) main effect of the factor X_T on the number of perceived points. The right X_T= 6.0 (EMM = 74.6% [66.2%, 81.5%]) edge resulted in the highest probability of perceiving a single point, followed by the left X_T= 1.0 (EMM = 68.3% [59.0%, 76.3%]) edge, and columns in the middle: X_T= 2.25 (EMM = 49.5% [39.7%, 59.4%]), X_T= 4.75 (EMM = 48.3% [38.5%, 58.3%]), and X_T= 3.5 (EMM = 35.2% [26.6%, 44.8%]). Post-hoc tests confirmed all pairwise contrasts as significant ($p < .001$) except the pair X_T= 2.25 and X_T= 4.75 ($p > .05$).

P5.4.5.4 Y_T

[MF-12] The analysis showed a significant ($\chi^2(8) = 359.388$, $p < .001$) main effect of the factor Y_T on the number of perceived points. The bottom part of the grid resulted in the highest probability of perceiving a single point Y_T= 11.5 (EMM = 81.2% [73.8%, 86.9%]) and Y_T= 10.25 (EMM = 71.2% [61.8%, 79.0%]). Followed by the rows at the top: Y_T= 1.5 (EMM = 65.5% [55.6%, 74.3%]) and Y_T= 2.75 (EMM = 58.3% [47.9%, 68.0%]). Finally, we observed comparable performance for the rows in the middle: Y_T= 4.0 (EMM = 38.9% [29.6%, 49.2%]), Y_T= 5.25 (EMM = 43.9% [34.0%, 54.3%]), Y_T= 6.5 (EMM = 48.0% [37.8%, 58.4%]), Y_T= 7.75 (EMM = 43.0% [33.2%, 53.4%]), and Y_T= 9.0 (EMM = 44.4% [34.4%, 54.8%]). Post-hoc tests confirmed significantly rising probability of one point perceived between the middle rows and the top rows ($p < .001$) and between the top rows and the bottom rows ($p < .001$).

P5.5 USER STUDY 1: DISCUSSION

In the following, we discuss the findings from the first user study.

P5.5.1 CONFIGURATION

In general, localization accuracy increased as the number of actuators increased ([MF-1], [MF-4], [MF-7]). Observing spatial error metrics measured in our experiment, the usage of 9 actuators with a spacing of 2.5 cm along the width of the palm and 5 cm along the length is enough for accurate stationary sensations. Although euclidean distance was lowest using 15 actuators, the results of using 9 actuators were comparable, with no significant difference. Reducing to 6 actuators, however, results in a significant increase in euclidean errors (20%) in comparison to 15 actuators ([MF-1]). Moreover, the additional column of actuators using 9 actuators decreases the X deviation significantly compared to configurations with a lower number of actuators, while being comparable to the configuration with 15 actuators ([MF-4]). Although the Y deviation is significantly lower with 15 actuators compared to 9 actuators ([MF-7]), this only results in a significant decrease in localization accuracy for the 2×5 resolution (Figure P5.6). For all other resolutions, localization accuracy with 9 actuators was comparable to 15 actuators.

INSIGHT-1 9 actuators result in comparable localization performance of *stationary* sensations as 15 actuators.

Regarding the perception of phantom sensations at a single location, results indicate that a 15 MOTOR CONFIGURATION results in significantly higher probability of perceiving phantom sensations at a single location than all other CONFIGURATIONS ([MF-9]). Although the probability of perceiving a single point is relatively low (65%), this can be due to the fact that by asking the participants if they perceived a single point or multiple points, it is implied that multiple points can occur and participants are more inclined to say multiple points if they are in doubt. We calculated the probability of perceiving a single point with real sensations (always caused by a single actuator), and observed a probability of 75% of users expressing that they felt a single point.

INSIGHT-2 15 actuators result in improved perception of phantom sensations at a single location.

P5.5.2 X_T & Y_T

We observed a systematic behaviour, where participants tend to localize vibrations closer to the edge of the device, leading to higher localization accuracies of locations at the edges and lower localization accuracies for locations in the middle ([MF-2], [MF-3], [MF-6], [MF-8]). A possible explanation for this behaviour is that with a lower number of actuators, phantom sensations are not perceived correctly at a single location and instead are perceived at the positions of the actuators generating them which are typically at the edges of the device (see Section P5.5.1, [**insight-2**]). We observed interaction effects supporting this ([IF-1], [IF-2]), where lower number of actuators show significant differences between locations at the edges and locations in the middle, and higher number of actuators show comparable performance across all locations – indicating correct perception of phantom sensations at target location.

INSIGHT-3 9 and 15 actuators led to more accurate localization at target location. 4 and 6 actuators led to more frequent localization at the edges.

Furthermore, results show that the X deviation values are considerably lower than the Y deviation values. This indicates that users could localize stationary sensations along the width of the palm more accurately than along the length. This is in line with prior work on localization accuracy of vibrotactile sensations on other body parts [12], where a transverse orientation resulted in better localization than a longitudinal orientation.

INSIGHT-4 Localizing sensations along the width of the palm is more accurate than along the length.

Lastly, we analyzed users' ability to correctly localize stationary sensations with varying resolution. Observing the relationship between resolution and accuracy, it is clear that there is a trade-off between high accuracy and the number of distinct locations that can be localized as defined by the resolution. Typically, an application would require high accuracy (> 90%) of localizing stationary sensations while still maintaining a reasonable resolution. A 3x3 resolution allows for identifying 9 different locations and maintains a high accuracy of localization (91% for the 9 MOTOR CONFIGURATION, see Figure P5.6).

INSIGHT-5 A 3×3 resolution can be accurately recognised.

P5.5.3 INTENSITY

INTENSITY of the vibrations does not seem to have an influence on participants' ability to localize stationary tactile sensations. However, we observed a significant increase in the probability of perceiving a single point when using a lower INTENSITY ([MF-10]). This is due to the fact that by increasing the intensity of the vibration, the positions of the actuators become more pronounced which affects the perception of phantom sensations.

INSIGHT-6 Lower intensity vibrations result in improved perception of phantom sensations at a single location.

P5.5.4 *Comparison Between Touch and Vibrotactile Stimulation*

A two-point discrimination threshold of approximately 0.8 cm was observed for touch on the palm [31]. Our findings show that for successful two-point discrimination of vibrotactile stimulation, a spacing of approximately 2.8 cm is required. This is calculated based on the upper CL of the euclidean distance with 15 actuators multiplied by two, to account for localization error of two locations. These values deviate considerably, highlighting the importance of basing design decisions for vibrotactile displays on vibrotactile perception.

INSIGHT-7 Vibrotactile sensitivity on the palm deviates considerably from touch.

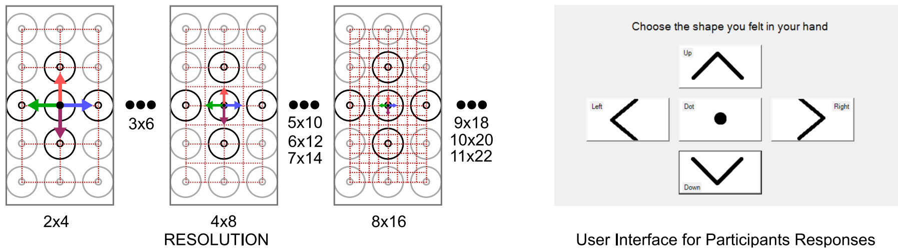


Figure P5.8: Study 2 evaluates 10 resolutions for *moving* tactile sensations with a 15 motor configuration. Each *moving* phantom sensation starts at the center motor and moves one step on the virtual resolution grid in one of four directions.

P5.6 USER STUDY 2: MOVING TACTILE SENSATIONS

Based on the results of the first user study, we conducted a second user study to investigate moving tactile sensations. In particular, we aimed to answer the following research questions:

RQ1 How does the resolution effect recognition accuracy of users? Prior work explored a variety of resolutions for *moving* sensations [19, 47, 56–58]. It is currently unclear, what the limits for accurate perception are.

RQ2 How does the resolution influence reaction time of users? We hypothesized that higher resolutions are more difficult to perceive and and hence lead to higher reaction times.

In the following, we detail on the study design, the procedure, apparatus, participants, dependent variables, and data analysis methods.

P5.6.1 *User Study Design*

We varied the RESOLUTION of the vibrotactile grid and the DIRECTION of the sensation in a within-subject study design. Figure P5.8 illustrates these independent variables. RESOLUTION had 10 levels: 2×4, 3×6, 4×8, 5×10, 6×12, 7×14, 8×16, 9×18, 10×20, and 11×22. We aimed to cover a wide spectrum in RESOLUTION for a better understanding of users' performance. DIRECTION had 4 levels: RIGHT, LEFT, UP, and DOWN. All sensations started at the middle actuator as shown in Figure P5.8 and moved a distance equivalent to one cell in the respective RESOLUTION. The speed of the sensation was fixed at 0.5cm/s. We informally tested the influence of speed in pilot tests and found no difference in perception in the range 0.1-2cm/s. Inter-actuator spacing was fixed at 2.5 cm, which resulted in robust 1D phantom sensations from extensive pilot tests and based on prior work [36].

This resulted in a total of 40 (10×4) conditions. We used a 10×10 balanced latin square to counterbalance the variable RESOLUTION. For each RESOLUTION, we randomized the order of appearance of the variable DIRECTION. Each condition was repeated three times, resulting in a total of 120 trials per participant

P5.6.2 *Procedure*

Similar to the first user study, participants were welcomed to the lab, given a brief overview of the task, asked to sign an informed consent, and to fill out a short demographic questionnaire.

Participants wore noise cancelling headphones playing white noise throughout the experiment. The vibrotactile grid was attached to their dominant hand. At the beginning, a few (< 10) test trials were conducted to familiarize the participant with the task that were not recorded. Afterwards, participants began the experiment. The task was to feel a vibration and indicate if it was moving and in which direction. The participants experienced sensations that moved in the DIRECTIONS UP, DOWN, RIGHT, and LEFT. However, an additional response was possible of feeling a point (Figure P5.8) to indicate if they could not determine the direction.

Participants took a break (approximately five minutes long) after completing five different RESOLUTIONS. In total, the experiment lasted about 20 minutes.

P5.6.3 *Apparatus*

We used the 15 MOTOR CONFIGURATION (for better perception of phantom sensations) throughout the experiment with the same hardware as the first user study. A pop-up window after each sensation was displayed to the users for inputting their response as shown in Figure P5.8.

P5.6.4 *Dependent Variables*

We recorded the following dependent variables:

ACCURACY: whether the correct direction was identified.

X ACCURACY: whether the correct direction was identified for left and right.

Y ACCURACY: whether the correct direction was identified for up and down.

TASK COMPLETION TIME (TCT): the time between the end of the vibration and the user's response.

P5.6.5 *Participants*

We recruited 20 participants (15 male, 4 female, and 1 identified as gender variant), aged between 21 and 32 years old ($\mu = 23.75$, $\sigma = 2.69$). 19 of our participants were right-handed and one participant was left-handed. Participants reported no prior haptic feedback experience beyond the use of everyday smartphones and game controllers. All our participants reported no sensory processing disorders.

P5.6.6 *Data Analysis*

For the analysis of the binary dependent variable accuracy, we used a logistic mixed model, estimated with ML and BOBYQA optimizer, with the fixed effects RESOLUTION and DIRECTION, and including the participant as a random effect. For computing the confidence intervals and the p-values, we used the Wald approximation.

For the analysis of the continuous variable task completion time, we used a two-way RM-ANOVA with the factors RESOLUTION and DI-

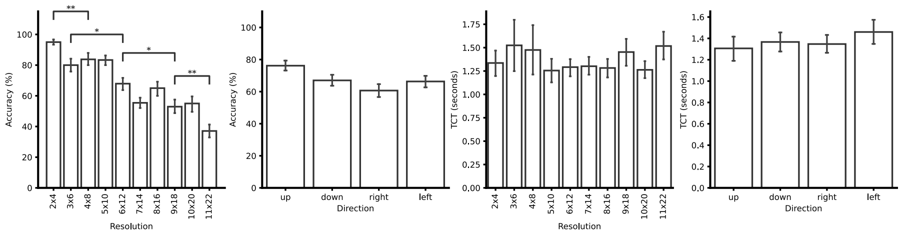


Figure P5.9: Accuracy and TCT for the factors RESOLUTION and DIRECTION. Error bars are the standard error. Results from post-hoc pairwise comparisons are shown (* $\leq$ 0.05, ** $\leq$ 0.01).

RECTION, to compute the F-score and p-value of main and interaction effects. We used the same method for spherecity correction (Greenhouse–Geisser) and report the generalized eta-squared as in the first user study. For post-hoc tests, we used pairwise t-tests with Tukey adjustment.

