Design and Effect of Continuous Wearable Tactile Displays

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Abstract

Our sense of touch is one of our core senses and while not as information rich as sight and hearing, it tethers us to reality. Our skin is the largest sensory organ in our body and we rely on it so much that we don't think about it most of the time. Tactile displays - with the exception of actuators for notifications on smartphones and smartwatches - are currently understudied and underused. Currently tactile cues are mostly used in smartphones and smartwatches to notify the user of an incoming call or text message. Specifically continuous displays - displays that do not just send one notification but stay active for an extended period of time and continuously communicate information - are rarely studied. This thesis aims at exploring the utilization of our vibration perception to create continuous tactile displays. Transmitting a continuous stream of tactile information to a user in a wearable format can help elevate tactile displays from being mostly used for notifications to becoming more like additional senses enabling us to perceive our environment in new ways. This work provides a serious step forward in design, effect and use of continuous tactile displays and their use in human-computer interaction. The main contributions include:

Exploration of Continuous Wearable Tactile Interfaces This thesis explores continuous tactile displays in different contexts and with different types of tactile information systems. The use-cases were explored in various domains for tactile displays - Sports, Gaming and Business applications. The different types of continuous tactile displays feature one- or multidimensional tactile patterns, temporal patterns and discrete tactile patterns.

Automatic Generation of Personalized Vibration Patterns In this thesis a novel approach of designing vibrotactile patterns without expert knowledge by leveraging evolutionary algorithms to create personalized vibration patterns - is described. This thesis presents the design of an evolutionary algorithm with a human centered design generating abstract vibration patterns. The evolutionary algorithm

was tested in a user study which offered evidence that interactive generation of abstract vibration patterns is possible and generates diverse sets of vibration patterns that can be recognized with high accuracy.

Passive Haptic Learning for Vibration Patterns Previous studies in passive haptic learning have shown surprisingly strong results for learning Morse Code. If these findings could be confirmed and generalized, it would mean that learning a new tactile alphabet could be made easier and learned in passing. Therefore this claim was investigated in this thesis and needed to be corrected and contextualized. A user study was conducted to study the effects of the interaction design and distraction tasks on the capability to learn stimulus-stimulus-associations with Passive Haptic Learning. This thesis presents evidence that Passive Haptic Learning of vibration patterns induces only a marginal learning effect and is not a feasible and efficient way to learn vibration patterns that include more than two vibrations.

Influence of Reference Frames for Spatial Tactile Stimuli Designing wearable tactile stimuli that contain spatial information can be a challenge due to the natural body movement of the wearer. An important consideration therefore is what reference frame to use for spatial cues. This thesis investigated allocentric versus egocentric reference frames on the wrist and compared them for induced cognitive load, reaction time and accuracy in a user study. This thesis presents evidence that using an allocentric reference frame drastically lowers cognitive load and slightly lowers reaction time while keeping the same accuracy as an egocentric reference frame, making a strong case for the utilization of allocentric reference frames in tactile bracelets with several tactile actuators.

Zusammenfassung

Das Fühlen ist einer unserer zentralen Sinne und obwohl Fühlen nicht so informationsreich ist wie Sehen oder Hören, verankert uns Fühlen doch stark in unserer physischen Realität. Die Haut ist das größte Sinnesorgan unseres Körpers, wir verlassen uns so sehr auf unsere Haut, dass wir die meiste Zeit kaum darüber nachdenken. Taktile Anzeigen - mit der Ausnahme von taktilen Benachrichtigungen in Smartphones und Smartwatches - werden aktuell nur sehr stiefmütterlich behandelt, benutzt und erforscht. Taktile Benachrichtigungen werden in Smartphones oder Smartwatches hauptsächlich dafür benutzt den Anwender auf eingehende Anrufe oder Nachrichten hinzuweisen. Kontinuierliche taktile Anzeigen - also Anzeigen, welche nicht nur einmalig, sondern für längere Zeit aktiv sind und Informationen bereitstellen - werden dabei nur selten untersucht. Diese Dissertation hat zum Ziel die Nutzung des menschlichen Tastsinns zu untersuchen um kontinuierliche taktile Anzeigen zu untersuchen und zu konstruieren. Das kontinuierliche Senden von taktilen Informationen an Benutzer mittels eines Wearables kann taktilen Anzeigen helfen die bekannten Benachrichtigungswege zu verlassen und mehr als eigenständige neue Sinnesinformation betrachtet zu werden. Diese Dissertation ist ein weiterer beträchtlicher Schritt in den Bereichen des Designs sowie der Effekte und Benutzung von kontinuierlich aktualisierenden taktilen Anzeigen und deren Verwendung in der Mensch-Maschine-Interaktion. Der wissenschaftliche Beitrag dieser Arbeit lässt sich wie folgt zusammenfassen:

Exploration Diese Dissertation exploriert kontinuierliche taktile Anzeigen in verschiedenen Kontexten und verschiednen Arten von taktilen Informationssystemen. Es wurden verschiedene Anwendungsfälle von Anzeigen in unterschiedlichen Domänen untersucht - Sport, Videospiele und Geschäftsanwendungen. Es wurden verschiendene Typen von kontinuerlichen taktilen Anzeigen (ein- bzw. mehrdimensionale Anzeigen, zeitliche taktile Anzeigen und diskrete Anzeigen) untersucht.

Automatische Generierung von Personalisierten Vibrotaktilen Mustern Diese Dissertation präsentiert einen neuartigen Ansatz zur Generierung von Vibrationsmustern - die Generierung von personalisierten vibrotaktilen Mustern ohne Expertenwissen mithilfe eines evolutionären Algorithmus. Dieser Ansatz wurde implementiert und in einer Nutzerstudie getestet. Die Ergebnisse der Studie belegen das es möglich ist wiedererkannbare, personalisierte Vibrationsmuster in einem interaktiven automatisierten Prozess zu generieren.

Passives Haptisches Lernen von Vibrotaktilen Mustern Vorangehende Untersuchungen über Passives Haptisches Lernen zeigten erstaunlich gute Resultate für das Lernen von Morse-Code. Falls diese Erkenntnisse bestätigt und generalisiert werden könnten, würde dies eine erhebliche Erleichterung des Lernvorgangs für neue taktile Alphabete bedeuten. Dieser Ansatz wurde in dieser Dissertation erneut untersucht und korrigiert. Eine Nutzerstudie wurde durchgeführt um die Effekte des Interaktionsdesigns sowie der Ablenkungsaufgaben auf das Potential von Passivem Haptischen Lernen von Stimulus-Stimulus-Assoziationen zu untersuchen. Diese Arbeit präsentiert die Erkenntnis, dass Passives Haptisches Lernen von Vibrationsmustern nur ein geringen Lerneffekt aufweist und daher nicht für das Lernen von komplexen Vibrationsmustern verwendbar ist.

Einfluss von Referenzrahmen auf räumliche taktile Stimuli Der Einfluss von natürlichen Körperbewegungen auf das Design von räumlichen taktilen Anzeigen ist eine nicht zu vernachlässigende Komponente dessen. Daher müssen Referenzrahmen für die Anzeige der taktilen Stimuli betrachtet werden. Diese Dissertation untersucht allozentrische und egozentrische Referenzrahmen am Handegelenk und vergleicht diese anhand von kongnitiver Last, Reaktionszeit und Genauigkeit in einer Nutzerstudie. Diese Dissertation präsentiert die Erkenntnis, dass allozentrische Refernzrahmen die kognitive Last drastisch verringern, Reaktionszeiten leicht verbessern und die gleiche Genauigkeit haben wie egozentrische Referenzrahmen.

Contents

1 Introduction and Motivation

Our sense of touch is one of our core senses and while not as information rich as sight and hearing, it tethers us to reality. Our skin is the largest sensory organ in our body and we rely on it so much that we don't think about it most of the time. Tactile displays - with the exception of actuators for notifications on smartphones and smartwatches - are currently understudied and underused. Currently tactile cues are mostly used in smartphones and smartwatches to notify the user of an incoming call or text message. Especially continuous displays - displays that do not just send one notification but stay active for an extended period of time and continuously communicate information - are rarely studied. This thesis aims at exploring the utilization of our vibration perception to create continuous tactile displays. Transmitting a continuous stream of information to a user in a wearable format can help elevate tactile displays from being mostly used for notifications to becoming more like additional senses with which we perceive our environment in new ways. This work provides a serious step forward in design, effect and use of continuous tactile displays and their use in human-computer interaction.

1.1 Motivation

Enhancing the capability of what our bodies can achieve is a dream as old as humanity. The idea of augmenting our physical, cognitive and perceptual capabilities through technological means can be seen rearing its head through all of history even though the term "human augmentation" was only established nearly 60 years ago by Engelbart in 1962 [34]. Riding the edge between utopic promises and dystopic nightmares, the promise of increasing our mental and perceptual capabilities is nearly omnipresent in pop-culture and influences research communities all over the world. Bach-y Rita et al. described a vision substitution system in 1969 that made vast strides towards encoding visual stimuli into tactile stimuli [10]. The inciting idea for this thesis was born in 2015 in a collision of a lecture in human-computer-interaction, a lecture in ubiquitous computing and a basic course in paragliding I took with a few friends and fellow students. Being somewhat familiar with tropes in science fiction of the augmentation of the body and the mind ("I know Kung-Fu") and hearing about the actual work done in human augmentation since the sixties, I was immediately fascinated and looked for opportunities to apply the new found knowledge in the newly found hobby of paragliding. We humans do not posses a sense of how fast we are traveling in space and only have a sense of our acceleration in space. A tactile wearable to transmit velocity by vibration continuously to the wearer gives the wearer a “sense” of their current velocity, so to speak. So, tinkering around with our perception of reality while up in the air seemed like a very good idea and thus an early prototype of the tactile variometer shown in chapter 3 was born. With wearables becoming more and more prevalent in the media and everyday life, the cost and size of tactile actuators becoming smaller and smaller and micro-controllers becoming also cheaper, smaller and easier to use, the opportunity to investigate continuous wearable tactile displays became too good too pass up.