Similar to the first user study, we report the EMMs with the 95% confidence intervals.

P5.7 USER STUDY 2: RESULTS

This section reports the results of the second user study investigating *moving* tactile sensations. Key observations are labelled with **[MF-#]** for main effects and **[IF-#]** for interaction effects.

P5.7.1 *Accuracy*

We analyzed the accuracy of users in identifying the direction of tactile sensation on the palm. Figure P5.9 illustrates the results. The explanatory power of the model was substantial $R^2 = 0.34$ and the part related to the fixed effects alone (marginal R^2) was 0.27.

P5.7.1.1 RESOLUTION

[MF-13] Our analysis revealed a significant ($\chi^2(9) = 86.96$, p < .001) main effect of the factor RESOLUTION on the probability of correctly perceiving the moving sensation. The highest accuracy was achieved by the 2 × 4 RESOLUTION (EMM = 96.2% [92.4%, 98.1%]), followed by 5 × 10 (EMM = 85.4% [79.0%, 90.1%]), 4 × 8 (EMM = 85.3% [79.0%, 90.0%]), 3 × 6 (EMM = 83.2% [76.1%, 88.5%]), 6 × 12 (EMM = 69.7% [61.1%, 77.2%]), 8x16 (EMM = 66.4% [57.5%, 74.2%]), 10 × 20 (EMM = 56.4% [47.0%, 65.3%]), 7 × 14 (EMM = 56.0% [46.8%, 64.8%]), 9 × 18 (EMM = 53.3% [44.1%, 62.2%]), and 11 × 22 (EMM = 35.6% [27.4%, 44.7%]). Post-hoc tests are summarized in Figure P5.9.

P5.7.1.2 Direction

We could not find a significant main effect of the factor DIRECTION on accuracy ($\chi^2(3) = 1.97$, $p > .05$). The accuracy was comparable between the DIRECTIONS UP (EMM = 79.9% [73.9%, 84.7%]), DOWN (EMM = 74.2% [66.6%, 80.7%]), LEFT (EMM = 71.3% [64.0%, 77.7%]), and RIGHT (EMM = 64.8% [57.0%, 71.8%]).

P5.7.2 *X Accuracy*

We analyzed the accuracy of users for the DIRECTIONS RIGHT and LEFT. The explanatory power of the model was $R^2 = 0.38$ and the marginal R^2 was 0.26.

P5.7.2.1 Resolution

[MF-14] Our analysis revealed a significant ($\chi^2(9) = 79.67$, $p < .001$) main effect of the factor RESOLUTION on the X accuracy. The 2 × 4 RESOLUTION resulted in the highest X accuracy (EMM = 95.5% [90.0%, 98.1%]), followed by 5 × 10 (EMM = 89.9% [82.0%, 94.6%]), 4 × 8 (EMM = 84.3% [74.7%, 90.8%]), 3 × 6 (EMM = 73.4% [61.4%, 82.6%]), 6 × 12 (EMM = 63.5% [50.6%, 74.7%]), 8 × 16 (EMM = 61.6% [48.6%, 73.1%]), 7 × 14 (EMM = 53.1% [40.1%, 65.7%]), 9 × 18 (EMM = 50.1% [37.4%, 62.9%]), 10 × 20 (EMM = 46.3% [33.8%, 59.3%]), and 11 × 22 (EMM = 27.6% [18.1%, 39.8%]). Figure P5.10 displays the result of post-hoc pairwise comparisons.

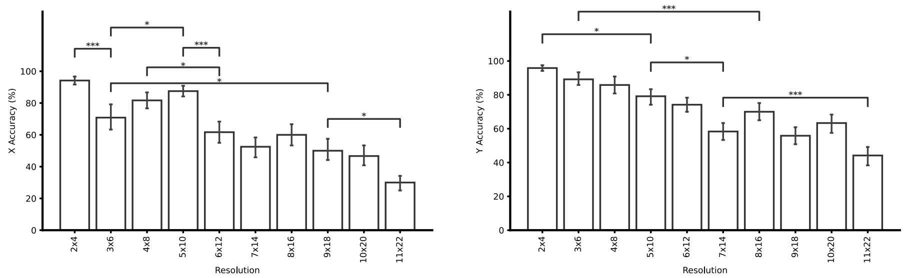


Figure P5.10: X accuracy and Y accuracy for the factor RESOLUTION. Error bars are the standard error. Results from post-hoc pairwise comparisons are shown (* ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001).

P5.7.2.2 DIRECTION

We could not find a significant effect of the factor DIRECTION on the X accuracy between LEFT (EMM = 72.3% [63.2%, 79.8%]) and RIGHT (EMM = 65.5% [55.7%, 74.1%]) ($\chi^2(1) = 0.16$, p > .05).

P5.7.3 *Y Accuracy*

We analyzed the accuracy of users for the DIRECTIONS UP and DOWN. The explanatory power of the model was $R^2 = 0.33$ and the marginal R^2 was 0.26.

P5.7.3.1 RESOLUTION

[MF-15] Our analysis revealed a significant ($\chi^2(9) = 85.25$, p < .001) main effect of the factor RESOLUTION on the Y accuracy. The 2×4 RESOLUTION resulted in the highest Y accuracy (EMM = 97.1% [91.4%, 99.0%]), followed by 3×6 (EMM = 90.3% [83.1%, 94.6%]), 4×8 (EMM = 87.2% [79.1%, 92.4%]), 5×10 (EMM = 80.9% [71.5%, 87.7%]), 6×12 (EMM = 75.8% [65.7%, 83.7%]), 8×16 (EMM = 71.3% [60.7%, 79.9%]), 10×20 (EMM = 65.7% [54.3%, 75.6%]), 7×14 (EMM = 59.0% [47.8%, 69.3%]), 9×18 (EMM = 56.4% [45.2%, 67.0%]), and 11×22 (EMM = 43.2% [32.4%, 54.7%]). Figure P5.10 shows the result of post-hoc pairwise comparisons.

P5.7.3.2 Direction

We could not find a significant effect of the factor DIRECTION on the X accuracy between DOWN (EMM = 74.2% [66.5%, 80.6%]) and UP (EMM = 79.8% [73.9%, 84.6%]) ($\chi^2(1) = 1.66$, p > .05).

P5.7.4 *Task Completion Time (TCT)*

We analyzed the time between the end of the stimulus and users' response.

P5.7.4.1 Resolution

We could not find a significant main effect of the factor RESOLUTION on the TCT ($F_{3.25,61.69}$ = 0.52, p > .05). TCT was comparable across RESOLUTIONS. The highest TCT was observed for 11×22 (EMM = 1.52s [1.21s, 1.83s]) and 3×6 (EMM = 1.52s [0.92s, 2.13s]), followed by 4×8 (EMM = 1.48s [0.91s, 2.05s]), 9×18 (EMM = 1.45s [1.15s, 1.76s]), 2×4 (EMM = 1.34s [1.05s, 1.62s]), 7×14 (EMM = 1.30s [1.09s, 1.49s]), 6×12 (EMM = 1.29s [1.10s, 1.49s]), 8×16 (EMM = 1.28s [1.07s, 1.50s]), 10×20 (EMM = 1.26s [1.06s, 1.46s]), and 5×10 (EMM = 1.25s [0.99s, 1.52s]).

P5.7.4.2 Direction

We could not find a significant main effect of the factor DIRECTION on TCT ($F_{2.17,41.30}$ = 0.79, p > .05). TCT was comparable for the DIRECTIONS UP (EMM = 1.31s [1.06s, 1.55s]), DOWN (EMM = 1.37s [1.18s, 1.56s]), LEFT (EMM = 1.46s [1.22s, 1.70s]), and RIGHT (EMM = 1.35s [1.16s, 1.53s]).

P5.8 USER STUDY 2: DISCUSSION

In the following, we discuss the findings of our second user study.

P5.8.1 RESOLUTION

In general, findings from our second user study show that more fine-grained resolutions are possible for *moving* sensations in comparison to resolutions for vibrotactile point localization. This is consistent with related work on touch [31], where the localization of successive stimuli on the skin was better than simultaneous stimuli.

Our findings (MF-13) show that a 2×4 resolution results in 96.2% correct recognition rate of the four directions UP, DOWN, RIGHT, and LEFT. This is equivalent to a motion of 2.5 cm on the palm. On the other hand, although a 5×10 resolution resulted in a significant decrease in recognition accuracy ([MF-13], [MF-15]) compared to a 2×4 resolution, we still observed a 85.4% recognition rate of the four directions investigated in the user study. With this resolution, tactile motion equivalent to 1.0 cm can be accurately recognized. These results apply to tactile motion generated with 1D phantom sensations. While 1D phantom sensations are frequently used in the literature, further work is required for determining appropriate resolutions for 2D phantom sensations and other tactile illusions.

INSIGHT-8 A 2×4 resolution results in high recognition accuracy (96.2%).

INSIGHT-9 A 5×10 resolution enables higher resolution output while still maintaining high accuracy (85.4%).

P5.8.2 DIRECTION

Findings from the first user study unveiled a higher localization accuracy along the width of the palm in comparison to the length. This effect does not seem to apply to *moving* sensations. We found comparable recognition rates for vertical and horizontal directions across RESOLUTION.

P5.8.3 *Comparison Between Touch and Vibrotactile Stimulation*

Typically, spatial acuity is measured by two-point discrimination thresholds. However, experiments were also conducted that measured the perception of successive spatially distributed stimuli [31] – similar to motion on the skin. Results show that for touch on the palm, successive stimuli (0.5 cm threshold) are discriminated more easily than simultaneous stimuli (0.8 cm threshold). This trend is present in our results on vibrotactile stimulation, however, with considerably different absolute values (1 cm to 2.5 cm for *moving* and 2.8 cm for *stationary*). This is further confirmed by the high recognition accuracies we observed for *moving* sensations with a length well below the localization accuracy of *stationary* sensations.

INSIGHT-10 Higher vibrotactile sensitivity was observed for *moving* compared to *stationary* sensations.

P5.9 APPLICATIONS OF PALM-BASED TACTILE DISPLAYS

Stationary and *moving* tactile sensations on the palm have many potential applications in the future (see Figure P5.11). These include high-resolution tactile feedback in video games and VR controllers to create more immersive experiences by simulating the exact contact points and shapes. The handlebar of a bicycle and the steering wheel of a car could embed haptic actuators to give precise feedback of the surrounding (e.g., by communicating the exact location of other cars through vibrations) or navigation (e.g., by drawing the exact path the user needs to take on the user's palm through a *moving* sensation). Finally, traditional input devices such as mouse or pen input could be improved by haptic gestures that allow for a more *expressive* and higher resolution tactile output. These applications can benefit from the knowledge gained by our experiments by implementing the following design implications.

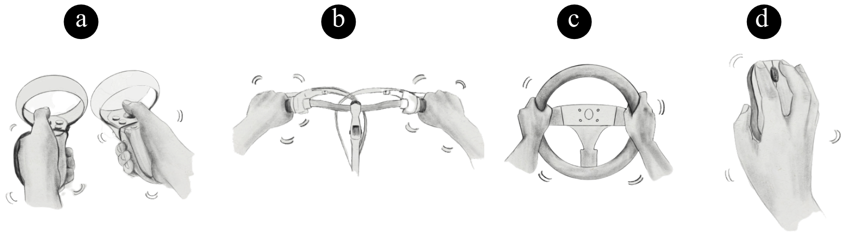


Figure P5.11: High-resolution palm-based tactile displays are applicable to many situations and can be embedded in a diverse set of devices, e.g., (a) VR controllers, (b) bicycle handlebar, (c) car steering wheel, and (d) computer mouse.

P5.10 DESIGN GUIDELINES FOR PALM-BASED TACTILE DISPLAYS

In this section, we outline design guidelines derived based on the findings of our controlled user studies. These guidelines are aimed at two main interaction requirements: *accurate* and *expressive* sensations. An example application where *accurate* interactions are required is pedestrian navigation [60] or generally for *accurate* communication of a *discrete* set of instructions [2]. For these situations, *accurate* sensations are required.

On the other hand, more *expressive* interaction is required for applications such as the communication of social touch [18] or generally for the communication of a more diverse set of *continuous* sensations [20] with more relaxed accuracy constraints. An example of this type of interaction in the context of *stationary* sensations would be augmenting videos on handheld displays with vibrotactile feedback. An object appears on the scene and the user can feel it at the correct location on the hand. In this case, *discrete* identification of a set of locations would not be the best approach. A tactile display with the ability to generate higher resolution sensations should be preferred.