1.1.1 Contributions

Contributions were made in the exploration of the design space of wearable tactile variometers and the continuous communication of important information through repeating structured vibration patterns, see chapter 3. Wearable tactile variometers were evaluated in a lab study with 11 participants and two field studies with 4 and 2 paraglider pilots.

Contributions in the area of continuous tactile feedback for video games presented in this thesis are the exploration of continuous tactile feedback with off-the-shelf hardware, the design and implementation of a continuous tactile feedback system with off-the-shelf hardware and the 29 person between-subject user study, see chapter 4.

Applications in dashboard environments were explored through continuous tactile cues on the wrist for attention guidance. Visual cues and spatial and temporal tactile cues for attention guidance with a wrist-worn wearable were compared in a 24 person within-subject user study, see chapter 5.

Contributions in the area of automatic user-centered generation of vibration patterns presented in this thesis are the design of an evolutionary algorithm for generating vibration patterns, the implementation of said algorithm and conducting an 11 person user study to evaluate the algorithm. This thesis presents evidence, that an interactive generation of vibration patterns is possible and leads to distinct personalized vibration patterns

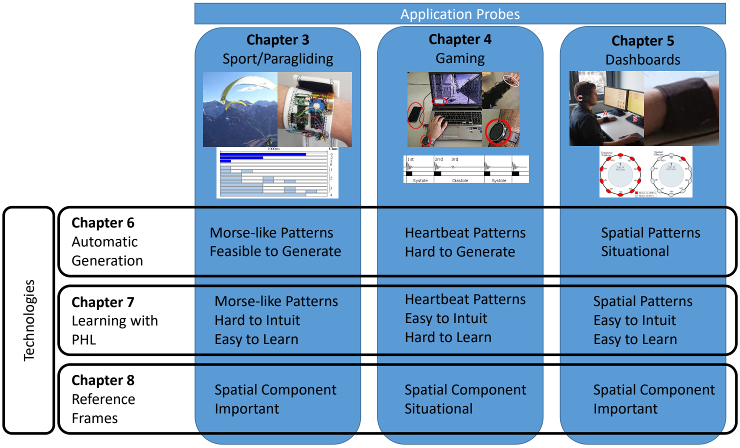

Figure 1.1: Thesis structure.

that are on par with vibration patterns found in the literature, see chapter 6.

Contributions made in the area of Passive Haptic Learning of Stimulus-Stimulus Associations are the design and execution of a 5 group user study with together 50 participants to test passive haptic learning of vibrotactile patterns. The user study presented in this thesis in chapter 7 found that previous studies in passive haptic learning of stimulus-stimulus-associations (like learning Morse code with PHL) leaked information in their testing protocol and therefore produced better results as it would be possible with passive haptic learning alone.

Contributions were also made by investigating reference frames for spatial tactile cues on the wrist with a 20 participant within-subject user study. This thesis presents evidence that allocentric reference frames on the wrist outperforms egocentric reference frames on the wrist for spatial localisation tasks while keeping accuracy stable.

1.2 Structure

A structural overview of this thesis can be seen in Figure 1.1. This thesis can be subdivided into two parts, an exploration part in which continuous tactile displays are studied in different application scenarios and shortcomings and areas for improvement are brought forward. In the technology part of this thesis three possible technologies are presented to deal with the areas for improvement of current continuous tactile displays found during the exploration.

1.2.1 Exploration of Continuous Wearable Tactile Interfaces in Different Application Areas

At first this thesis explores continuous tactile displays in different contexts and with different types of tactile information systems. The use-cases were explored in three different domains for tactile displays - Sport [89; 90], Gaming [92] and Business applications [93; 95; 77; 94]. The different types of continuous tactile displays feature one- or multidimensional tactile patterns [89; 90], temporal patterns [94] and discrete tactile patterns [77; 92].

In the sports context the thesis looks at paragliding and the opportunity that tactile interfaces present for continuous, hands-free information systems in the air. To this end tactile variometers were explored and two different tactile modalities to implement tactile variometers were studied [89; 90]. This thesis presents evidence that continuous tactile feedback with distinct vibration patterns is a feasible way to communicate vital information to the paraglider with a high differentiability and learnability.

In the Gaming context a continuous tactile display was investigated as a way to communicate abstract information in video games[92]. This thesis presents evidence that encoding game information as a pseudo heartbeat provides the player with a rich and immersive game environment without unnecessarily compromising the clarity of the game information. Drawing from experiences made in the gaming and sports domain with continuous wearable tactile interfaces, potential applications in business were investigated, like enriching shop floors with tactile cues [77; 95], as well as tactile displays for large dashboard environments [94]. This thesis presents evidence that while tactile interfaces are naturally not as accurate as visual or auditory displays of data [95; 91], but spatial tactile feedback can help in dashboard environments by reducing cognitive load and reaction time [94; 98].

All three exploration chapters reveal openings for the technologies studied in chapter 6, chapter 7 and chapter 8, although some chapters are more connected than others. If the reader is interested in the applications presented in chapter 3 and chapter 4, the technologies presented in chapter 6 and chapter 7 might be of interest. If the reader is interested in the applications presented in chapter 5 and chapter 4, the technologies presented in chapter 8 might be of interest.

1.2.2 Automatic Generation of Personalized Vibration Patterns

Tactile systems often rely on vibrotactile patterns to communicate abstract information to the user. These vibration patterns are usually hand crafted by researchers and evaluated in a laboratory study before being deployed. This approach doesn't factor in the individual differences of perception and taste of the different users but presents a one-size-fits-all solution. Personalized vibration patterns can use individuals specific features and need to craft patterns directly designed for the individual user and the application. In this thesis a novel approach - designing vibrotactile patterns without expert knowledge by leveraging evolutionary algorithms to create personalized vibration patterns [97] - is described. This thesis presents the design of an evolutionary algorithm with a human centered design generating abstract vibration patterns. The evolutionary algorithm was tested in a user study with 11 participants. The user study offers evidence that interactive generation of abstract vibration patterns is possible and generates diverse set of vibration patterns that can be recognized with a high recognition rate and high confidence by the participants.

This thesis discusses automatic generation of personalized vibration patterns in chapter 6 and pulls on ideas and experiences presented in chapter 3 and chapter 4, for a well-rounded reading experience it is advised to read chapter 3 and chapter 4 before reading chapter 6.

1.2.3 Passive Haptic Learning for Vibration Patterns

Learning new skills can be a long and tedious process and learning a new tactile alphabet to decipher tactile patterns certainly is. In the past studies have shown that people can learn passively or without paying active attention to learning. Combined with tactile stimuli that process is called „Passive Haptic Learning“ and has shown potential in learning new motor skills. Previous studies in passive haptic learning have also shown surprisingly strong results for learning Morse Code. If these findings could be confirmed and generalized, it would mean that learning a new tactile alphabet could be made easier and learned in passing. Therefore this claim was investigated in this thesis and needed to be corrected and contextualized [96]. To this end a user study with 50 participants in 5 groups was conducted to study the effects of the interaction design and distraction tasks on the participants capability to learn stimulus-stimulus-associations with Passive Haptic Learning. This thesis presents evidence that Passive Haptic Learning of vibration patterns induces only a marginal learning effect and is not a feasible and efficient way to learn vibration patterns that include more than two vibrations.

This thesis discusses Passive Haptic Learning for vibration patterns in chapter 7 and pulls on ideas and experiences presented in chapter 3 and chapter 4 and to a lesser extent presented in chapter 5), for a well-rounded reading experience it is advised to read at least chapter 3 before reading chapter 7.

1.2.4 Influence of Reference Frames for Spatial Tactile Stimuli

Designing wearable tactile stimuli that contain spatial information can be a challenge due to the natural body movement of the wearer. An important consideration therefore is what reference frame to use for spatial cues. For example if a tactile bracelet indicates to the user to look up, there are several possibilities to design a tactile cue that does this, depending on the reference frame used. This thesis investigated allocentric versus egocentric reference frames on the wrist and compared them for induced cognitive load, reaction time and accuracy in a 20 participants user study [98]. This thesis presents evidence that using an allocentric reference frame drastically lowers cognitive load and slightly lowers reaction time while keeping the same accuracy as an egocentric reference frame, making a strong case for the utilization of allocentric reference frames in tactile bracelets with several tactile actuators.

This thesis discusses the influence of reference frames on spatial tactile stimuli in chapter 8 and pulls ideas and experiences from chapter 5 and to a lesser extent from chapter 3, for a well-rounded reading experience it is advised to read chapter 5 before chapter 8.

1.3 Papers

Erik Pescara, Michael Beigl, and Matthias Budde. 2016. *RüttelFlug: a wrist-worn sensing device for tactile vertical velocity perception in 3d-space*. In Proceedings of the 2016 ACM International Symposium on Wearable Computers (ISWC '16). Association for Computing Machinery, New York, NY, USA, 172–175.

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Erik Pescara, Alexander Wolpert, Matthias Budde, Andrea Schankin, and Michael Beigl. 2017. *Lifetact: utilizing smartwatches as tactile heartbeat displays in video games*. In Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia (MUM '17). Association for Computing Machinery, New York, NY, USA, 97–101.

Andrei Miclaus, **Erik Pescara**, Alexander Mädche, and Michael Beigl. 2019. *Drive by maintenance: towards adaptive work environments with improved industrial HCI*. In Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments (PETRA '19). Association for Computing Machinery, New York, NY, USA, 382–388.

Erik Pescara, Vincent Diener, and Michael Beigl. 2019. *VibrAid: comparing temporal and spatial tactile cues in control room environments*. In Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments (PETRA '19). Association for Computing Machinery, New York, NY, USA, 138–145.

Erik Pescara, Florian Dreschner, Karola Marky, Kai Kunze, and Michael Beigl. 2020. *GenVibe: Exploration of Interactive Generation of Personal Vibrotactile Patterns*. In Proceedings of the Augmented Humans International Conference (AHs '20). Association for Computing Machinery, New York, NY, USA, Article 8, 1–9.

Erik Pescara, Tobias Polly, Andrea Schankin, and Michael Beigl. 2019. *Reevaluating passive haptic learning of morse code*. In Proceedings of the 23rd International Symposium on Wearable Computers (ISWC '19). Association for Computing Machinery, New York, NY, USA, 186–194.