For *stationary* vibrotactile sensations, we derive the following design guidlines (DG):

DG-1 A smaller (approximately 2:1 ratio) inter-actuator spacing should be used along the width of the palm than the length. [**insight-4**]

DG-2 A 3×3 grid of points can be used for significantly *accurate* interactions on the palm. [**insight-5**]

DG-3 Favor the use of a tactile display consisting of nine actuators with a spacing of 2.5 cm along the width and 5 cm along the length for *accurate* interactions. [**insight-1**, **insight-4**]

DG-4 A high number (spacing $\leq$ 2.5 cm) of actuators should be used for *expressive* interactions. [**insight-1**, **insight-2**, **insight-3**]

DG-5 Lower intensity vibrations result in a higher probability of perceiving a phantom sensation at a single location. [**insight-6**]

For *moving* tactile sensations we derive the following guidelines:

DG-6 *Accurate* interactions with *moving* sensations can be achieved with a 2×4 resolution. [**insight-8**]

DG-7 A resolution of 5×10 maintains a reasonable recognition accuracy. This resolution can be used to generate more *expressive* sensations. [**insight-9**]

P5.11 LIMITATIONS

The design and results of our experiments impose some limitations and directions for future work.

P5.11.1 *Choice of Actuator*

Different vibrotactile actuators have been introduced and used by the literature, e.g. eccentric rotating mass (ERM) [12] and linear resonant actuators (LRA) [17]. These actuators differ in the mechanisms with which they produce vibrations on the skin. While LRAs vibrate perpendicular to the skin surface, ERMs rotate along the skin surface. We used an LRA actuator, known for its ability to produce localized sensations. Future work should investigate if and how much the choice of actuator affects perception.

P5.11.2 *Hand Pose*

The human hands are capable of a wide variety of poses and grips. We evaluated a flat hand pose in our user studies. Furthermore, our participants had to reduce the spacing between their fingers to make sure that actuators were in contact with the skin. While our results provide a valuable baseline for future research, further work is required to investigate how the hand pose affects perception.

P5.11.3 *Interface Size*

We chose our prototype size based on prior work on back-of-device (smartphone) tactile interfaces and on the average hand size. While this allowed us to conduct our user studies with all our participants, our prototype covered only parts of the hand. The palm was always fully covered and depending on the hand size, the base of the fingers. Future devices should be tailored to users' hand sizes.

P5.11.4 *Real-World Applicability*

In our work, we investigated the perception of *stationary* and *moving* tactile sensations in a lab setting. We chose this approach to focus on the mere influence of the factors and to exclude external influences. While we are convinced that our results make a strong contribution to the future palm-based tactile displays, we also acknowledge that other settings might yield other results. Therefore, further work is necessary to understand how these results are transferable to in-the-wild settings.

P5.12 CONCLUSION

This work explored the perception of vibrations on the palm. In a first user study, we evaluated the localization accuracy and perception of real and phantom *stationary* sensations. Our findings show that a 9 actuator display with a 3×3 grid of points can be localized accurately.

For better perception of phantom sensations, a display consisting of at least 15 actuators should be used combined with lower intensity vibrations. In a second controlled user study, we investigated the recognition accuracy of *moving* tactile sensations. Findings show that a 2×4 resolution leads to accurately perceived *moving* sensations, while a 5×10 resolution enables higher resolution output while maintaining high recognition rates. Based on the results, we derive and describe a set of design and usage guidelines for future palm-based tactile displays.

REFERENCES

[1] D. S. Alles. "Information Transmission by Phantom Sensations." In: *IEEE Transactions on Man-Machine Systems* 11.1 (Mar. 1970), pp. 85–91. ISSN: 0536-1540. DOI: 10.1109/TMMS.1970.299967.

[2] Jessalyn Alvina, Shengdong Zhao, Simon T. Perrault, Maryam Azh, Thijs Roumen, and Morten Fjeld. "OmniVib: Towards Cross-body Spatiotemporal Vibrotactile Notifications for Mobile Phones." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 2487–2496. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702341.

[3] K. Bark, E. Hyman, F. Tan, E. Cha, S. A. Jax, L. J. Buxbaum, and K. J. Kuchenbecker. "Effects of Vibrotactile Feedback on Human Learning of Arm Motions." In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 23.1 (Jan. 2015), pp. 51–63. ISSN: 1534-4320. DOI: 10.1109/TNSRE.2014.2327229.

[4] Christoph Borst and Charles Cavanaugh. "Touchpad-Driven Haptic Communication using a Palm-Sized Vibrotactile Array with an Open-Hardware Controller Design." In: (Jan. 2004).

[5] Harold Ernest Burtt. "Tactual illusions of movement." In: *Journal of Experimental Psychology* 2 (1917), pp. 371–385.

[6] Jessica R. Cauchard, Janette L. Cheng, Thomas Pietrzak, and James A. Landay. "ActiVibe: Design and Evaluation of Vibrations for Progress Monitoring." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: ACM, 2016, pp. 3261–3271. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858046.

[7] Qin Chen, Simon T. Perrault, Quentin Roy, and Lonce Wyse. "Effect of Temporality, Physical Activity and Cognitive Load on Spatiotemporal Vibrotactile Pattern Recognition." In: *Proceedings of the 2018 International Conference on Advanced Visual Interfaces*. AVI '18. Castiglione della Pescaia, Grosseto, Italy: ACM, 2018, 25:1–25:9. ISBN: 978-1-4503-5616-9. DOI: 10.1145/3206505.3206511.

[8] Roger Cholewiak. "Spatial factors in the perceived intensity of vibrotactile patterns." In: *Sensory processes* 3 (July 1979), pp. 141–56.

[9] Roger W. Cholewiak and Amy A. Collins. "Vibrotactile localization on the arm: Effects of place, space, and age." In: *Perception & Psychophysics* 65.7 (Oct. 2003), pp. 1058–1077. ISSN: 1532-5962. DOI: 10.3758/BF03194834.

[10] RW Cholewiak. "Spatial factors in the perceived intensity of vibrotactile patterns." In: *Sensory processes* 3.2 (June 1979), pp. 141–156. ISSN: 0363-3799.

[11] Jacob Cohen. *Statistical Power Analysis for the Behavioral Sciences*. Routledge, July 1988. ISBN: 9780203771587. DOI: 10.4324/9780203771587.

[12] Hesham Elsayed, Martin Weigel, Florian Müller, Martin Schmitz, Karola Marky, Sebastian Günther, Jan Riemann, and Max Mühlhäuser. "VibroMap: Understanding the Spacing of Vibrotactile Actuators across the Body." In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4.4 (Dec. 2020). DOI: 10.1145/3432189.

[13] Frank Arthur Geldard. "Sensory saltation : metastability in the perceptual world." In: *American Journal of Psychology* 90 (1977), p. 328.

[14] Sebastian Günther, Sven Kratz, Daniel Avrahami, and Max Mühlhäuser. "Exploring Audio, Visual, and Tactile Cues for Synchronous Remote Assistance." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. PETRA '18. Corfu, Greece: ACM, 2018, pp. 339–344. ISBN: 978-1-4503-6390-7. DOI: 10.1145/3197768.3201568.

[15] Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. "TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. PETRA '18. Corfu, Greece: Association for Computing Machinery, 2018, pp. 273–280. ISBN: 9781450363907. DOI: 10.1145/3197768.3197785.

[16] Aakar Gupta, Antony Irudayaraj, Vimal Chandran, Goutham Palaniappan, Khai N. Truong, and Ravin Balakrishnan. "Haptic Learning of Semaphoric Finger Gestures." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: Association for Computing Machinery, 2016, pp. 219–226. ISBN: 9781450341899. DOI: 10.1145/2984511.2984558.

[17] Eve Hoggan and Stephen Brewster. "Designing audio and tactile crossmodal icons for mobile devices." In: Jan. 2007, pp. 162–169. DOI: 10.1145/1322192.1322222.

[18] Gijs Huisman, Aduén Darriba Frederiks, Betsy Van Dijk, Dirk Hevlen, and Ben Kröse. "The TaSSt: Tactile sleeve for social touch." In: *2013 World Haptics Conference (WHC)*. 2013, pp. 211–216. DOI: 10.1109/WHC.2013.6548410.

[19] Gi-Hun Yang, Moon-sub Jin, Yeonsub Jin, and Sungchul Kang. "T-mobile: Vibrotactile display pad with spatial and directional information for hand-held device." In: *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*. Oct. 2010, pp. 5245–5250. DOI: 10.1109/IROS.2010.5651759.

[20] Ali Israr and Ivan Poupyrev. "Tactile Brush: Drawing on Skin with a Tactile Grid Display." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: ACM, 2011, pp. 2019–2028. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1979235.

[21] Paul Johnson and Holger Schielzeth. "The coefficient of determination R2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded." In: *Journal of The Royal Society Interface* 14 (Sept. 2017), p. 20170213. DOI: 10.1098/rsif.2017.0213.

[22] Jacob H. Kirman. "Tactile apparent movement: The effects of interstimulus onset interval and stimulus duration." In: *Perception & Psychophysics* 15 (1974), pp. 1–6.

[23] Matti Krüger, Heiko Wersing, and Christiane B. Wiebel-Herboth. "Approach for Enhancing the Perception and Prediction of Traffic Dynamics with a Tactile Interface." In: *Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '18. Toronto, ON, Canada: ACM, 2018, pp. 164–169. ISBN: 978-1-4503-5947-4. DOI: 10.1145/3239092.3265961.

[24] Jaeyeon Lee, Jaehyun Han, and Geehyuk Lee. "Investigating the Information Transfer Efficiency of a 3x3 Watch-back Tactile Display." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 1229–1232. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702530.

[25] Seungyon "Claire" Lee and Thad Starner. "BuzzWear: Alert Perception in Wearable Tactile Displays on the Wrist." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '10. Atlanta, Georgia, USA: ACM, 2010, pp. 433–442. ISBN: 978-1-60558-929-9. DOI: 10.1145/1753326.1753392.

[26] Ville Lehtinen, Antti Oulasvirta, Antti Salovaara, and Petteri Nurmi. "Dynamic Tactile Guidance for Visual Search Tasks." In: *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology*. UIST '12. Cambridge, Massachusetts, USA: ACM, 2012, pp. 445–452. ISBN: 978-1-4503-1580-7. DOI: 10.1145/2380116.2380173.

[27] Yi-Chi Liao, Yi-Ling Chen, Jo-Yu Lo, Rong-Hao Liang, Liwei Chan, and Bing-Yu Chen. "EdgeVib: Effective Alphanumeric Character Output Using a Wrist-Worn Tactile Display." In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. UIST '16. Tokyo, Japan: ACM, 2016, pp. 595–601. ISBN: 978-1-4503-4189-9. DOI: 10.1145/2984511.2984522.

[28] Granit Luzhnica, Sebastian Stein, Eduardo Veas, Viktoria Pammer, John Williamson, and Roderick Murray Smith. "Personalising Vibrotactile Displays Through Perceptual Sensitivity Adjustment." In: *Proceedings of the 2017 ACM International Symposium on Wearable Computers*. ISWC '17. Maui, Hawaii: ACM, 2017, pp. 66–73. ISBN: 978-1-4503-5188-1. DOI: 10.1145/3123021.3123029.

[29] Granit Luzhnica and Eduardo Veas. "Optimising Encoding for Vibrotactile Skin Reading." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Glasgow, Scotland Uk: ACM, 2019, 235:1–235:14. ISBN: 978-1-4503-5970-2. DOI: 10.1145/3290605.3300465.

[30] Granit Luzhnica, Eduardo Veas, and Caitlyn Seim. "Passive Haptic Learning for Vibrotactile Skin Reading." In: *Proceedings of the 2018 ACM International Symposium on Wearable Computers*. ISWC '18. Singapore, Singapore: Association for Computing Machinery, 2018, pp. 40–43. ISBN: 9781450359672. DOI: 10.1145/3267242.3267271.

[31] Flavia Mancini, Armando Bauleo, Jonathan Cole, Fausta Lui, Carlo Porro, Patrick Haggard, and Gian Iannetti. "Whole-Body Mapping of Spatial Acuity for Pain and Touch." In: *Annals of Neurology* 75 (June 2014). DOI: 10.1002/ana.24179.

[32] Alexander Marquardt, Jens Maiero, Ernst Kruijff, Christina Trepkowski, Andrea Schwandt, André Hinkenjann, Johannes Schöning, and Wolfgang Stuerzlinger. "Tactile Hand Motion and Pose Guidance for 3D Interaction." In: *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. VRST '18. Tokyo, Japan: Association for Computing Machinery, 2018. ISBN: 9781450360869. DOI: 10.1145/3281505.3281526.

[33] Troy McDaniel, Morris Goldberg, Daniel Villanueva, Lakshmie Narayan Viswanathan, and Sethuraman Panchanathan. "Motor Learning Using a Kinematic-Vibrotactile Mapping Targeting Fundamental Movements." In: MM '11. Scottsdale, Arizona, USA: Association for Computing Machinery, 2011, pp. 543–552. ISBN: 9781450306164. DOI: 10.1145/2072298.2072369.

[34] Scott Novich and David Eagleman. "Using space and time to encode vibrotactile information: toward an estimate of the skin's achievable throughput." In: *Experimental brain research* 233 (June 2015). DOI: 10.1007/s00221-015-4346-1.

[35] Gunhyuk Park and Seungmoon Choi. "Tactile Information Transmission by 2D Stationary Phantom Sensations." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: ACM, 2018, 258:1–258:12. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173832.

[36] Jaeyoung Park, Jaeha Kim, Yonghwan Oh, and Hong Z. Tan. "Rendering Moving Tactile Stroke on the Palm Using a Sparse 2D Array." In: *Proceedings, Part I, of the 10th International Conference on Haptics: Perception, Devices, Control, and Applications - Volume 9774*. EuroHaptics 2016. London, UK: Springer-Verlag, 2016, pp. 47–56. ISBN: 9783319423203. DOI: 10.1007/978-3-319-42321-0_5.

[37] Linda Petrosino and Donald Fucci. "Temporal Resolution of the Aging Tactile Sensory System." In: *Perceptual and Motor Skills* 68.1 (1989). PMID: 2928060, pp. 288–290. DOI: 10.2466/pms.1989.68.1.288. eprint: https://doi.org/10.2466/pms.1989.68.1.288.

[38] Max Pfeiffer, Stefan Schneegass, Florian Alt, and Michael Rohs. "Let Me Grab This: A Comparison of EMS and Vibration for Haptic Feedback in Free-hand Interaction." In: *Proceedings of the 5th Augmented Human International Conference*. AH '14. Kobe, Japan: ACM, 2014, 48:1–48:8. ISBN: 978-1-4503-2761-9. DOI: 10.1145/2582051.2582099.

[39] Jukka Raisamo, Roope Raisamo, and Veikko Surakka. "Evaluating the Effect of Temporal Parameters for Vibrotactile Saltatory Patterns." In: *Proceedings of the 2009 International Conference on Multimodal Interfaces*. ICMI-MLMI '09. Cambridge, Massachusetts, USA: Association for Computing Machinery, 2009, pp. 319–326. ISBN: 9781605587721. DOI: 10.1145/1647314.1647381.

[40] Jussi Rantala, Kalle Myllymaa, Roope Raisamo, Jani Lylykangas, Veikko Surakka, Pete Shull, and Mark Cutkosky. "Presenting spatial tactile messages with a hand-held device." In: *2011 IEEE World Haptics Conference*. 2011, pp. 101–106. DOI: 10.1109/WHC.2011.5945469.

[41] Anke Verena Reinschluessel, Sarah Christin Cebulla, Marc Herrlich, Tanja Döring, and Rainer Malaka. "Vibro-Band: Supporting Needle Placement for Physicians with Vibrations." In: *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI EA '18. Montreal QC, Canada: ACM, 2018, LBW039:1–LBW039:6. ISBN: 978-1-4503-5621-3. DOI: 10.1145/3170427.3188549.

[42] Julie Rowin and Matthew N. Meriggioli. "Chapter 19 - Proprioception, Touch, and Vibratory Sensation*." In: *Textbook of Clinical Neurology (Third Edition)*. Ed. by Christopher G. Goetz. Third Edition. Philadelphia: W.B. Saunders, 2007, pp. 343–361. ISBN: 978-1-4160-3618-0. DOI: https://doi.org/10.1016/B978-141603618-0.10019-0.

[43] Dongseok Ryu, Gi-Hun Yang, and Sungchul Kang. "T-Hive: Vibrotactile Interface Presenting Spatial Information on Handle Surface." In: *Proceedings of the 2009 IEEE International Conference on Robotics and Automation*. ICRA'09. Kobe, Japan: IEEE Press, 2009, pp. 3542–3547. ISBN: 9781424427888.

[44] Oliver S. Schneider, Ali Israr, and Karon E. MacLean. "Tactile Animation by Direct Manipulation of Grid Displays." In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST '15. Charlotte, NC, USA: ACM, 2015, pp. 21–30. ISBN: 978-1-4503-3779-3. DOI: 10.1145/2807442.2807470.

[45] Christian Schönauer, Kenichiro Fukushi, Alex Olwal, Hannes Kaufmann, and Ramesh Raskar. "Multimodal Motion Guidance: Techniques for Adaptive and Dynamic Feedback." In: *Proceedings*

of the 14th ACM International Conference on Multimodal Interaction. ICMI '12. Santa Monica, California, USA: ACM, 2012, pp. 133–140. ISBN: 978-1-4503-1467-1. DOI: 10.1145/2388676.2388706.

[46] Shayle R Searle, F Michael Speed, and George A Milliken. "Population marginal means in the linear model: an alternative to least squares means." In: *The American Statistician* 34.4 (1980), pp. 216–221.

[47] Jongman Seo and Seungmoon Choi. "Edge flows: Improving information transmission in mobile devices using two-dimensional vibrotactile flows." In: *2015 IEEE World Haptics Conference (WHC)*. 2015, pp. 25–30. DOI: 10.1109/WHC.2015.7177686.

[48] Carl E. Sherrick and Ronald Rogers. "Apparent haptic movement." In: *Perception & Psychophysics* 1 (1966), pp. 175–180.

[49] Katherine Sofia and Lynette Jones. "Mechanical and Psychophysical Studies of Surface Wave Propagation during Vibrotactile Stimulation." In: *Haptics, IEEE Transactions on* 6 (July 2013), pp. 320–329. DOI: 10.1109/TOH.2013.1.

[50] Daniel Spelmezan, Mareike Jacobs, Anke Hilgers, and Jan Borchers. "Tactile Motion Instructions for Physical Activities." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: ACM, 2009, pp. 2243–2252. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1519044.

[51] Tim Claudius Stratmann, Andreas Löcken, Uwe Gruenefeld, Wilko Heuten, and Susanne Boll. "Exploring Vibrotactile and Peripheral Cues for Spatial Attention Guidance." In: *Proceedings of the 7th ACM International Symposium on Pervasive Displays*. PerDis '18. Munich, Germany: ACM, 2018, 9:1–9:8. ISBN: 978-1-4503-5765-4. DOI: 10.1145/3205873.3205874.

[52] Hong Tan, Rob Gray, and J. Young. "A Haptic Back Display for Attentional and Directional Cueing." In: *Haptics-e* 3 (July 2003).

[53] EH Weber. *De subtilitate tactus. Ross HE, Murray DJ, eds*. 1834.

[54] Ernst Heinrich Weber and Helen Elizabeth Ross. *The sense of touch*. Academic Press for [the] Experimental Psychology Society, 1978.

[55] S. Weinstein. "Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality." In: *The skin senses. Proceedings of the First International Symposium March*, (1968), pp. 195–222.

[56] Gi-Hun Yang, Yeonsub Jin, Moon-sub Jin, and Sungchul Kang. "Vibrotactile cradle for smart cell-phone providing spatial and directional cues." In: *2011 IEEE International Conference on Robotics and Biomimetics*. 2011, pp. 938–943. DOI: 10.1109/ROBIO.2011.6181408.

[57] Gi-Hun Yang, Yeonsub Jin, Moon-sub Jin, and Sungchul Kang. "Vibrotactile display for hand-held devices and its preferable pattern generation." In: *2011 15th International Conference on Advanced Robotics (ICAR)*. 2011, pp. 223–228. DOI: 10.1109/ICAR.2011.6088602.

[58] Gi-Hun Yang, Yeonsub Jin, and Sungchul Kang. "Development of vibrotactile cradle for smart cell-phone providing spatial and directional cues." In: *2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication*. 2012, pp. 259–264. DOI: 10.1109/ROMAN.2012.6343763.

[59] Nesra Yannier, Ali Israr, Jill Fain Lehman, and Roberta L. Klatzky. "FeelSleeve: Haptic Feedback to Enhance Early Reading." In: CHI '15. Seoul, Republic of Korea: Association for Computing Machinery, 2015, pp. 1015–1024. ISBN: 9781450331456. DOI: 10.1145/2702123.2702396.

[60] Koji Yatani, Nikola Banovic, and Khai Truong. "SpaceSense: Representing Geographical Information to Visually Impaired People Using Spatial Tactile Feedback." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. Austin, Texas, USA: Association for Computing Machinery, 2012, pp. 415–424. ISBN: 9781450310154. DOI: 10.1145/2207676.2207734.

[61] Koji Yatani and Khai Nhut Truong. "SemFeel: A User Interface with Semantic Tactile Feedback for Mobile Touch-Screen Devices." In: *Proceedings of the 22nd Annual ACM Symposium on User Interface Software and Technology*. UIST '09. Victoria, BC, Canada: Association for Computing Machinery, 2009, pp. 111–120. ISBN: 9781605587455. DOI: 10.1145/1622176.1622198.

[62] Siyan Zhao, Ali Israr, Frances Lau, and Freddy Abnousi. "Coding Tactile Symbols for Phonemic Communication." In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: ACM, 2018, 392:1–392:13. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173966.

P6

TACTILE VECTORS FOR OMNIDIRECTIONAL ARM GUIDANCE

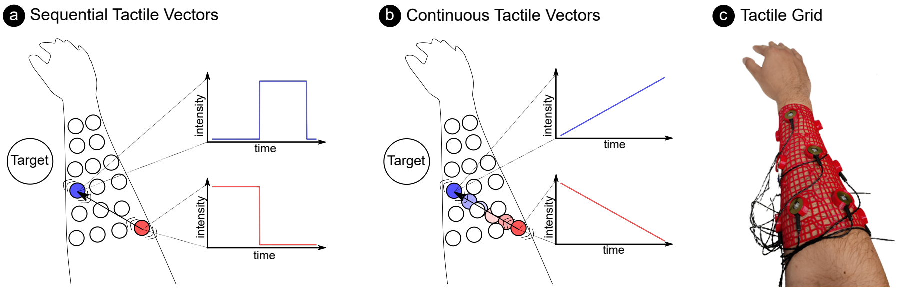


Figure P6.1: Motion guidance interaction techniques developed in this paper. We introduce (a) sequential tactile vectors (STV) and (b) continuous tactile vectors (CTV). (c) shows an example prototype used to conduct the user study.

ABSTRACT

We introduce and study two omnidirectional movement guidance techniques that use two vibrotactile actuators to convey a movement direction. The first vibrotactile actuator defines the starting point and the second actuator communicates the endpoint of the direction vector. We investigate two variants of our tactile vectors using phantom sensations for 3D arm motion guidance. The first technique uses two sequential stimuli to communicate the movement vector (*Sequential Tactile Vectors*). The second technique creates a continuous vibration vector using body-penetrating phantom sensations (*Continuous Tactile Vectors*). In a user study (N = 16), we compare these two new techniques with state of the art push and pull metaphors. Our findings show that users are 20% more accurate in their movements with sequential tactile vectors.

P6.1 INTRODUCTION

In recent years, a line of research investigated augmenting humans with on-body vibrotactile feedback for motion guidance [1, 5, 11, 13, 32]. Vibrotactile displays have been shown beneficial, for instance, to teach novice users violin [16], choreographed dance [3, 24], to support with practicing and learning sports (e.g., snowboarding [29], rowing [25], and tennis [20]), and for various forms of physical rehabilitation such as gait retraining [17] and stroke rehabilitation [12].

Prior work [7, 10, 19, 27, 29] identified two main interaction techniques for vibrotactile motion guidance: *push* and *pull*. Both communicate a direction with a single actuator: In the *push* metaphor, vibrations on the user's body push the user in a particular direction. The *pull* metaphor pulls the user in the direction of the vibration. While useful and intuitive, these interaction techniques are limited in the accuracy of communicated directions as the interpretation of a pulling/pushing sensation can vary greatly. Primarily because it is difficult to interpret a direction from a single actuator, leading researchers to encode one direction per actuator [16, 19]. This is even more difficult for vibrotactile guidance in 3D as the space of possible movements expands greatly compared to 2D guidance.