Erik Pescara, Anton Stubenbord, Tobias Röddiger, Likun Fang, and Michael Beigl. 2021. *Where should I look? Comparing Reference Frames for Spatial Tactile Cues*. In Proceedings of the 25th International Symposium on Wearable Computers (ISWC '21). Association for Computing Machinery, New York, NY, USA.

2 Background and Related Work

2.1 Information Appliances

Bergman defined information appliances as “a computer-enhanced consumer device dedicated to a restricted cluster of tasks”. According to Bergman the concept of information appliances is borrowed from the traditional notion of the appliance as a household appliance, a device that only performs a certain task (like dish-washing or vacuuming) but performs these tasks well, efficiently and without the user putting much thought into it[11]. The concept of the information appliance builds upon this by transferring the idea of a specialized tool that only performs a few tasks into the sphere of computer technology [11]. Information appliances can not do all things, a fully fledged desktop computer can do, but neither should they. Where a desktop computer offers the broadest possible range of applications, from checking your emails, surfing the web and gaming to video editing and programming, an information appliance focuses on a rather small cluster of tasks and performs them well. Bergman states a list of key characteristics that separate an information appliance from a traditional desktop computer, these are [11]:

- Limited purpose and functionality
- Not necessarily extensible or upgrade-able
- Expectation of replacement
- Perceived as less expensive
- Perceived as less complicated
- Very easy to learn and use
- No expectation of expert users

Bergman states two broad target domains of the information appliance, firstly Entertainment and secondly Information Access & Communication [11]. Bergman proposes the following interaction categories to differentiate between these domains:

- Duration
- Structure
- Approach
- Attention

Interaction duration is the time that the user spends with the information appliance, while information appliances for entertainment typically have a longer interaction duration (more than 30 minutes), information appliances for Information Access & Communication tend to have shorter interactions of less then 10 minutes.

Interaction structure according to Bergman is how clearly defined the user's goal of the interaction is. While users of entertainment information appliances „may not know exactly what sort of entertainment is of interest„[11], users of Information Access & Communication information appliances tend to have a clear goal in mind when interacting with the appliance.

Interaction approach is defined in a similar direction by Bergman by characterizing the approach towards the interaction as relaxed versus direct. While Entertainment information appliances typically are approached in a more relaxed attitude and in a less directed environment (i.e. playing a video game on your couch) an information appliance for Information Access & Communication typically are interacted with in a more directed and goal oriented way (i.e. finding a cinema where a movie is playing and reserving a seat).

The rise of the smart phone in the last ten years is a testament to the strength of the information appliance [1] and works well towards Bergman's view of information appliances, although smartphones fulfill the functions of an Entertainment information appliances as well as an Information Access & Communication information appliance.

2.2 Somatosensory System

The human skin is the largest and one one of the most important sensory organs of our body, beside our eyes and ears (see [75]). The skin interfaces with the environment and plays a large part in protecting us from pathogens and water loss, enabling us to survive on a dry planet (see [74]). There are two general types of skin, hairy and glabrous (hairless) skin as seen in Figure 2.1.

The human somatosensory system is responsible for interpreting tactile, temperature and pain stimuli. There are four different types of highly sensitive mechanoreceptive units in the glabrous skin area of the human hand (see [62]). The properties of these units are very similar to the ones already shown in other species such as monkeys (see [68]).

The end-organs of these units are the following:

- Merkel cell neurite complexes:
  React to low vibrations (5–15 Hz) and deep static touch like shapes and edges.
- Meissner corpuscels:
  React to moderate vibrations (10–50 Hz) and light touch they are primarily located in the fingertips and lips. They are responsible for feeling gentle stimuli such as Braille writing.
- Pacinian corpuscles:
  React to quick action potentials like vibrations from 40 to over 500 Hz. They are most sensitive to vibrations and have a large receptor field. They only react to sudden stimuli, so any stimulus spanning a longer period of time such as clothes are quickly ignored.
- Ruffini corpuscles:
  React slowly and react to sustained skin stretch, they are responsible for the feeling of object slippage and play a major role in the kinesthetic sense and control finger positions and movement.

2.2.1 Merkel cell neurite complex

Found in hairy and glabrous skin similarly, the Merkel complex (see Figure 2.2) is located in the basal layer of the epidermis. The Merkel complex is unencapsulated and consists of the Merkel cell as a specialized receptor and the Merkel disk as a terminal ending. The Merkel cell is thightly coupled to its surrounding by thick, short, finger-like

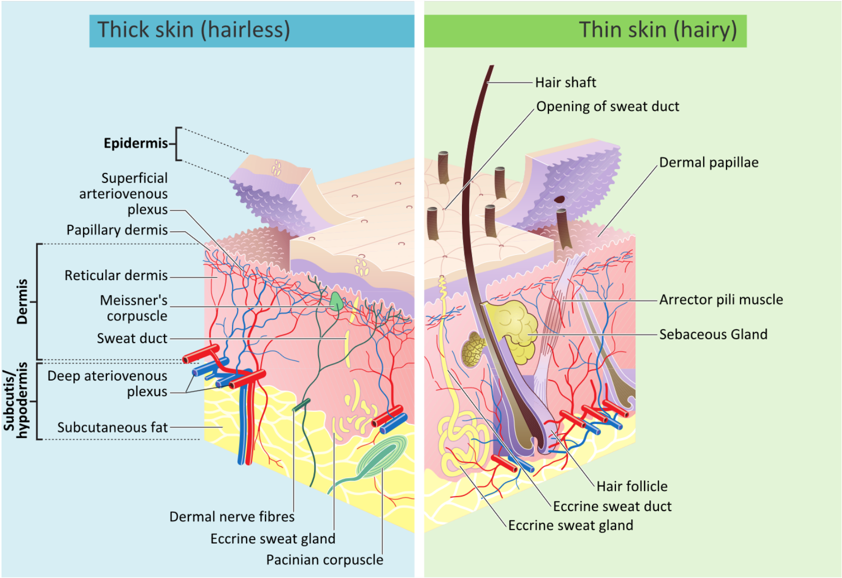


Figure 2.1: The skin layers [73].

protrusions and cannot shift its position relative to the surrounding. Therefore a distortion of the overlying skin translates to a distortion of the Merkel cell for the duration of the distortion. The Merkel complex responds to small forces applied to discrete patches of the skin (see [33]).

2.2.2 Meissner corpuscles

Found in glabrous skin within the dermal papillae, the Meissner corpuscle (see Figure 2.3) consists of an elongated, encapsulated stack of flattened laminar cells. When force is applied to glabrous skin the laminar cells in the Meissner corpuscle slide past one another, which distorts the membranes between the cells. The displacement of the membranes emits a signal of the force. When the force remains static and the laminar cells remain in the same position no signal is sent. The Meissner corpuscles therefore react to rapidly changing situation and only react when the force is first applied (see [33]).

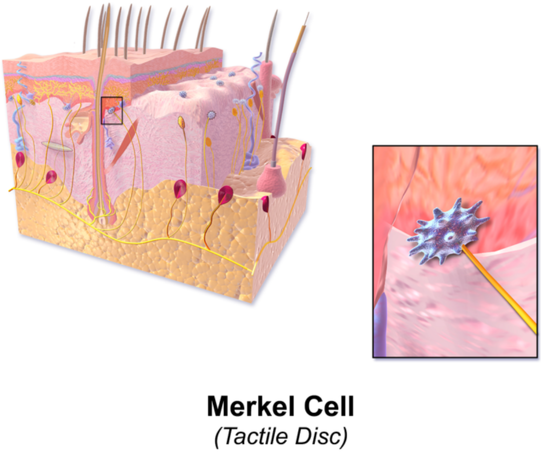


Figure 2.2: Merkel Cell [116].

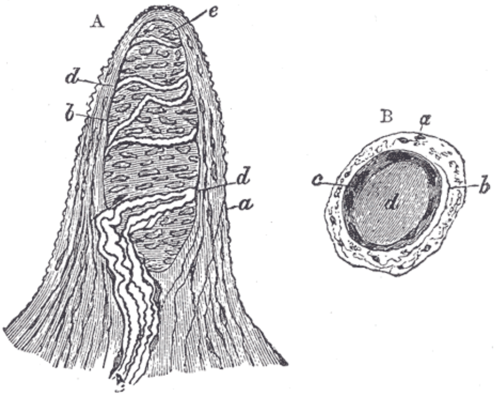


Figure 2.3: Meissner Corpuscle [116].

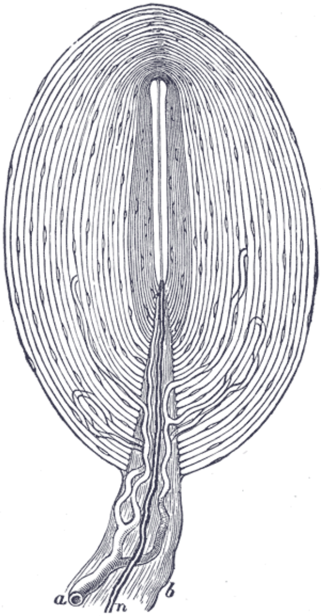


Figure 2.4: Pacinian Corpuscle [20].

2.2.3 Pacinian corpuscles

The Pacinian corpuscles (see Figure 2.4) are found in subcutaneous tissue beneath the dermis and other places such as the body cavity. The Pacinian corpuscle is oval, encapsulated and contains concentrically layered laminar cells. The outer laminar cells contain fluid that is displaced when force is applied on the corpuscle. When a force is applied for the first time to the Pacinian corpuscle, it initially displaces the laminar cells. If the force is maintained the fluid in the outer laminar cells is displaced and the applied force dissipates inside the Pacinian corpuscle. The Pacinian corpuscle is most sensitive to vibrating stimuli and unresponsive to steady pressure (see [33]). Pacinian corpuscles react best to vibrations with a frequency at about 250 Hz (see [42]).

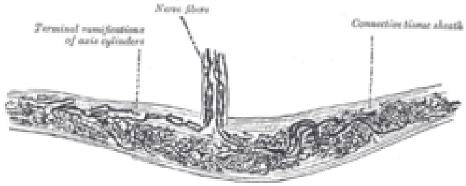


Figure 2.5: Ruffini Corpuscel [21].