To overcome these limitations, we propose increasing the precision and space of feasible directions by using two vibrotactile actuators to communicate movement directions, i.e., spanning a vector between two vibration points. We introduce two novel interaction techniques for tactile motion guidance: *Sequential Tactile Vectors (STV)* and *Continuous Tactile Vectors (CTV)*. In *STV*, consecutive activations of actuators create the required direction vector of the motion (see Figure P6.1a). The first actuator communicates to the user the starting point of the vector and the second actuator communicates the end point. Taken together, they can be interpreted as a movement vector in 3D space. Similarly, *CTV* also uses two actuators to communicate a direction vector. However, instead of sequential activation, the actuators vibrate at the same time with changing intensities to elicit a body-penetrating phantom sensation [14]. This gives the impression of one stimulus moving in the direction of the vector (Figure P6.1b). The start and end points of STV and CTV are not limited to physical actuators. Instead, the techniques utilize phantom sensations [23] to increase the resolution

Table P6.1: Overview of approaches in related work.

	Jansen et al. [10]	Günther et al. [7]	Weber et al. [32]	Jin et al. [11]	Salazar Luces et al. [27]	Aggravi et al. [1]	Tsai et al. [31]	Kaul and Rohs [13]	Kaul and Rohs [13]	Salazar et al. [26]	Lieberman and Breazeal [15]	Linden et al. [16]	Kapur et al. [12]	Marquardt et al. [18]	McDaniel et al. [19]
Pull	✓	✓	✓	✓	✓	✓	✓	✓							✓
Push	✓	✓			✓				✓	✓	✓	✓	✓		✓
Other Interaction Technique							✓							✓	✓
Body part	Arm	Hand	Wrist	Wrist	Wrist	Wrist	Wrist	Head	Full body	Wrist	Arm	Arm	Arm	Hand	Arm
Number of tactors	5	10	6	6	6	4	4	22	34	6	8	7	8	27	12

of the display and create vectors starting and ending from virtual actuators.

We compare the two interaction techniques in a user study to push and pull as a baseline for current state of the art from prior work. We quantitatively analyse the accuracy of users' movements using the different guidance methods and collected qualitative feedback through a NASA-TLX and a questionnaire. The results show that using *STV* users are 20% more accurate in their movements in comparison to *push*, *pull*, and *CTV*. Subjective quantitative results further support the viability of *STV* and show a clear user preference for *pull* over *push*.

In summary, this paper contributes two novel interaction techniques for omnidirectional movement guidance: STV and CTV. These techniques aim to expand the possible guidance space by enabling movements in more directions than possible with a single vibration and by increasing the accuracy of the feedback. In a user study we compare STV and CTV with the state of the art in movement guidance, i.e. the push and pull metaphor for tactile guidance of 3D arm movements. The findings of our user study show a high accuracy for the STV technique.

P6.2 RELATED WORK

To better contextualize our research and contributions, we outline existing research on tactile motion guidance. Many technologies have been used for Human-Computer Integration [21, 22]. This work focuses on the use of wearable vibrotactile displays for movement guidance. Table P6.1 provides an overview of the different approaches.

P6.2.1 *Pull*

Jansen et al. [10] used five vibrotactile actuators arranged around the arm to guide wrist rotations. In this work, the authors identified two basic interaction techniques for tactile motion guidance: *push* and *pull*. Using *push* vibrations are interpreted to push the user in the direction of the vibration. Conversely, vibrations using the *pull* interaction technique pull the user along the direction of the vibration. Jansen et al. measured reaction times to vibrotactile stimuli and concluded that pull should be favoured over push. Günther et al. [7] proposed and evaluated a vibrotactile glove that uses push and pull for spatial guidance in 3D. Findings of the user study indicated that pull resulted in a lower number of errors while guiding users to spatial targets, and was prefered by the majority of users over push. Weber et al. [32] used six vibrotactile actuators arranged around the wrist to guide translations of the hand following the pull interaction technique, and rotation in two directions. Similarly, Jin et al. [11] introduced VT-Ware, a wearable wrist device with six actuators that was used to guide users in six directions and two rotation directions. For directional guidance the authors use the pull interaction technique. Rotational guidance was achieved by using the cutaneous rabbit illusion to produce moving tactile sensations along the required rotation. In work by Salazar et al. [27], motion path efficiency using push and pull were compared and the findings showed improvements with pull, however, with no statistical significance. Aggravi et al. [1] used pull with four actuators around the wrist for motion guidance in human-robot teams. Tsai et al. [31] compared a similar setup to force-feedback guidance from a haptic device. In HapticHead [13], Kaul et al. used 22 vibrotactile actuators arranged in concentric ellipses around the head for spatial guidance, where actuators pull the user towards the target.

P6.2.2 *Push*

Spelmezan et al. [29] used vibrotactile actuators placed across the body to guide users during physical activities into performing a particular movement instuction from a discrete set of 10 instructions. The authors stated that the interpretation of a vibration as either push or pull is a matter of preference and decided to use push. Salazar et al. [26] conducted a user study to evaluate the use of vibrotactile cues around the wrist for hand movement guidance in two dimensions. The authors used phantom sensations to be able to generate cues at all locations around the wrist with six vibrotactile actuators. In their work, Salazar et al. [26] used the push interaction technique. Lieberman and Breazeal [15] used push with eight vibrotactile actuators (four arranged around the wrist and four around the upper arm) to aid with performing complex 5 degrees of freedom arm motions. In MusicJacket [16], van der Linden et al. used the push interaction technique with seven actuators placed on the arm and torso to guide violin bowing techniques. Kapur et al. [12] presented a wearable tactile interface that uses magnetic motion tracking and eight vibration motors to provide feedback to apraxic stroke patients through a series of desired movements. They decided to use push as it is similar to a therapist pushing the patient's arm to perform the correct motion.

P6.2.3 *Other interaction techniques*

Besides push and pull, approaches were introduced that rely on moving tactile sensations for guiding movements. Marquardt et al. [18] developed a vibrotactile glove and forearm prototype that uses 27 actuators to guide hand movements and postures. Patterns were used to trigger movements such as pinching (vibrations from the back of the hand to the fingertips), forward (vibrations from forearm to fingers), and backward (vibrations from fingers to forearm) movements of the hand. In a similar approach, McDaniel et al. [19] introduced the "follow me" interaction technique, where the user is required to follow the movement of the tactile sensation, e.g vibrations from the back of the forearm to the front indicate bending the elbow. The authors compared the use of moving tactile sensations according to the "follow me", push and pull approaches for guidance of fundamental arm movements, and concluded that the naturalness of the interaction technique depended on the movement to be performed. Although these approaches are promising, reaction times of users depends on the duration of the vibrotactile stimuli and can reach 2.5 s to 4.5 s for stimuli with longer durations [19], rendering them unsuitable for real-time motion guidance. On the other hand, vibrotactile stimuli with shorter duration demonstrated reaction times of about 500 ms [30], making them more appropriate for real-time guidance. In this work,

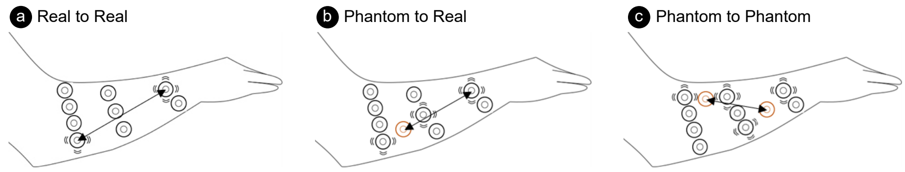


Figure P6.2: Tactile vectors for directional guidance: (a) using only real tactors, (b) using a combination of phantom and real tactors, and (c) using phantom sensations.

we therefore focus on interaction techniques that stimulate the user for short periods of time (1 s) to elicit faster reaction to feedback. Most similar to our work, Schönauer et al. [28] introduced the use of sequential activations to communicate eight directions, however, no user study was conducted to validate their approach. In this work, we introduce the concept of tactile vectors based on phantom sensations that can generate up to 2,652 directions with 15 physical actuators, thus enabling omnidirectional guidance in 3D. Figure P6.2 shows the different guidance possibilities developed in our work.

Prior work primarily focuses on the push and pull metaphors. However, there is no clear favorite in the community: some researchers use pull while others use push. In our work, we quantitatively and qualitatively compare the use of push and pull. Moreover, we introduce two new interaction techniques: *STV* and *CTV*. In contrast to the state-of-the-art these techniques allow for omnidirectional movement guidance by expanding the range of possible directions communicated through haptic feedback.

P6.3 INTERACTION TECHNIQUES FOR VIBROTACTILE MOTION GUIDANCE

This section contributes two new interaction techniques – Sequential Tactile Vectors (STV) and Continuous Tactile Vectors (CTV) – for vibrotactile motion guidance. We describe their fundamental mechanism and detail on the chosen parameterization used in our implementation. Finally, we provide details on the parameters for the baseline techniques (pull and push). STV and CTV are visualized in Figure P6.1.

P6.3.1 *Sequential Tactile Vectors (STV)*

The Sequential Tactile Vectors interaction technique uses two vibrations to convey a movement direction (see Figure P6.1a). The two vibrations are activated sequentially: the first vibration defines the starting point and the second vibration defines the endpoint of the direction vector in which the user should move. Both vibrations together produce a direction vector in which the person should move the body.

P6.3.2 *Continuous Tactile Vectors (CTV)*

The Continuous Tactile Vectors interaction technique uses body-penetrating phantom sensations [14] to create omnidirectional vibration cues. The vectors are created through the same start- and endpoints as in STV. However, instead of sequential vibrations, CTV creates a single continuous stimuli moving from the start point towards the endpoint. CTV can create the same vectors as STV, but is perceived differently. We evaluate both techniques to better understand which tactile vector stimuli is preferred by participants and leads to a higher movement accuracy.

P6.3.3 *Tactile Vector Types*

This work investigates three types of sequential and continuous tactile vectors (shown in Figure P6.2):

REAL → REAL The most straight-forward possibility to create a sequential tactile vector is by vibrating a physical actuator and afterwards a second physical actuator (Figure P6.2a). Hence, both perceived vibrations are *real*, i.e., created by physical actuators. Although Schönauer et al. [28] described this concept for motion guidance, its accuracy has not been evaluated.

REAL ↔ PHANTOM We extend the idea of tactile vectors by adding a variation using one real vibration and one vibration through phantom sensation (Figure P6.2b). This variation has the potential to increase the resolution of tactile vectors. It can create

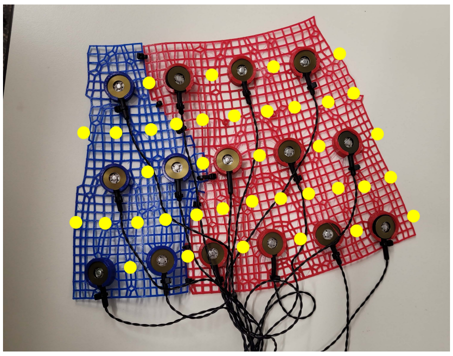


Figure P6.3: An unwrapped tactile grid with 15 actuators attached. The yellow points indicate the position of the vibrations created through phantom sensations.

vectors to arbitrary points between two or more physical actuators. Inverting this variation (*Phantom to Real*) allows for tactile vectors between a phantom sensation (start-point) and real vibration (endpoint).

PHANTOM → PHANTOM Tactile vectors can consist of two vibrations created through phantom sensations (Figure P6.2c). This allows for a wider variety of direction vectors, since both start- and endpoint can be placed anywhere between two or more real actuators.

For best usage of STVs and CTVs, we recommend choosing the pair of supported (real and phantom) vibrations that span the vector with the lowest deviation from the target vector.

P6.3.4 *Implementation of Tactile Vectors*

Both techniques (CTV and STV) are implemented and evaluated on a 3D printed vibrotactile grid with 15 vibrotactile actuators (C-2 tactors from Engineering Acoustics). We extend the real actuators using phantom sensations to include virtual actuators placed in the middle of each pair of neighbouring physical actuators. This created 52 vibration points that could be chosen as start- or endpoint of the tactile vector (see Figure P6.3). In total, this allows for 2,652 possible tactile vectors. However, we limit the combinations of actuators to those placed at least 10 cm apart, because our pilot tests showed: (1) actuators that were too close to each other were difficult to distinguish and (2) close

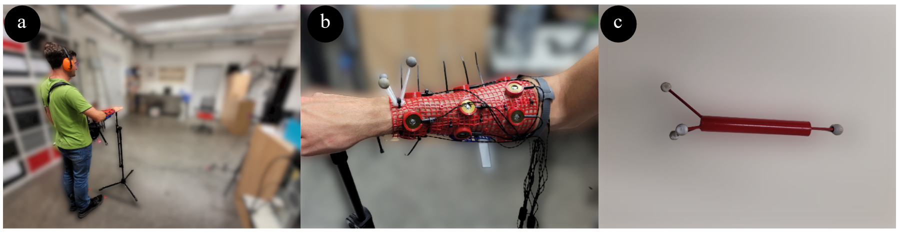


Figure P6.4: Experimental setup: (a) neutral pose used during our experiment, (b) vibrotactile grid with wrist trackable, and (c) pointer used for calibrating the position of the tactors.

actuators created unintentional phantom sensations for continuous tactile vectors. The chosen 10 cm threshold exceeds the maximum distance for producing a phantom sensation [6].