2.2.4 Ruffini corpuscles

Ruffini corpuscles are found inside the dermis as well as inside joint ligaments and joint capsules. The Ruffini corpuscle is tube-shaped, encapsulated and contains longitudinal strands of collagenous fiber that are continous with the connected tissue of the skin or joint. The Ruffini corpuscles are orientated parallel to the skin with their long axes and are sensitive to stretch. When the surrounding skin is stretched, the collagenous fibers inside the Ruffini corpuscles are also strechted and transmit the stimulus. As long as the collagenous fibers remain stretched the stimulus is maintained.

2.3 Wearable Technology and Wearability

Wearable technology is a broad field as any technology that is worn on or close to the body or interacts with the body can be considered a wearable. Naturally the field is very wide and spans the whole body of the wearer, from smart glasses and instrumented headphones to smart garments, jewelry and implants to the near omnipresent smartphones and smartwatches. More than 20 years ago Gemperle et al. wrote the seminal work "Design for Wearability" in which she laid out the human factor principles to consider when designing a wearable for the human body. Gemperle et al. proposed six easy to generalize guidelines [37]:

- Placement
- Form Language
- Human Movement
- Proxemics
- Sizing
- Attachment

Placement: The placement has to be unobtrusive for the wearer with the intended use in mind. Generally it is important to use surface areas of the body that fulfill certain conditions [37]:

- Relativley same size across adults
- Areas with low movement/flexibility
- Areas with a large surface

Gemperle et al. proposed the areas of the body as seen in Figure 2.6.

Form Language: Gemperle et al. proposed a humanistic form language that works with the human body to achieve a stable fit of the wearable. The wearable device should form a concavity on the inside of the device to match the natural form of the human body [37]. On the outside convexity deflects objects and protects the wearer from getting stuck with the wearable. An example for humanistic form language can be seen in Figure 2.6.

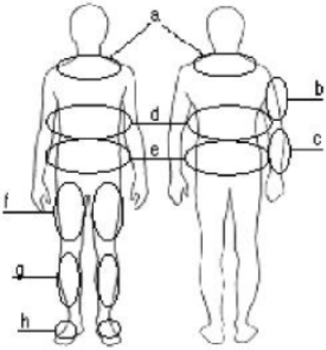


Figure 2.6: Good placement areas for wearables according to Gemperle et al.: (a) collar area, (b) rear of upper arm, (c) forearm/wrist, (d) rear, side and front of ribcage, (e) waist and hip, (f) thigh, (g) shin and (h) top of foot [37].

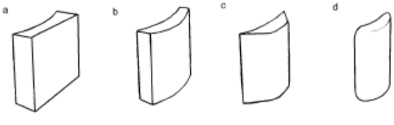


Figure 2.7: Transformation to humansitic form language [37].

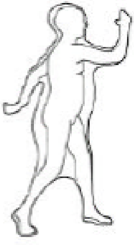


Figure 2.8: Rule of thumb of the aura around the human body that will be perceived as part of the body [37].

Human Movement: The wearable should not interfere with the normal movement of the user, unobtrusiveness is key. Wearable devices can either be designed around the active areas of the joints to allow freedom of movement or the wearable device can include free spaces into which the body can move [37].

Proxemics: An important aspect is the concept of proxemics – the aura around the body that is considered part of the body as seen in Figure 2.8. According to Gemperle et al. the form of the wearable should stay inside the intimate space of the wearer to be perceived as a part of the wearer's body. As there are no hard rules what is and is not part of the "aura" the wearables should be as flat as possible to fit inside the proxemic hull of the wearer.

Sizing: Persons have different sizes drastically in some areas of the body, this has to be accounted for in the design of a wearable device. Gemperle et al. proposed a two-pronged approach to deal with the variability in sizes, firstly consulting standard measurement data of body sizes (see for example Tilley et al. [126]) and secondly by considering the fat and muscles growth of the wearer in its entirety and designing appropriate wearables to allow for wearers of different shapes and sizes [37].

Attachment: For the wearable to be comfortable it is generally advised to wrap the wearable around the body and avoid using single point fastening systems [37]. Attachment of wrist clothing can be done in different ways, popular methods are flexible tubes like wristbands, clips or buckles like watches or hook and loop fasteners (otherwise known as velcro). It is important for comfortable attachment to distribute the pressure around the wrist evenly and avoid rigid structures which distribute the pressure unevenly. Due to the possibility of different wrist circumferences of the users the attachment method has to be flexible.

2.4 Tactile Displays

A tactile display according to Chouvardas et al. is a human computer interface that utilizes exclusively tactile signals to present information (see [24]). Tactile displays can reproduce the tactile parameters of an object, such as shape, surface texture and temperature. They can be used in multitude ways, from guidance systems for visually and hearing impaired persons, applications in mobile environments up to interfaces in virtual reality applications. Tactile displays differ from haptic displays in the fact, that they present information in 2D. Haptic interfaces present information with 3D surfaces and use force feedback. The movement and energy needed in a tactile display can be generated in a variety of ways, like piezoelectric crystals, RC servo-motors, pneumatic systems and other methods. Tactile displays, depending on the receptors of the skin for information transfer use the following modalities for information transfer:

- pressure
- vibration
- electric field
- temperature

The information transfer via vibration relies on several properties as Brewster and Brown observed in their research [16]. As tactile interfaces are becoming ubiquitous they coined the phrase „Tacton“ for structured, abstract messages encoded in vibrations to communicate non-visually. Tactons rely on different parameters which can be used for the creation:

Frequencies: As already described the pacinian corpuscles react best to frequencies at around 250Hz although a range of 20 to 1000 Hz is perceivable [42]. Nevertheless the human skin is poor at frequency discrimination compared to the ear and only between 3 and 5 values of vibration rate can be distinguished [132].

Amplitude: The intensity of the stimulation can be used as a tool to encode information [16]. The intensity can reach 55 dB above the detection threshold before the stimulus becomes painful [41], although the perception deteriorates above 28 dB which therefore is a useful maximum [27]. It has been proposed, that no more than four different intensities should be used to encode information [16].

Pulse-duration: Vibrations lasting 100ms or less are preceived as taps whereas vibrations lasting longer are perveived as continous vibrations [41].

Rhythm: As vibrations of different lengths are percieved differently, they can be grouped together to form rhythms [16]. Rhythms are a powerful cue in sound and touch and allow us to communicate different informations at different times to the same area of skin or group different events together [41].

Location: The choice where the stimulus is placed is very important because of the different levels of sensitivity and spatial acuity of different body locations [16].

A display can use several body locations, with the result that the location of the stimulus is another parameter of the display. It has to be condsidered that the largeness of the perceptive region of the pacinian corpuscles can cause a problem when two actuators are too close to each other to allow differentiation between the stimuli [32].

Tactons can be used in different environments, either as an enhancement for desktop interfaces, helping visually impaired users or in mobile and/or wearable devices.

3 Exploring Continuous Wearable Tactile Displays in Sport and Outdoor Activities

This chapter explores continuous wearable tactile displays in sport and outdoor activities and presents two continuous wearable tactile displays for outdoor sport and paragliding. Sport and outdoor activities can profit and are already profiting from the adoption of wearables, this chapter explores the use of continuous wearable tactile displays in paragliding. The work in this focused on developing wearable tactile interfaces to constantly communicate vital information to the paraglider pilot and testing these wearables in laboratory and field studies.

There are several factors at work that make the case for paragliding as a good use-case to study the design and effects of continuous wearable tactile displays in sport and outdoor activities. The factors are dependence on continuous external information, need for wearability and affinity for technology. There are only a few outdoor activities that heavily rely on external information for the safe and enjoyable execution of the outdoor activity. The need for continuous external information in outdoor activities like hiking, running, surfing or skiing is minimal and usually is limited to the weather and the location of the activity. A hiker might want to know how the weather will be on the day of the hike, where to endpoint of the hike is and how to get to the endpoint. These are all important facts to know, but continuous reminders or updates are generally not needed. Paragliding and several other outdoor activities like skydiving or scuba diving depend on continuous external information to even be able to perform the activity safely and enjoyably. For example in scuba diving the scuba diver needs to know about the air supply and needs to check it as often as possible. The same is true for paragliding and the need of knowing the vertical velocity of the paraglider in the air. The need for wearability is an important factor in nearly all outdoor activities, as most activities are not stationary and if technology is brought with it should not be cumbersome and be wearable instead. In paragliding the need for wearability is given as the equipment needed for paragliding is already heavy and saving weight and avoiding additional cumbersome devices is greatly appreciated. As for the technical affinity, paraglider pilots are already used to having technology around them when pursuing their hobby and are dependent of receiving a continuous stream of information about their environment while in the air. All these factor contribute in making paragliding a good fit for exploring continuous wearable tactile displays in outdoor activities.

While the velocity of up- and downwards movement in 3D-space is not relevant for most activities, for air sports like paragliding and hang gliding such knowledge is crucial for a long, safe and pleasant flight [65]. The human vestibular system, which is located in the inner ear, is a very good perceptor of spatial orientation, rotation and linear acceleration. However, it lacks a sense for constant velocity, as soon as there is no acceleration humans are not capable of feeling their linear movement. This can be a problem for scuba divers, astronauts, pilots or in this case paraglider pilots. Humans have no natural sense to determine their velocity. This counts for both horizontal velocity (forwards or backwards movement, velocity over ground) and vertical velocity (upwards or downwards movement). Though humans can estimate their velocity using their visual orientation by observing their changing surrounding. Horizontal velocity is easier to estimate because the landscape below the pilot can be used for orientation. If the pilot flies beneath the mountain summit he can look at the landscape to his side to estimate the velocity over ground. Because of its engine-less nature, the paraglider has to exploit thermals (areas of rising air) to gain altitude and extend the flight. While there is no legal obligation to use one, virtually every pilot has a so-called *variometer* as a tool to measure the vertical velocity of her movement in 3D-Space. Variometers encode velocity as auditory and visual signals, enhancing the pilots' capabilities to extend the flight time or avoid dangerous zones. A variometer is a very good example for a information appliance, as its core functionality is highly specialized (informing the user about the vertical velocity of the user) and having little to no interaction between the user and the appliance, as the user is focused on flying and not interacting with the appliance (e.g. pushing buttons and controlling the variometer) during the flight. Due to the nature of the sport variometers can't just rely on a visual representation of the vertical velocity but need a second dimension to present the vertical velocity for added redundancy. This is mostly done with an auditory output using pitch and rhythm depending on the variometers reading. Due to the loud sounds that are generated by the gilder and the air stream variometers have to be comparatively loud to be heard by the pilot. This can spoil the flying experience and in worst-case can even be dangerously distracting. As stress levels are elevated in paragliding [13] stress sources should be minimized.

This chapter proposes and explores the use of vibrotactile cues to communicate the up or downward velocity in 3D-space, it also presents the design and implementation of two tactile variometers: A 6-channel tactile variometer cuff (published in Proceedings of the 2017 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2017 ACM International Symposium on Wearable Computers [90]) and *RüttelFlug*(published in Proceedings of the 2017 ACM International Symposium on Wearable Computers [89]), a wrist-worn tactile variometer that relays the information with two vibration actuators.

3.1 Related Work

Modern variometers provide the pilot with a multitude of useful information besides vertical velocity, such as air speed, speed over ground and location. In contrast to that, the design concept underlying the proposed continuous wearable tactile displays is that of a minimalistic variometer with only the core functionality which is absolutely needed. Other research efforts also focus on connecting variometers with each other to form a distributed real-time detection system for thermal hotspots [135]. This allows pilots in one area to pool their knowledge regarding the present thermals. While the tactile variometers discussed here are designed as a single user appliances, the collected information could easily be disseminated.

While there has been extensive research on the stimulation of the skin senses to expand our perception of our environment [29], none of this was applied in tactile wearables for paraglider or glider pilots before my work. Specifically, Brown and Brewster [16] proposed the concept of so-called *tactons* to transfer information easily via tactile feedback. This work incorporates patterns of tactons to relay information in a similar way.

Tactons are structured abstract tactile icons to communicate with the user in a non-visual way. Brown et al. [17] later showed, that users reached a 93% recognition rate for different rhythms of three successive tactons.

Kaczmarek et al. surveyed technologies, definitions and implications of sensory substitution, i.e. using one human sense to receive information normally received by another

Figure 3.1: *RüttelFlug* is a wrist-worn tactile variometer, e.g. for paragliding. It was designed to be unobtrusive and fits well even under thick clothing.

sense [61]. Kaczmarek et al. found that while the tactile information flow is generally slower than speech (40 bits/s) or reading (30 bits/s), vibrotactile substitution systems can still be reliably used to transfer information with 5 bits/s. This is more than enough to communicate a set of different states, as done in this work for vertical velocity change.

3.2 *RüttelFlug*

This chapter presents the design and implementation of *RüttelFlug*, a wrist-worn continuous tactile wearable that measures vertical velocity with a pressure sensor and relays the information via tactile output with two vibration actuators on opposite sites of the wrist using different vibration patterns to tell up or downward movement and different velocities apart. The users' ability to discriminate vibration patterns was measured in a lab study with 13 participants and the whole system was evaluated in two field studies with four and two paraglider pilots. The results indicate a good differentiability between the developed patterns and an unobtrusive user experience.

3.2.1 System Design

RüttelFlug was designed as continuous wearable tactile display and its design follows the guidelines proposed by Gemperle et al. [38] in being lightweighted, small, worn on the skin and flexible. The system satisfies the need of being inside the proxemic aura

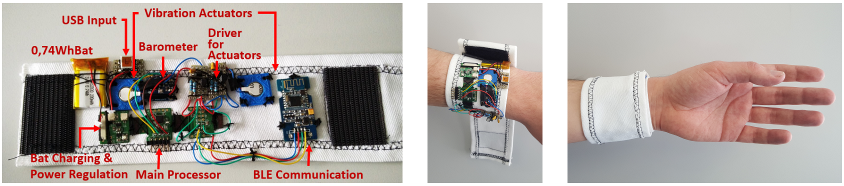


Figure 3.2: The *RüttelFlug* wristband prototype is built based on a flexible *Seeeduino Film* development platform and features two *Shenzhen Anda Electronic ANDA-B1020* vibration actuators, a *Bosch BMP280* barometric pressure sensor and a *Grove BLE v1* Bluetooth module for communication with smartphone for data logging. Its wriststrap is designed to cover the electronics when closed (right hand side).

of the pilot [37]. The form language of the *RüttelFlug* is very simplisic in only being a piece of clothing which entwines the wrist of the pilot (see Figure 3.2). Important requirements for the *RüttelFlug* design were:

- *Minimalistic:* In contrast to conventionel variometers, *RüttelFlug* provides only the core functionality of informing the pilot of the vertical velocity of the glider.
- *Non-Intrusive: RüttelFlug* is silent and does not distract the pilot with loud noises or otherwise.
- *Low Maintenance:* The pilot does not need to interact with *RüttelFlug* while flying, nor can the pilot interact with the device, because the only possible interaction is turning it on or off.

The design of the *RüttelFlug* system was informed by interviews with four experts (general requirements, system interaction) before start of the system design. Additionally, six single-subject tests concerning the wearability of the system were conducted with both experts and non-experts in an agile process while designing and building iterations of the system. Experts (1 experienced paraglider, 3 paragliding instructors, 1 tailor) reported in open interviews of about 30 minute length. In a workshop session with the tailor various fabric, sewing and attachment options where discussed leading to the design in Figure 3.2.

Hardware

As shown in Figure 3.2, *RüttelFlug*'s electronic components are sewn onto a cotton wristband of ca. 6.5cm width and an average thickness of 3mm. The prototype is based on a Seeeduino Film microcontroller board (Atmega168) and powered by a rechargeable LiPo-battery pack with a capacity of 200mAh. For measuring of altitude changes, a Bosch BMP280 piezoresistive barometric pressure sensor is integrated via I2C. Two Shenzhen Anda Electronic Co., Ldt. ANDA-B1020 coin type coreless vibration motors (amplified via drivers, 2mm size, packed in custom 3D printed housing) are used for user interaction. A Grove BLE v1 shield with a Bluetooth V4.0 HM-11 BLE Module (TI2540) was connected to the Arduino via UART temporarily in order to enable data logging for evaluation. Vibration actuators were placed 8cm apart from each other to be placed on opposite sides of the wrist when worn (see Figure 3.2).

Wearable Sensing

The human skin is the largest and most important sensory organ together with eyes and ears [14]. Vibrations are mostly felt with Pacinian corpuscles which react to excitation frequencies from 40 to $>$500Hz [12]. Although the perceptive region of the Pacinian corpuscels is quite large the weaker spatial resolution of vibrations was counterbalanced by maximizing distance between vibration actuators by placement on opposite sides of the wrist and chose vibration patterns as a reliable way to transfer information [37]. *RüttelFlug* samples the barometric pressure every 50ms. The BMP280 is very sensitive but also shows considerable noise which requires 20× oversampling to read stable values (overall sample cycle=1Sec). Raw values are computed to standard atmospheric sea level pressure using the internal calibration settings of the BMP280. Velocity is then calculated as the difference in air pressure of two measurement times measurement interval.

3.2.2 Vibration Pattern Design

In interviews that were conducted for the design of the tactile display of *RüttelFlug*, paragliding experts reported that not absolute velocity values but certain classes of sink/ascend situations are of interest to a paraglider pilot. Consequently the velocity value has to be coded into an information representing a velocity situation class rather than just transfer the velocity into an analogue output (e.g. vibration frequency) value. This concept is in contrast to the working principle of existing variometers where e.g. a sound cue gets louder and faster continuously based on the velocity of a paraglider.

Together with one of the experts 8 classes of vertical velocity (see Table 3.1) have been identified. Classes are non-linear ordered to velocity values because they depend on paragliding situation rather than physical measurements. The velocity classes represent also situations that indicate standard behavior for a safe paragliding trip. Because of this, but also because higher resolution is required for certain paragliding maneuvers in some of the classes, subclasses have been assigned to certain classes in a second step.

For coding each class a vibration pattern is assigned. Subclasses result in a variance of the basic vibration pattern of the class. Weak sink was identified as the "zero" situation, so no pattern is assigned. The number of subclasses can be found in the last column in Tab. Table 3.1. The next section will present the initial pattern assignment and some results from experiments when using the *RüttelFlug* device with these patterns.

3.2.3 Lab Evaluation

Initially the vibration patterns seen in Figure 3.3 were proposed and evaluated in a lab study. Patterns for sink (blue) are applied to the vibration actuator *inside the wrist*, patterns for lift (light blue) are applied to the vibration actuator *outside the wrist*.

For an initial vibration pattern evaluation, 13 participants [(12m, 1f) between the age of 19 and 66 (median 23)] were invited to the lab. Participants were instructed to solve 3 overarching tasks with up to 3 subtasks within 45 minutes.

Tasks are always executed in the same order but the order of the vibration actuator

Velocity [$\frac{m}{s}$]	**Category**	**Implication**	**Class**	**# Subclass**
< -2.5	abnormal sink	leave area!	-3	1
-2.5 to -1.5	strong sink	leaving area advised	-2	1
-1.5 to -0.5	normal sink	glider sink	-1	1
-0.5 to 0.0	weak sink		0	1
0.0 to 0.5	zero lift	active flying	1	2
0.5 to 2.0	weak thermal	circling possible	2	3
2.0 to 4.0	thermal	circling advised	3	3
> 4.0	strong thermal	hang tight	4	1

Table 3.1: Rate of vertical velocity and its implications.

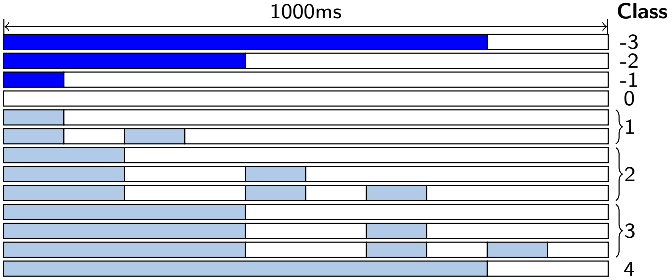


Figure 3.3: Vibration Patterns: Wrist: Inside (Blue), Wrist: Outside (Light Blue).