For STV, each vibration (i.e., start- and endpoint) lasted 0.5 s. The physical actuators vibrated with 200 Hz at 10 dB over Sensation Level (SL). SL is the intensity at which a vibration became perceptible, as determined during our calibration. Phantom sensations were generated using a linear model.

For CTV, we use a linear function for the amplitudes of the actuators to generate body penetrating sensations. The first actuator starts at full intensity (10 dB over SL) and decreases linearly over 1 s to 0 dB, while the second actuator increases from 0 dB to 10 dB over SL. Similar to the other interaction techniques, the frequency of vibration was constant at 200 Hz and the amplitudes of the actuators were updated at 100 Hz.

P6.3.5 *Baselines: Pull and Push*

Depending on the mental model of the user vibrations can be interpreted in different ways [7, 29]. Hence, we chose the *pull* and *push* interaction techniques as baseline interaction techniques. In our implementation, we actuate the real or phantom actuator that pushes or pulls the arm at the midpoint (midpoint of the middle row of motors) towards the target direction for one second (200 Hz at 10 dB over SL). For example, a push stimulus communicates the direction vector going from the position of the actuator to the midpoint of the arm. In contrast, a pull stimulus communicates the direction vector from the midpoint of the arm to the position of the actuator.

P6.4 USER STUDY: EVALUATION OF VIBROTACTILE MOTION GUIDANCE TECHNIQUES

To evaluate the interaction techniques introduced in this paper, we conducted a controlled user study that is described in the following. In particular, our user study aims to address the following hypotheses:

$H1_{STV/CTV}$: STV/CTV results in higher accuracy in guiding arm movements compared to push and pull.

$H2_{STV/CTV}$: STV/CTV reduces workload compared to push and pull.

$H3_{STV/CTV}$: STV/CTV is more intuitive than push and pull.

$H4_{STV/CTV}$: STV/CTV results in higher confidence ratings compared to push and pull.

$H5_{STV/CTV}$: Willingness to use of STV/CTV is higher than push and pull.

P6.4.1 *Participants*

16 right-handed individuals (11 male and 5 female) between 21 and 70 years old (M = 37.8) participated in our user study. Participation was voluntary, with no compensation offered. 14 of our participants had no experience with vibration based motion guidance. The remaining participants participated in prior experiments with vibrotactile feedback for purposes other than motion guidance.

P6.4.2 *Experimental Design*

Throughout our experiment we varied the guidance method (pull, push, sequential tactile vectors, and continuous tactile vectors) and target. The targets were defined as equidistant points on a sphere with an angle of 45°. The sphere had a radius of one meter and was centered at the midpoint of the arm. The midpoint of the arm was defined to be in the center of the middle row of tactors in the grid. We group the targets in our analysis along the x, y, and z axes. Figure P6.5 shows the

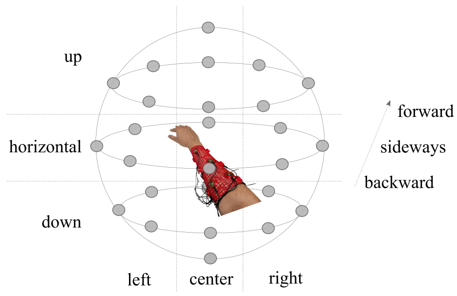


Figure P6.5: Targets used in our experiment

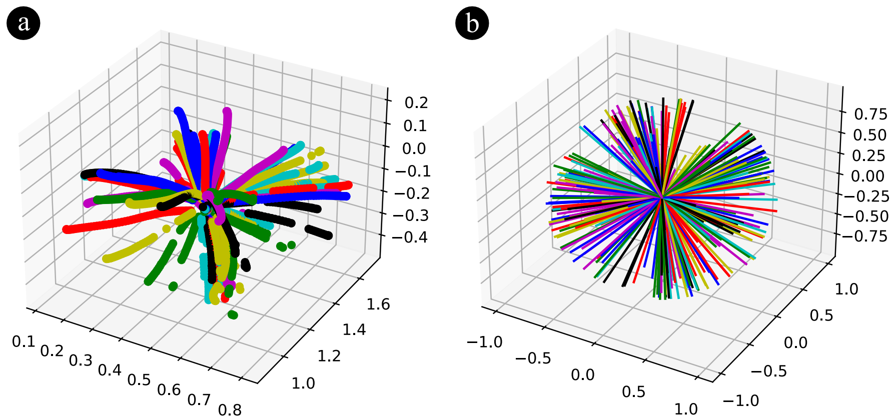


Figure P6.6: The Figure shows (a) example movements as measured by the motion capture system and (b) the normalized direction vectors of the computed best fit lines.

distribution of the targets in the sphere and their division along the main axes. We used a 4×4 balanced latin square to counterbalance the variable guidance method in a within subjects design. For each guidance method, the order of targets was randomized. Participants performed three repetitions resulting in a total of 312 movements per participant.

P6.4.3 *Procedure*

After obtaining informed consent from the participants, we collected their demographic data. Then, we explained the task and provided a brief overview of the procedure. The task was to move the arm in the direction indicated by the vibrations.

At the beginning of the experiment, we calibrated the position of the vibrotactile actuators relative to the position of the wrist. Each actuator in the grid was activated and its position was recorded using the pointer in Figure P6.4c. The experimenter could choose which actuator to activate using a graphical user interface and then subsequently record the position when the tip of the pointer is in contact with the actuator. Furthermore, SL thresholds were determined for each actuator by increasing vibration amplitude until the participant indicated perceiving a vibration. Every trial started with the participant standing in a fixed location indicated by markings on the floor with their hands resting on a tripod (see Figure P6.4).

After finishing performing a movement, the participants returned their arm to the neutral position with their hands on the tripod. Upon reaching the neutral position, there was a 5 seconds pause followed by the next trial. To reduce the amount of questionnaires, upon completing all targets in a guidance method, our participants filled out a short questionnaire with three 7-point Likert-scale statements followed by filling out a NASA-TLX. We consider this time as resting time. The total duration of the experiment was approximately 80 minutes.

P6.4.4 *Apparatus*

We used a Prusa MK3 for printing the wearable grids using thermoplastic polyurethane (TPU) filament. The experiment was conducted on a i7 dual core 3.6 GHz, 16 GB RAM desktop PC with a NVIDIA GeForce GTX 970 graphics card. The vibrotactile actuators used were the C-2 tactors from Engineering Acoustics, Inc. The tactors were controlled by a tactor control unit connected to the desktop PC over USB. Additionally, an Optitrack V100:R2 motion capture system with six cameras (submillimeter accuracy) was used for tracking the markers placed at the wrist and the participants' movements.

P6.4.5 *Dependent Variables*

Our main evaluation metric is the angle error. This is the angle between the target movement and the movement actually performed by the user. To obtain the movement vector of the user, we compute a best fit line with orthogonal regression based on the tracked points from our

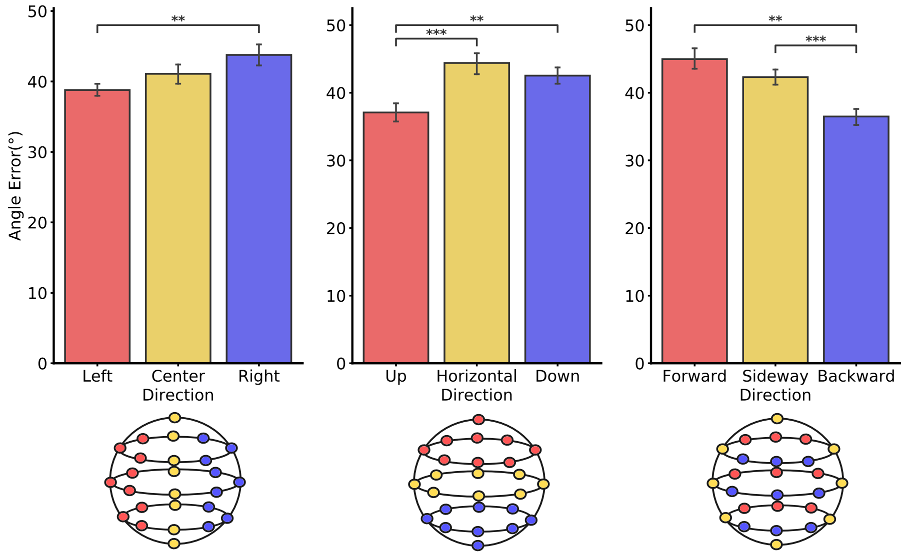


Figure P6.7: Angle error for the targets. All error bars indicate the standard error. Statistical significance of post-hoc pairwise contrast test are marked with asterisks ($* = p < .05$, $** = p < .01$, $*** = p < .001$).

motion capture system. The angular difference in degrees between the target vector and movement vector is the angle error.

Additionally, we measured participants' ratings on a 7-point Likert-scale for each guidance method to the following three statements:

- Interacting with the system was intuitive.
- I am confident I could follow the direction cue correctly.
- I would like to use this type of guidance for movement guidance.

Finally, we collected participants' answers to a NASA-TLX questionnaire.

P6.4.6 *Data Analysis*

We tested the data for normality with Shapiro Wilk's test and found no significant deviations. The recorded data was analyzed using a 2-way repeated measures ANOVA, followed by Bonferroni corrected pairwise t-tests where significant effects were present. We further report the eta-squared η^2 as an estimate of the effect size and use Cohen's suggestions to classify the effect size as small, medium or

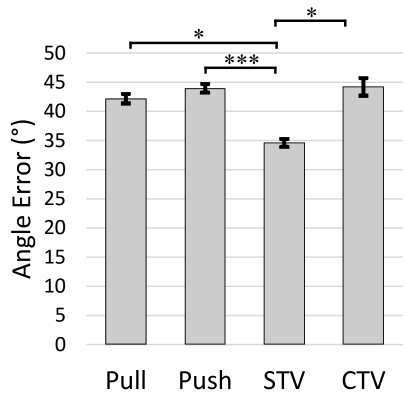


Figure P6.8: Angle errors for the guidance methods.All error bars indicate the standard error. Statistical significance of post-hoc pairwise contrast test are marked with asterisks ($* = p < .05$, $** = p < .01$, $*** = p < .001$).

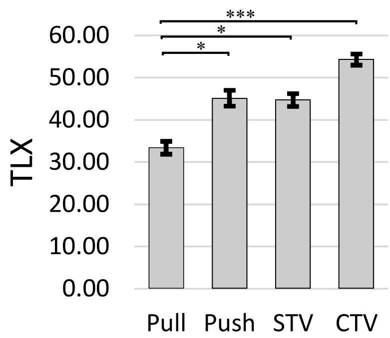


Figure P6.9: NASA-TLX scores for the guidance methods. All error bars indicate the standard error. Statistical significance of post-hoc pairwise contrast test are marked with asterisks ($* = p < .05$, $** = p < .01$, $*** = p < .001$).

large [2]. For the Likert questionnaires, we performed an Aligned Rank Transformation as suggested by Wobbrock et al. [33]. For the analysis of the NASA-TLX questionnaires, we used the raw method, indicating an overall workload as described by Hart [8].

P6.4.7 *Results*

In the following, we present the results of our user study in terms of the measured angle error, NASA-TLX, and questionnaire responses.

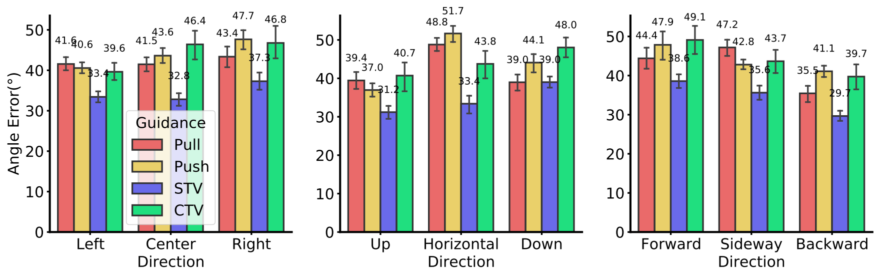


Figure P6.10: Angle error of the interaction between guidance method and target direction. All error bars indicate the standard error.

P6.4.7.1 *Angle Error*

We calculated the R^2 over all movements and participants to estimate how well the best fit lines represent the measured data from participants. The average R^2 value indicated a good fit of 0.98. Figure P6.6 shows example movements of a participant and the computed best fit lines.

We found that STV (M = 34.58°, SD = 5.33°) resulted in the lowest angle errors in comparison to pull (M = 42.16°, SD = 6.43°), push (M = 43.96°, SD = 5.87°), and CTV (M = 44.19°, SD = 12.03°). The analysis showed a significant ($F_{3,45} = 6.19$, $p < .001$) main effect of the *guidance method* on the angle error with a small η^2=.038 effect size. Post-hoc tests confirmed significant differences between STV and pull ($p < .05$), STV and push ($p < .001$), and between STV and CTV ($p < .05$).

For a more meaningful analysis of the effect of *target*, we clustered the targets along the x, y, and z axes to compare the following movement directions: (1) left, center and right (grouping along the x-axis), (2) up, horizontal and down (grouping along the y-axis), and (3) forward, sideway and backward (grouping along the z-axis). Figure P6.7 depicts the results.

Our analysis of targets left (M = 38.79, SD = 3.48), center (M = 41.09, SD = 6.13) and right (M = 43.77, SD = 7.67) revealed a significant ($F_{2,30} = 5.60$, $p < .01$) main effect of *target* on the angle error with a medium η^2=.103 effect size. Post-hoc tests confirmed significantly lower angle errors for targets to the left in comparison to targets to the right ($p < .01$).

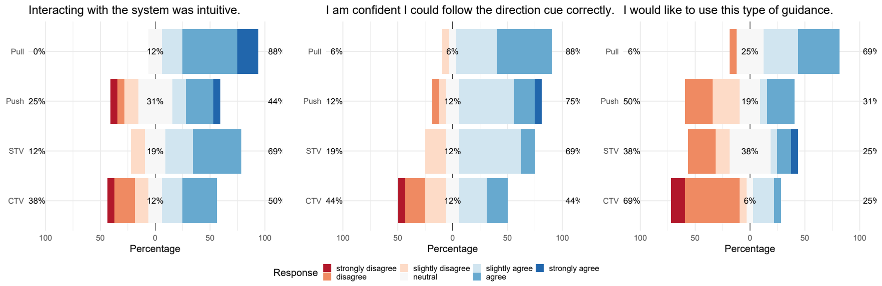


Figure P6.11: Participants' ratings to our statements.

For the grouping up (M = 37.08, SD = 6.25), horizontal (M = 44.41, SD = 6.02) and down (M = 42.53, SD = 6.53), our analysis showed a significant ($F_{2,30}$ = 10.1, p < .001) main effect of *target* on the angle error with a large η^2=.197 effect size. Post-hoc tests confirmed significant differences between up and down (p < .05), and up and horizontal (p < .001).

The analysis of the grouping forward (M = 44.98, SD = 9.17), sideway (M = 42.32, SD = 4.65) and backward (M = 36.49, SD = 4.55) showed a significant ($F_{2,30}$ = 10.6, p < .001) main effect of *target* on the angle error with a large η^2=.230 effect size. Post-hoc tests confirmed significant differences between forward and backward (p < .01), and sideway and backward (p < .001).

Figure P6.10 shows the interaction between *guidance method* and *target*. Figure P6.12 displays heatmaps of the angle error for the different guidance methods and targets.

P6.4.7.2 *NASA-TLX*

The analysis of the NASA-TLX questionnaires revealed a significant ($F_{3,45}$ = 10.8, p < .001) effect of *guidance method* on participants' ratings with a large η^2=.260 effect size. The pull (M = 33.39, SD = 12.16) condition resulted in the lowest overall workload, followed by STV (M = 44.69, SD = 11.96), push (M = 45.10, SD = 14.97), and CTV (M = 54.27, SD = 10.52). Post-hoc tests confirmed significant differences between pull and push (p < .05), pull and STV (p < .05), and pull and CTV (p < .001).

P6.4.7.3 *Questionnaire*

Intuitiveness: we asked our participants to rate how intuitive interacting with the system was on a 7-point Likert-scale (1: strongly disagree 7: strongly agree). Our analysis showed a significant ($F_{3,45} = 5.53$, $p < .01$) effect of *guidance method* on our participants' ratings of intuitiveness. The pull (MED = 6, MAD = 0.5) condition showed the highest ratings of intuitiveness, followed by STV (MED = 5, MAD = 1), CTV (MED = 4.5, MAD = 1.5), and finally push (M = 4, SD = 1). Post-hoc tests confirmed significantly higher ratings for pull than for push ($p < .01$), as well as significantly higher ratings for pull in comparison to the CTV condition ($p < .01$).

Confidence: our participants rated their confidence in following the direction cue correctly. The analysis revealed a significant ($F_{3,45} = 4.53$, $p < .01$) effect of *guidance method* on the ratings of participants. Confidence ratings in decreasing order for the conditions were pull (MED = 5.5, MAD = 0.5), STV (MED = 5, MAD = 0), push (MED = 5, MAD = 0.5), and CTV (MED = 4, MAD = 1). Post-hoc tests confirmed significantly higher confidence ratings for the pull condition in comparison to CTV ($p < .01$).

Willingness to use: for the last statement in our questionnaire, we asked participants to rate if they would like to use this type of guidance. Our analysis showed a significant ($F_{3,45} = 6.23$, $p < .01$) effect of *guidance method* on participants' ratings. Participants were most willing to use the pull (MED = 5, MAD = 1) condition, followed by STV (MED = 4, MAD = 1), push (MED = 3.5, MAD = 1.5), and CTV (MED = 2, MAD = 0.5). Post-hoc tests confirmed significantly higher willingness to use ratings for the pull condition in comparison to CTV ($p < .001$).

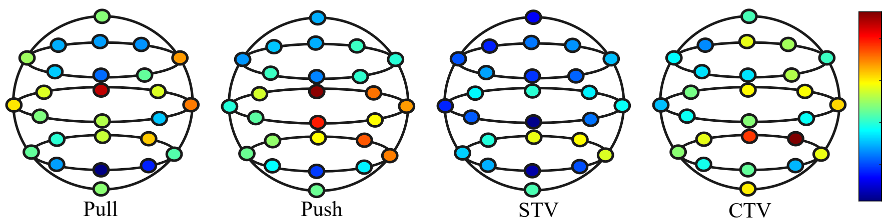


Figure P6.12: Heatmaps of angle error in ° for the different guidance methods.

P6.5 DISCUSSION

We introduced two new interaction techniques to improve the range of possible directions for movement that can be communicated to the user through vibrations. These interaction techniques were compared to the current state of the art push and pull metaphors. While the results of our experiment demonstrate large errors 35° (STV), 42° (Pull), and 44° (Push & CTV) for 3D guidance of arm movements, this was to be expected based on more restricted prior work showing that vibrotactile 2D guidance has an upper limit of 23-25° [9] for guiding wrist movements. However, our results pave the way for investigating novel approaches to further reduce movement error, or to use our tactile vectors on more sensitive body locations such as the hand for improved accuracy.

Prior work has identified advantages for pull over push using error metrics, such as reaction time [10], number of errors in movements [7], and motion path efficiency [27]. Based on our findings, we found comparable performance in terms of angle error between the metaphors. However, pull was subjectively preferred by our participants, similar to findings by Günther et al. [7].

In the following we summarize and discuss the findings from our user study:

P6.5.1 *STV for higher accuracy*

The results of our user study show that using STV, users achieved the highest accuracy in their movements compared to the other interaction techniques. Thus, we can accept $H1_{STV}$. Compared to current state of the art push and pull techniques, the advantage of STV is particularly evident for guiding movements where no actuator is present to push/pull the user, e.g forward and backward (Target 0 & 12, see Figure P6.12). In addition, STV had the highest accuracy for guiding upward and backward directions (see Figure P6.10). This information can be useful, e.g while designing gestures for interaction, where the user is guided by a wearable vibrotactile display.

Contrary to our initial hypothesis $H1_{CTV}$, CTV did not lead to an improvement in user accuracy compared to the other interaction techniques. CTV resulted in higher angular deviation compared to STV, and comparable angular deviation to pull and push. Thus, we cannot support $H1_{CTV}$. A possible explanation for this was provided by our participants where they expressed that it was difficult to determine which motor was first and which was second (P4, P11, P14, P15, P16). We used a linear function for determining the amplitude of the actuators that was shown to work on the hand and torso [14]. A possible solution can be the use of a higher order polynomial for determining the intensities of the actuators to allow for better differentiation of the start and endpoints.

Although subjective data collected from our participants showed higher median ratings for pull in comparison to STV regarding intuitiveness, confidence, and willingness to use, these differences were not significant and do not reflect the results of the angle error. A possible explanation for this behavior is that participants were inclined to overestimate their performance as demonstrated by the confidence ratings when the stimulus was a vibration at a single location. This finding further demonstrated that self-assessment with vibrotactile guidance is more difficult in comparison to visual guidance for example.

P6.5.2 *Pull for applications with low accuracy requirements*

For applications that do not require high accuracy of guidance, e.g guidance of a discrete set of directions with a large angle between them such as right/left, up/down, and forward/backward, pull should be used. We hypothesized that STV and CTV reduce workload in comparison to push and pull. However, this was not reflected in our results, as pull resulted in lower workloads in comparison to all the other guidance methods. Hence, we cannot support $H2_{STV/CTV}$. Furthermore, pull was rated to be significantly more intuitive than push and CTV. Although intuitiveness ratings were lower for STV, this difference was not significant. Nevertheless, we cannot support $H3_{STV/CTV}$. Similarly, our initial hypotheses were that STV and CTV increase participants' confidence in the perceived direction. However, pull received the highest confidence ratings among the guidance methods, with a significant increase compared to CTV. Thus, we cannot support $H4_{STV/CTV}$. Regarding willingness to use of the guidance methods, participants were most willing to use pull. Thus, we cannot support $H5_{STV/CTV}$.

P6.5.3 *Pull instead of push*

Although pull and push had comparable accuracy for motion guidance, there were significant differences between them. Pull was favoured by our participants in the qualitative results. It resulted in lower workload for our participants and was rated to be significantly more intuitive than push. This was reflected in the participants' comments where P6 expressed *"I preferred pulling for one motor guidance"*, *"pull is better than push"* (P12), and *"I found pull most intuitive"* (P10). Participants further mentioned that using both interaction techniques is *"confusing"* (P1, P10) after getting accustomed to one of them.

P6.5.4 *Movement direction affects accuracy of guidance*

Based on prior work investigating vibrotactile guidance of 2D hand movements [9], we expected the movements of our participants to be biased towards the cardinal directions. This was, however, not the case for 3D movements as can be seen in Figure P6.12. We found differences in accuracy showing that users are more accurate in movements toward the body than movements away from the body. Moving the right arm to targets to the left (towards the body) was more accurate than targets to the right (away from the body). Similarly, targets requiring a forward (away from the body) movement were less accurate compared to targets requiring a backward (towards the body) movement.

When evaluating the influence of movement direction on the accuracy it is also important to note the guidance method and actuator arrangement used. Push and pull guide the user in the direction defined between the actuator location and the midpoint of the arm. Since the actuators are arranged around the arm, directions such as forward become more difficult to communicate. A possible solution for this could be the attachment of an actuator at the elbow/tip of the hand to push/pull the user forward. An overview of the effect of movement direction for all guidance methods and directions investigated can be seen in Figure P6.12.

P6.6 LIMITATIONS & FUTURE WORK

We are confident that our results provide valuable insights into the influence of different interaction techniques on the accuracy and user experience of vibrotactile motion guidance systems. However, design as well as the results of our user study impose some limitations and starting points for future work.

P6.6.1 *Movement Direction*

Consistent with prior work on spatial guidance [13], we chose to use targets for eliciting movements that are uniformly distributed on a sphere. This arrangement of targets appropriately covered the wide range of movement directions possible by the arm. However, other arrangements are possible, e.g., distributing targets in a cube [7] that can be investigated in future work.

P6.6.2 *Dynamic Tactile Guidance*

For a more fundamental analysis independent of the use-case, our user study focused on guiding arm movements from a fixed neutral posture. However, this is not the case while performing activities such as physical rehabilitation, yoga or tai-chi, where the arm posture is dynamic. While our results provide a valuable baseline showing that our interaction technique outperforms current state of the art, further work is necessary to apply these findings to tasks where continuous guidance of user motion is required.

P6.6.3 *Real-World Applicability*

In this paper, we investigated vibrotactile motion guidance in a lab setting. We chose this approach to focus on the mere influence of the factors and to exclude external influences. While we are convinced that our results make a strong contribution to the future of such systems, we also acknowledge that other settings might yield other results. Therefore, further work is necessary to understand how these results are transferable to in-the-wild settings. For example, by integrating the haptic sleeve with a visual posture guidance approach that uses a mobile motion capture system [4].