Actuator Position	800ms	400ms	200ms	100ms
Wrist: Outside	95% (0.18)	85% (0.22)	90% (0.21)	100% (0.00)
Wrist: Inside	90% (0.16)	87% (0.22)	77% (0.39)	95% (0.13)

Table 3.2: Success rate (and std.dev.) of vibration length recognition.

tested (above wrist, below wrist) were randomized. Details of tasks and subtasks were explained briefly beforehand. Then participants were fitted with the *RüttelFlug* wristband to execute the tasks and instructed to sit in an upright position, holding the arm fitted with the *RüttelFlug* in a vertical position.

Vibrations of length 800ms, 400ms, 200ms and 100ms were applied to the one of the vibration actuators. Participants were asked where the vibration was coming from. No training was given. The 800ms vibrations were detected correctly in 97.6% (SD 0.04) of times. The 400ms and 200ms were detected with 100% accuracy. The 100ms vibrations were detected correctly in 90.7% (SD 0.16) of times. It was observed that the participants while overall having a very good detection rate had the most problems in detecting the 100ms vibrations.

Participants were asked to recognize and name the length of the vibrations. They had a brief training phase, demonstrating each vibration once on both vibration actuators separately. The results are shown in Table 3.2.

Participants were asked to identify vibration patterns for lift (see Figure 3.3) with and without the help a visual cue listing the patterns. The visual cue consisted of a printout of the patterns for lift (see Figure 3.3). In a brief training phase every pattern was applied

Actuator Position	Visual Cue	First Half	Second Half
Wrist: Inside	YES	77% (0.19)	92% (0.12)
Wrist: Outside	YES	87% (0.19)	92% (0.14)
Wrist: Inside	NO	82% (0.20)	91% (0.10)
Wrist: Outside	NO	88% (0.09)	92% (0.09)

Table 3.3: Success rate (and std.dev.) of vibration pattern recognition.

on both vibration actuators seperately. Each test iteration applied 20 vibration patterns. Recognition with visual cues was tested first and without cues second. Results are plotted in Table 3.3.

Using a visual cue participants had a recognition rate of 89% (SD 0.16) outside the wrist and 84% (SD 0.14) inside the wrist. Without visual cue the recognition rate was 90% (SD 0.07) outside the wrist and 87% (SD 0.12) inside the wrist. It was noticeable that nearly all participants improved considerably during the experiment. This is shown in Table 3.3 where in all iterations mean recognition rate went up and standard deviation improved from the first 10 patterns and the next 10 patterns of an iteration.

3.2.4 Evaluation

First Field Evaluation

In the first field evaluation four male paragliding pilots between the age of 22 and 29 as participants were recruited. Experience level spanned from intermediate to expert, all were used to flying with conventional variometers. The velocity categorization seen in Table 3.1 and vibration patterns described in Figure 3.3 were used. The evaluation was conducted during a cold weather period, thus participants wore layers of (thick) clothing above the *RüttelFlug* wearable (see Figure 3.1).

The participants were fitted with *RüttelFlug* and briefed for 10 to 15 minutes in using and interpreting it. Particpants were asked to fly with *RüttelFlug* and their own variometers until they felt comfortable using only *RüttelFlug*, at which point they should independently switch of their variometer and only fly with *RüttelFlug* feedback.

After the flight participants filled out a Raw TLX [18] survey regarding usability of *RüttelFlug* (see Figure 3.5) and answered questions regarding their flight experience with *RüttelFlug*. Of the four flights two were very short (10 minutes, no thermal), two flights were of medium length (45 and 60 minutes) with thermals. All participants reported problems localizing vibration sources for 100ms (zero lift or normal sink) and deciding accordingly. All participants were able to differentiate between patterns and use them to circle efficiently in a thermal if present. Overall idea and concept of *RüttelFlug* was well liked due to its silent and non-intrusive nature. All participants were positive that with more training *RüttelFlug* would be a viable alternative for conventional variometers.

Figure 3.4: Optimized Vibration Patterns for sink (Wrist: Inside).

Second Field Evaluation

Vibration patterns for sink were changed after the feedback of our first field study to allow for greater differentiability between sink and lift patterns (see Figure 3.4). The updated System was evaluated by two experienced male paraglider pilots (age 25 and 30) who were used to variometers. The evaluation design stayed the same. Both participants were able to use and interpret *RüttelFlug* to center thermals. Although the difference between zero lift and weak sink was reported as "subtle", none of them had problems telling them apart. One participant wore *RüttelFlug* for over two hours (2 flights) and praised it on it’s non-obtrusiveness where he only felt it when he "wanted to feel" it. The preliminary results of the Raw TLX results (see Figure 3.5) by our two pilots suggest a lower mental demand, increased performance and reduced frustration. The assumption can be made that the reduced mental load and better flying experience stems form the better differentiability between zero lift and sink.

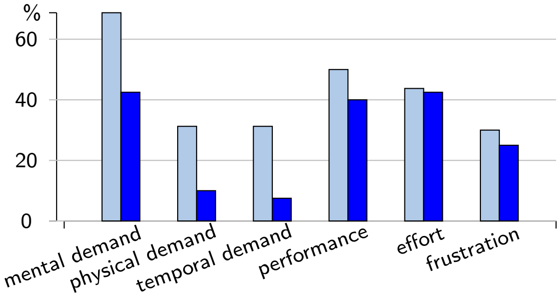


Figure 3.5: Raw TLX: first (light blue) and second (blue) field evaluation, lower is better.

Figure 3.6: Cuff: Pockets with actors inside

3.3 6-Channel Tactile Variometer Cuff

The 6-Channel Tactile Variometer Cuff was developed to explore spatio-temporal vibration patterns to communicate sink and lift in paragliding. The core design idea of this work was to create a continuous wearable tactile display with a tactile sensation that moves around the arm of the user in a circle and builds upon the previous work done with *RüttelFlug* to expand the dimensions of the tactile display. This “moving around” sensation might be beneficial to the user as it is interpreted as a fluid motion of the vibration with a directional component (clockwise or counter-clockwise movement) that can be coded as sink or lift depending of the direction of the vibration. The design was evaluated in a field study with five paraglider pilots who flew with the variometer cuff,

Figure 3.7: Worn cuff

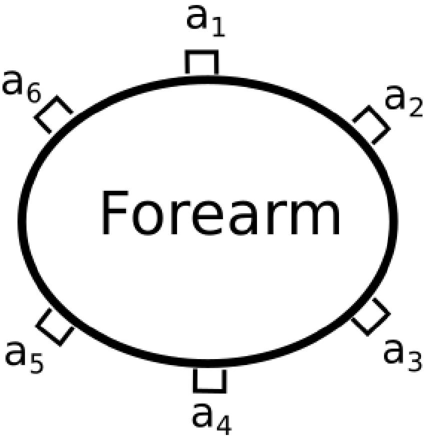


Figure 3.8: Cross section of the worn cuff

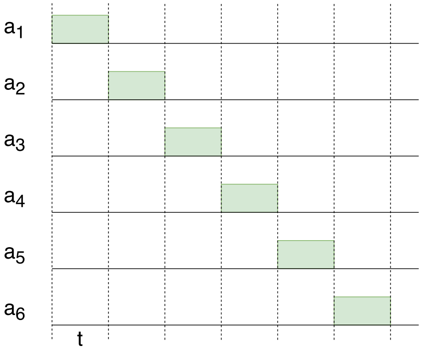


Figure 3.9: Simple loop

however only data of three pilots could be collected.

3.3.1 System Design

Three different spatio-temporal patterns were proposed as shown in Figure 3.9, Figure 3.10 and Figure 3.11 and build upon a circle of actuators evenly placed around an arm or a leg (see Figure 3.8 as an example with six evenly placed actuators).

The spatial aspect of the spatio-temporal patterns are described as follows.

For the **simple loop** a single actuator is activated in each step for a certain *activation time* t. In the next step the actor is deactivated and the neighbouring actuator is activated (see Figure 3.9).

For the **cross loop** two active actuators "push" around the arm (see Figure 3.10). At the beginning of each step, the current active actuators change from a_{k-1} and a_k to a_k and a_{k+1}.

The **incremental loop** activates at the beginning of each step one additional actuator (see Figure 3.11). When all actuators are active, the next step deactivates all actuators and the procedure starts at the beginning.

All loops can be activated either in clockwise or in counter-clockwise direction and at different activation speeds.

The activation speed of the loop is used to encode the absolute value of the climb rate. A higher climb rate leads to a faster activation speed and a lower climb rate relates to

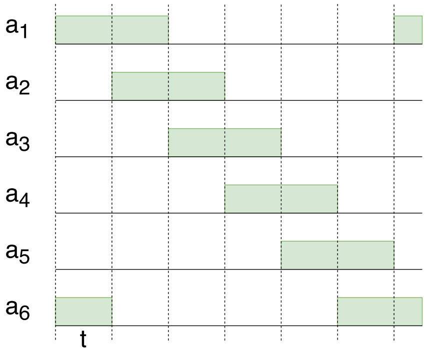


Figure 3.10: Cross loop

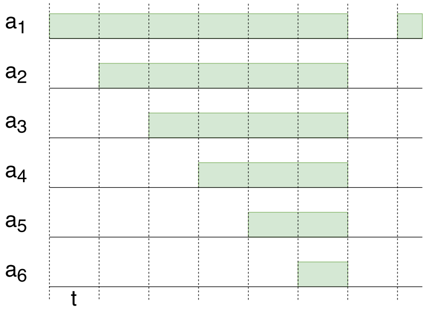


Figure 3.11: Increment loop

Speed	c	f
simple loop	$(-2\frac{m}{s}, 2\frac{m}{s})$	$(0.19\frac{r}{s}, 0\frac{r}{s})$
cross loop	$(-4\frac{m}{s}, -2\frac{m}{s})$, $(2\frac{m}{s}, 4\frac{m}{s})$	$(0.56\frac{r}{s}, 0.19\frac{r}{s})$
incremental loop	$(-\infty, -4\frac{m}{s})$, $(4\frac{m}{s}, \infty)$	$(0.56\frac{r}{s}, 1.67\frac{r}{s})$

Table 3.4: Assignment of the pattern depending on climb rate (c) and the corresponding frequency (f).

a slower activation speed, i.e. the loop is moving around the arm faster or slower. The climb rate c was mapped to the activation time t as follows:

$$t = \max(100, 1500 - 300 \cdot |c|)$$

Where the unit of c is $\frac{m}{s}$ and the unit of t is ms.