P6.7 CONCLUSION

We presented two new omnidirectional guidance techniques for arm movements: Sequential Tactile Vectors and Continuous Tactile Vectors. We studied both techniques and compared them to the state of the art (push/pull) in a user study. The results of our evaluation show Sequential Tactile Vectors to be the most promising interaction technique of the four, outperforming push and pull, as well as Continuous Tactile Vectors in terms of accuracy. Qualitative results further support the viability of our interaction technique for accurate and intuitive vibrotactile motion guidance.

REFERENCES

[1] Marco Aggravi, Gionata Salvietti, and Domenico Prattichizzo. "Haptic wrist guidance using vibrations for Human-Robot teams." In: *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)* (2016), pp. 113–118.

[2] Jacob Cohen. *Statistical Power Analysis for the Behavioral Sciences*. Routledge, July 1988. ISBN: 9780203771587. DOI: 10.4324/9780203771587.

[3] Dieter Drobny and Jan Borchers. "Learning Basic Dance Choreographies with Different Augmented Feedback Modalities." In: *CHI '10 Extended Abstracts on Human Factors in Computing Systems*.

CHI EA '10. Atlanta, Georgia, USA: Association for Computing Machinery, 2010, pp. 3793–3798. ISBN: 9781605589305. DOI: 10.1145/1753846.1754058.

[4] Hesham Elsayed, Philipp Hoffmann, Sebastian Günther, Martin Schmitz, Martin Weigel, Max Mühlhäuser, and Florian Müller. "CameraReady: Assessing the Influence of Display Types and Visualizations on Posture Guidance." In: *Designing Interactive Systems Conference 2021*. DIS '21. Virtual Event, USA: Association for Computing Machinery, 2021, pp. 1046–1055. ISBN: 9781450384766. DOI: 10.1145/3461778.3462026.

[5] Hesham Elsayed, Kenneth Kartono, Dominik Schön, Martin Schmitz, Max Mühlhäuser, and Martin Weigel. "Understanding Perspectives for Single- and Multi-Limb Movement Guidance in Virtual 3D Environments." In: *28th ACM Symposium on Virtual Reality Software and Technology*. VRST '22. Tsukuba, Japan: Association for Computing Machinery, 2022. ISBN: 9781450398893. DOI: 10.1145/3562939.3565635.

[6] Hesham Elsayed, Martin Weigel, Florian Müller, Martin Schmitz, Karola Marky, Sebastian Günther, Jan Riemann, and Max Mühlhäuser. "VibroMap: Understanding the Spacing of Vibrotactile Actuators across the Body." In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4.4 (Dec. 2020). DOI: 10.1145/3432189.

[7] Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. "TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation." In: *Proceedings of the 11th PErvasive Technologies Related to Assistive Environments Conference*. PETRA '18. Corfu, Greece: Association for Computing Machinery, 2018, pp. 273–280. ISBN: 9781450363907. DOI: 10.1145/3197768.3197785.

[8] Sandra G. Hart. "Nasa-Task Load Index (NASA-TLX); 20 Years Later." In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 50.9 (2006), pp. 904–908. DOI: 10.1177/154193120605000909. eprint: https://doi.org/10.1177/154193120605000909.

[9] Jonggi Hong, Lee Stearns, Jon Froehlich, David Ross, and Leah Findlater. "Evaluating Angular Accuracy of Wrist-Based Haptic Directional Guidance for Hand Movement." In: *Proceedings of the 42nd Graphics Interface Conference*. GI '16. Victoria, British

Columbia, Canada: Canadian Human-Computer Communications Society, 2016, pp. 195–200. ISBN: 9780994786814.

[10] Chris Jansen, Arjen Oving, and Hendrik-Jan Veen. "Vibrotactile movement initiation." In: (Jan. 2004).

[11] Yeon Sub Jin, Han Yong Chun, Eun Tai Kim, and Sungchul Kang. "VT-ware: A wearable tactile device for upper extremity motion guidance." In: *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*. 2014, pp. 335–340. DOI: 10.1109/ROMAN.2014.6926275.

[12] Pulkit Kapur, Mallory Jensen, Laurel J. Buxbaum, Steven A. Jax, and Katherine J. Kuchenbecker. "Spatially distributed tactile feedback for kinesthetic motion guidance." In: *2010 IEEE Haptics Symposium*. 2010, pp. 519–526. DOI: 10.1109/HAPTIC.2010.5444606.

[13] Oliver Beren Kaul and Michael Rohs. "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. Denver, Colorado, USA: Association for Computing Machinery, 2017, pp. 3729–3740. ISBN: 9781450346559. DOI: 10.1145/3025453.3025684.

[14] Jinsoo Kim, Seungjae Oh, Chaeyong Park, and Seungmoon Choi. "Body-Penetrating Tactile Phantom Sensations." In: CHI '20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–13. ISBN: 9781450367080. DOI: 10.1145/3313831.3376619.

[15] Jeff Lieberman and Cynthia Breazeal. "TIKL: Development of a Wearable Vibrotactile Feedback Suit for Improved Human Motor Learning." In: *IEEE Transactions on Robotics* 23.5 (2007), pp. 919–926. DOI: 10.1109/TRO.2007.907481.

[16] Janet van der Linden, Erwin Schoonderwaldt, Jon Bird, and Rose Johnson. "MusicJacket—Combining Motion Capture and Vibrotactile Feedback to Teach Violin Bowing." In: *IEEE Transactions on Instrumentation and Measurement* 60.1 (2011), pp. 104–113. DOI: 10.1109/TIM.2010.2065770.

[17] Kristen L. Lurie, Pete B. Shull, Karen F. Nesbitt, and Mark R. Cutkosky. "Informing haptic feedback design for gait retraining." In: *2011 IEEE World Haptics Conference*. 2011, pp. 19–24. DOI: 10.1109/WHC.2011.5945455.

[18] Alexander Marquardt, Jens Maiero, Ernst Kruijff, Christina Trepkowski, Andrea Schwandt, André Hinkenjann, Johannes Schöning, and Wolfgang Stuerzlinger. "Tactile Hand Motion and Pose Guidance for 3D Interaction." In: *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. VRST '18. Tokyo, Japan: Association for Computing Machinery, 2018. ISBN: 9781450360869. DOI: 10.1145/3281505.3281526.

[19] Troy McDaniel, Morris Goldberg, Daniel Villanueva, Lakshmie Narayan Viswanathan, and Sethuraman Panchanathan. "Motor Learning Using a Kinematic-Vibrotactile Mapping Targeting Fundamental Movements." In: MM '11. Scottsdale, Arizona, USA: Association for Computing Machinery, 2011, pp. 543–552. ISBN: 9781450306164. DOI: 10.1145/2072298.2072369.

[20] Tony Morelli, John Foley, Luis Columna, Lauren Lieberman, and Eelke Folmer. "VI-Tennis: A Vibrotactile/Audio Exergame for Players Who Are Visually Impaired." In: *Proceedings of the Fifth International Conference on the Foundations of Digital Games*. FDG '10. Monterey, California: Association for Computing Machinery, 2010, pp. 147–154. ISBN: 9781605589374. DOI: 10.1145/1822348.1822368.

[21] Florian Floyd Mueller, Pedro Lopes, Paul Strohmeier, Wendy Ju, Caitlyn Seim, Martin Weigel, Suranga Nanayakkara, Marianna Obrist, Zhuying Li, Joseph Delfa, Jun Nishida, Elizabeth M. Gerber, Dag Svanaes, Jonathan Grudin, Stefan Greuter, Kai Kunze, Thomas Erickson, Steven Greenspan, Masahiko Inami, Joe Marshall, Harald Reiterer, Katrin Wolf, Jochen Meyer, Thecla Schiphorst, Dakuo Wang, and Pattie Maes. "Next Steps for Human-Computer Integration." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Honolulu, HI, USA: Association for Computing Machinery, 2020, pp. 1–15. ISBN: 9781450367080. DOI: 10.1145/3313831.3376242.

[22] Florian 'Floyd' Mueller, Nathan Semertzidis, Josh Andres, Martin Weigel, Suranga Nanayakkara, Rakesh Patibanda, Zhuying Li, Paul Strohmeier, Jarrod Knibbe, Stefan Greuter, Marianna Obrist, Pattie Maes, Dakuo Wang, Katrin Wolf, Liz Gerber, Joe Marshall, Kai Kunze, Jonathan Grudin, Harald Reiterer, and Richard Byrne. "Human–Computer Integration: Towards Integrating the Human Body with the Computational Machine." In: *Foundations and Trends® in Human-Computer Interaction* 16.1 (2022), pp. 1–64. ISSN: 1551-3955. DOI: 10.1561/1100000086.

[23] Gunhyuk Park and Seungmoon Choi. "Tactile Information Transmission by 2D Stationary Phantom Sensations." In: CHI '18. Montreal QC, Canada: Association for Computing Machinery, 2018, pp. 1–12. ISBN: 9781450356206. DOI: 10.1145/3173574.3173832.

[24] Jacob Rosenthal, Nathan Edwards, Daniel Villanueva, Sreekar Krishna, Troy McDaniel, and Sethuraman Panchanathan. "Design, Implementation, and Case Study of a Pragmatic Vibrotactile Belt." In: *IEEE Transactions on Instrumentation and Measurement* 60.1 (2011), pp. 114–125. DOI: 10.1109/TIM.2010.2065830.

[25] Emanuele Ruffaldi, Alessandro Filippeschi, Antonio Frisoli, Oscar Sandoval, Carlo Alberto Avizzano, and Massimo Bergamasco. "Vibrotactile perception assessment for a rowing training system." In: *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. 2009, pp. 350–355. DOI: 10.1109/WHC.2009.4810849.

[26] Jose Salazar, Keisuke Okabe, and Yasuhisa Hirata. "Path-Following Guidance Using Phantom Sensation Based Vibrotactile Cues Around the Wrist." In: *IEEE Robotics and Automation Letters* 3.3 (2018), pp. 2485–2492. DOI: 10.1109/LRA.2018.2810939.

[27] Jose V. Salazar Luces, Keisuke Okabe, Yoshiki Murao, and Yasuhisa Hirata. "A Phantom-Sensation Based Paradigm for Continuous Vibrotactile Wrist Guidance in Two-Dimensional Space." In: *IEEE Robotics and Automation Letters* 3.1 (2018), pp. 163–170. DOI: 10.1109/LRA.2017.2737480.

[28] Christian Schönauer, Kenichiro Fukushi, Alex Olwal, Hannes Kaufmann, and Ramesh Raskar. "Multimodal Motion Guidance: Techniques for Adaptive and Dynamic Feedback." In: ICMI '12. Santa Monica, California, USA: Association for Computing Machinery, 2012, pp. 133–140. ISBN: 9781450314671. DOI: 10.1145/2388676.2388706.

[29] Daniel Spelmezan, Mareike Jacobs, Anke Hilgers, and Jan Borchers. "Tactile Motion Instructions for Physical Activities." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: Association for Computing Machinery, 2009, pp. 2243–2252. ISBN: 9781605582467. DOI: 10.1145/1518701.1519044.

[30] Andrew A. Stanley and Katherine J. Kuchenbecker. "Evaluation of Tactile Feedback Methods for Wrist Rotation Guidance." In: *IEEE Transactions on Haptics* 5.3 (2012), pp. 240–251. DOI: 10.1109/TOH.2012.33.

[31] Hsin-Ruey Tsai, Yuan-Chia Chang, Tzu-Yun Wei, Chih-An Tsao, Xander Chin-yuan Koo, Hao-Chuan Wang, and Bing-Yu Chen. "GuideBand: Intuitive 3D Multilevel Force Guidance on a Wristband in Virtual Reality." In: *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. New York, NY, USA: Association for Computing Machinery, 2021. ISBN: 9781450380966.

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

[33] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. "The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: ACM, 2011, pp. 143–146. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1978963.

ERKLÄRUNG

Hiermit erkläre ich, die vorgelegte Arbeit zur Erlangung des akademischen Grades Doktor rerum naturalium (Dr. rer. nat.) mit dem Titel

Computer-Supported Movement Guidance: Investigating Visual/Visuotactile Guidance and Informing the Design of Vibrotactile Body-Worn Interfaces

selbständig und ausschließlich unter Verwendung der angegebenen Hilfsmittel erstellt zu haben. Ich habe bisher noch keinen Promotionsversuch unternommen.

Darmstadt, Januar 2023

Hesham Nabil Abdelrahman
Elsayed, M.Sc.