With six actuators the frequency (rounds per second) f is:

$$f = \frac{1000}{6 \cdot t}$$

t is limited since very fast signals aren't well perceived by the users. Limiting t to a value of at least $100ms$ (or $f = 1.67\frac{r}{s}$) is equivalent to an absolute climb rate of $4.66\frac{m}{s}$. Although higher climb rates can occur, this is sufficient as the typical climb range is between $-4\frac{m}{s}$ and $4\frac{m}{s}$.

The direction of the pattern is used to encode whether the climb rate is positive or negative. I.e. if the glider is climbing or sinking. Positive climb rates lead to a clockwise direction, negative climb rates to a counterclockwise moving pattern.

All three proposed spatio-temporal patterns were used to emphasize between weak, medium and strong climb or sink. In associating the climb rate with the activation time, a pattern gives also a roughly classification of the climb rate, with the simple loop (see Figure 3.9) standing for weak climb between 0 and 2 meters per second, the cross loop (Figure 3.10) standing for medium climb between 2 and 4 meters per second and finally the incremental loop (see Figure 3.11) for speeds above 4 meters per second. The assignment between classification and climb rate / frequency / pattern is given in table Table 3.4. Although it was stated that the signal is not interrupted, there is one exception. To avoid a high frequency direction switching, the signal is interrupted between $\pm 0.07\frac{m}{s}$.

3.3.2 Hardware

The technical system described by [31] was used as the technical platform for the Variometer Cuff. As described by Diener et. al. (2017) the central unit is the nRF51822 chip on the BLE Nano Board (16MHz, 256 KB Flash, 16KB RAM) [31]. The vibration motors (Adafruit Product ID 1201) are thin (2.7 mm) and lightweight (0.9 g) and produce vibration patterns at a comfortable and noticeable frequency of 121 Hz at 3.3V [31]. As pressure sensor a BME280 piezoresistive pressure sensor was utilized. The whole system is powered by a 730 mAh LiPo-battery pack [31].

The micro-controller, battery and a pressure sensor are also included in the cuff (see Figure 3.6). The cuff is worn on the forearm and can be easily zipped on and off. The actuators are placed in the bottom part of the cuff (defined as ’near the ellbow’) and form a ’ring’ around the arm when worn (see Figure 3.7). The actuators are ordered from a_1 to a_6. For the actuator a_k the right neighbour is a_{k+1} and the left neighbour is a_{k-1} (see Figure 3.8).

3.3.3 Evaluation

To evaluate the variometer scuff five pilots were asked to test it during flight in a field study. The pilots were equipped with the cuff and wore them directly on the skin beneath all other clothing. The participants were briefed shortly on the different types of vibration patterns and the different speeds. After the briefing the participants were free to start their flights and fly as long and as often as possible. The participants were asked to file a short questionnaire directly after their flight. The questionnaire consists of four brief questions: ’Could you recognize if the cuff signalled climb or sink?’ (Q_1), ’How well could you, by means of the vibration, center the thermals?’ (Q_2), ’Could you recognize if the updrafts got stronger or weaker?’ (Q_3) and ’Did the cuff supported you through your flight?’ (Q_4). These questions could be rated from 0 (worst) to 5 (best). A longer interview was conducted after the pilots finished all their flights.

Due to a busy take-off zone only three pilots recorded two flights each (see Table 3.5). The records contain duration of the flight and the sum of the height gained using updrafts (cumClimb). Only four filed questionnaires were received (Table 3.6). The main problem was that the recording of the flights were made with smartphones, which also holds the questionnaire. The configuration between cuff and smartphone sometimes took too

Pilot	A_1	A_2	B_1	B_2	C_1	C_2
Duration (h)	0:10	1:51	0:23	1:48	0:27	0:38
cumClimb (m)	41	2555	362	2121	62	696

Table 3.5: Duration and cumulated climb of the recorded flights.

Question	Q_1	Q_2	Q_3	Q_4
A_1	4	1	3	3
A_2	5	4	3	5
B_1	4	0	4	4
B_2	3	1	0	5

Table 3.6: Ratings of received questionnaires by participant A and B after their first and second flight. Scale 0 (worst) to 5 (best).

long, so that the participants proceeded with their flight only wearing the cuff.

A flight typically lasts for seven to twenty minutes, if no updrafts are used at all. Such a flight would also have a accumulated climb of 0. As a rule of thumb one could say, higher accumulated climb leads to longer flights and vice versa. Two of the pilots undertook a flight with a duration of almost two hours. After his first flight, participant *A* reported that he got along with the cuff very well. However in this flight were only few weak updrafts. On his second flight, the thermals got stronger and he centered some of them supported by the cuff. Participant *B* was not able to center thermals. However, he reported that he detected weak updrafts with the cuff, which he normally, without any vario, would not have used. On his second flight he gained height through several thermals, without centering them properly.

Although participant *C* could extend his flights slightly, he mentioned after the first flight that some of the actuators didn't work properly, leading to a non comprehensible perception of the vibrotactile display. After being provided with a working scuff he said it was 'better but not perfect'. During the interviews some participants also reported difficulties recognizing the direction of the vibration, especially around zero lift situations ($0\frac{m}{s}$). Additionally, the cognitive load to detect the direction of the signal was perceived as high. Some of the participants also mentioned that the speed of the signal was perceived easier than the direction.

3.4 Conclusion

In this chapter two tactile variometers were presented. For both variometers the patterns were designed in an iterative manner to have a high differentiability and learnability. *RüttelFlug* used two actuators and temporal patterns to distinguish between different classes of vertical velocity, while the 6-channel Variometer Cuff used spatio-temporal patterns that moved around the arm to display the vertical velocity as the speed in which the pattern moves around the arm.

While *RüttelFlug* used a straightforward approach and simple and Morse Code inspired vibration patterns, the 6-channel Variometer Cuff used a more complex pattern set with activation speed and direction as additional variables. This added complexity proved to be detrimental in the evaluation for two reasons, the display was harder to "read" and understand for the users and the added technical complexity resulted in more technical glitches during the field study and with this less use-able results. The simplicity and readability of a tactile display is of great importance, especially if the information is critical for the users safety and its surrounding. When comparing the two tactile displays *RüttelFlug* performed better in the field, had less technical issues and thus had more users who tested and liked the device. Participants in a lab study and two real-world field studies were able to distinguish patterns quickly and learned "to feel the vertical velocity". In the two field studies, experienced paraglider pilots used *RüttelFlug* in-flight and rated the final pattern design as enjoyable and unobtrusive.

From the results of this chapter there are several implications that inform the contributions of this thesis in the areas of creating vibrotactile patterns, learning vibrotactile patterns and the spatial stability of vibrotactile patterns.

The user study results for *RüttelFlug* and the 6-channel tactile variometer clearly show the importance and the challenge in creating a set of expressive vibrotactile patterns. For *RüttelFlug* multiple iterations in the pattern design were necessary to reach a point in which paraglider pilots could use the variometer in the field without problems and confusions about the different velocity classes that were transmitted. The design space of the vibrotactile patterns used by *RüttelFlug* was rather strict, two actuators could be used, the maximum length of a pattern should be 1000ms and the number of distinct patterns was 13. The patterns were optimized for their expressiveness and legibility when played in a loop. The limited design space made it easier to craft the vibration patterns by hand, but another route could be using generative models to create expressive patterns and optimize the patterns for their intended purposes. An approach of generating expressive vibrotactile patterns with evolutionary algorithms will be discussed in chapter 6.

Regarding the need to learn vibration patterns and their associated meanings the exploration in the sport domain helped to clarify the design. Paragliding is a sport in which mountains are necessary and driving or hiking up a mountain is nearly always required of the paraglider. This fact needs to be considered in combination with the necessity to learn the vibration pattern before the flight starts. Driving up a mountain or hiking up a mountain are activities in which both hands are needed and the driver or hiker is mentally occupied with driving or hiking. To learn the vibration patterns while doing something else would require passive learning. In chapter 7 this thesis investigated the claim that learning stimulus-stimulus associations like the associations of vibration patterns to their meaning can be done passively.

Paragliding is an outdoor sport with lots of movement involved, even though paraglider pilots are in a sitting or lying position during most of the flight. Both tactile displays shown in this chapter had a spatial design component of the tactile display, *RüttelFlug* used two different actuators located on opposite sides of the wrist to show upwards or downwards velocity and the 6-channel variometer used clockwise and counterclockwise movement of the pattern to indicate upwards velocity or downwards velocity respectively. As the paraglider pilots moves his or her arm to steer the paraglider and uses different grips to hold the steering lines, the tactile output of the displays can be interpreted differently. Especially in the *RüttelFlug* case upwards and downwards velocity are indicated by different actuators, upwards is indicated by the actuator on the outside of the wrist near the back of the hand and downwards is indicated by the actuator on the inside of the wrist near the palm of the hand. As the wearable is fixed in place on the wrist the relative position of the actuators change when the hand or the wrist is turned. This begs the question how the wearer reacts to spatial impulses coming from the "wrong" direction and what reference frame should be used for spatial cues like in the *RüttelFlug* case. These questions will be answered in chapter 8.

4 Exploring Continuous Wearable Tactile Displays in Gaming and Entertainment

This chapter presents one continuous wearable tactile display for gaming and entertainment ([90]), as well as a continuous wearable tactile displays which was developed for gaming but also shows some potential for a business use case, bridging the gap between these worlds [77].

In the past, tactile feedback in video games in the commercial mass market has been almost exclusively used in the form of vibration-enabled game controllers. The function of the feedback is as diverse as games themselves, ranging from informing the player about certain events (e.g. low life) over providing feedback on user input (e.g. button presses) to providing sensory narration (e.g. accompanying an explosion) [56]. In 'classic' PC gaming, i.e. with mouse and keyboard, tactile feedback is practically absent and only available with specialized hardware like gamepads, joysticks or racing wheels. In the last years wearables like smartwatches and fitness trackers started to enter the main stream and are now firmly lodged there. This offers the possibility to use their sensors and actuators to form new interactions and information interfaces for the user, like for example vibrotactile displays.

4.1 LifeTact

Tactile feedback is mostly event based, for example to inform the player about a missed goal-shot in FIFA, a Quick-time Event in console games or vibrations to inform the player about weapon recoil. This chapter explores the possibility and feasibility to integrate existing wide-spread smartwatch-based continuous vibrotactile feedback into video games. For this purpose *LifeTact*is presented, a continuous tactile feedback system to display the current hit points (HP) in form of a tactile heartbeat in the First Person Shooter (FPS) *Half-Life 2* (Valve Corporation, 2004) [129].

Figure 4.1: User playing Half-Life 2 with *LifeTact* over the smartwatch on the left wrist. The hit point display is concealed.

The effect of *LifeTact* on the user experience was evaluated in a between-subject user study with 29 participants. The results indicate that users are sufficiently accurate in determining their current hit points. Additionally, users self-reported having a richer and more immersive user experience by using *LifeTact*. The results of the user study were published in [92].

4.1.1 Related Work

In gaming contexts, researchers created accessories (see [56] or [69]) to enhance the gaming experience. Tactile feedback is either integrated in the controllers [80] or complex wearables like the ARAIG (As Real As It Gets) [117] or the Woojer [2]. This leaves the door open for multi-purpose wearables like smartwatches or smartphones to act as tactile displays during gaming sessions. Multi-purpose wearables like smartwatches have the benefit of already being in a lot of households, combing this availability with optional features for gaming is an enticing perspective. Using smartwatches as tactile displays in video games seemed to be unexplored at the time of the research. To the best of our knowledge smartwatch-based tactile feedback systems for gaming currently do not exist. Sra et al. have used arm-worn tactile diplays as additional interface in social mobile games [115]. They proposed exploring smartwatches as a platform to continue their research but did not investigate this.

4.1.2 Interaction Design

LifeTact was developed as a tool to enhance the perception of player character health in games and its design follows the design principles for tactile displays proposed by Gemperle et al. [38] in being lightweight, silent and physically discrete. Additional important requirements were:

- *Robustness:* The system has to work efficiently and should not be error prone not to diminish the gaming experience.
- *Responsivity:* The system should be responsive and quickly adapt to changes in the game [25].
- *Intuitivity:* The tactile display should be intuitive [130], especially in gaming contexts.

Tactile Heartbeat Design

The design goal was to represent the hit points (HP) in a game via tactile vibration in a responsive and intuitive way, as "*health should deplete in an obvious manner, because with every hit, a player is closer to losing their life*" [103]. Nishimura et al. showed, that "*the affective feeling towards others can be controlled by presenting a pseudo tactile heartbeat as stimulus*" [82]. Therefore using a pseudo heartbeat feedback seems appropriate to increase the players perception of the characters health in games. The specific tactile design was inspired by the phonocardiogram representation of heartbeats consisting of first, second and third heart tone (see Figure 4.2) which is best known as audible representation of heartbeats, e.g. in movies.

The parameters of a sufficiently realistic tactile heartbeat using the vibration actuator of a smartwatch were found in an initial user testing with 5 users (30 minute sessions each). Participants were subjected to vibrotactile heartbeats with initial settings for vibration duration. These were adjusted according to the participant's feedback so that the resulting vibrations were subjectively recognizable as a heartbeat. The third heart tone was left out, because it is virtually absent from the known audible representation.

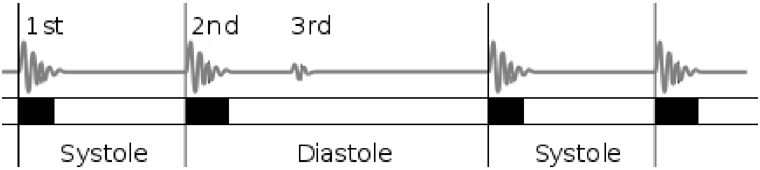


Figure 4.2: Phonocardiogram of a healthy heartbeat (top) (*Wiggers diagram*) with corresponding tactile heartbeat (bottom).

The final tuple describing the heartbeat for in-game representation was defined by the following formula depending on the current hit points h:

$$\begin{aligned} f(h) &= (ht_1, p_1(h), ht_2, p_2(h)) \\ &= (80, 3*h+60, 90, 6.5*h+130), h \in [1,100] \end{aligned}$$

The parameters defining the tactile heartbeat are:

- ht_1: Duration of the first heart tone vibration
- $p_1(h)$: Systole pause
- ht_2: Duration of the second heart tone vibration
- $p_2(h)$: Diastole pause

Although the resting pulse of a healthy adult ranges from 60 to 100 [84], 100% of hit points (i.e. full health) is represented with a heart rate of 45 bpm. On the other end of the continuum, 1% hit points was set to correspond to a comparatively low maximum heart rate of 166 bpm [102]. This was a suggestion in the expert workshop, which encouraged the usage of artistic license to help the user differentiate high heart rates as well as give the user a very calm and collected feeling at full health.

By having a steady function for each value between 0 and 100, we can adapt the virtual heart beat's vibration pattern to represent every change of hit points, which gives the system the required responsiveness. Death (i.e. zero hit points) is represented by a pattern of five heartbeats that are slowing down and stopping completely.

4.1.3 Prototype System

The system consists of several software components to integrate the haptic interface into the game play (see Figure 4.3). In the first step the game information is read every second and constantly published on the PC. The smartphone then works as a gateway and reads the published information and sends it to the smartwatch to implement the haptic interface. The hit point (HP) values are accessed with a HP reader service via memory access once per second and then published via a small Apache http server on the PC. An Android smartphone service reads these data every 100ms and pushes them as a message to the smartwatch. The Android based smartwatch (Moto 360) calculates the heartbeat from the hit point value and displays the out-coming value via its vibration actuator. If the hit point value is the same as before the pattern continues, if the health point value is changed the heartbeat starts with the new pulse even if the old pulse is not finished yet.

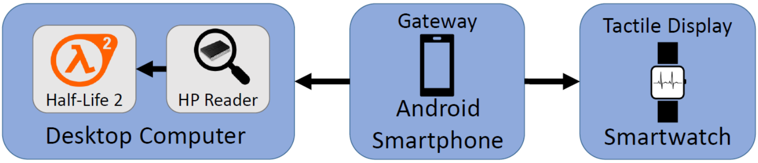


Figure 4.3: The system components of *LifeTact*.

Expert Workshop on Feasibility

After implementation we conducted an expert workshop (2 hours) with a game designer of a major game development company. The workshop consisted of a think-aloud session while playing Half-Life 2 with *LifeTact* followed by an unstructured interview.

Overall the system was found very robust and reliable. Additionally, it was mentioned that the use of a wristband or smartwatch is in terms of wearing comfort the optimal solution for PC based gaming. The interviewee reported, that the responsiveness of the system with a maximum of one second delay is sufficient for use in casual and single player games, although it might be too slow for competitive games. It was especially (and unsolicited) noted that sharply increasing or decreasing hit points (player health) with the following rapid acceleration or deceleration of the tactile heartbeat had an impressively immersive effect.

Otherwise it was mentioned that the heartbeat, which at that point used to range from 70bpm at 100% hit points to 190bpm at 1% hit points, was too fast to estimate player health when the hit point were very low. Also the heart rate was considered to be too high which led to the adaption of a lower heart rate between 45bpm an 166bpm. Furthermore, upon the death of the character we implemented a death-pattern instead of the former 0 bpm at recommendation of the interviewee. Minor criticism was mentioned regarding the commercial use of the system. The interviewee reported that for *LifeTact* to be established as a commercial system it needs improvement to make the utilization less cumbersome.

Summarizing, the interviewee stated, that for the sole purpose of helping to display hit points, the traditional Head-Up-Display (HUD) is better suited, however as a tool to improve the immersion, *LifeTact* is very helpful, among other things because of its intuitiveness.

4.1.4 Evaluation

The evaluation was conducted with the following hypothesis in mind: Using *LifeTact* instead of or additional to a traditional HUD increases the user experience in gaming because the user does not need to look at the hit points. This hypothesis was based on experiences made while developing the system and the feedback received in the expert game designer workshop.

Experimental Design

The effect of tactile feedback on user experience was evaluated in a A/B/C user study with the following groups of participants (between-subject design):

- A *control group* (C-Group, N=9) played the game without *LifeTact*, only relying on the visual HUD.
- A *visual-tactile group* (VT-Group, N=10) played the game with both *LifeTact* and the visual HUD to display the health points in the game.
- A *tactile group* (T-Group, N=10) used *LifeTact* as only information display of their health points, the visual HUD was concealed (see Figure 4.1).

User experience was assessed with a standardized questionnaire, the User Experience Questionnaire (UEQ, [64]). The UEQ is a questionnaire that measures the user experience of interactive systems on six independent scales. Attractiveness describes the overall impression of the system in terms of like / dislike. Perspicuity, effectiveness, and dependability measure the pragmatic quality (or usability), whereas stimulation and novelty measures the hedonic quality of the system. A custom survey with open questions and likert-scale questions was additionally used to assess qualitative feedback about the experience while playing.

Participants

29 participants (25 male, 4 female, aged between 18 and 39 with 66% between 21 and 24) volunteered in the user study. All participants were students and young professionals with interest in games and basic knowledge in FPS gaming. The proficiency in playing FPS games was balanced between groups, i.e. each group had one or two participants with basic FPS skill, all other participants were experienced FPS players.

Task

Participants were asked to play the first part of the Level *Route Canal* in Half-Life 2 (see Figure 4.1). Half-Life 2 is a single-player FPS that also contains a few puzzles and platforming sections and is widely regarded as a milestone in PC gaming. The players' field of vision, aiming and shooting behavior are controlled by mouse movements, whereas the players' movement is controlled by keyboard controls. The duration of playtime varied between participants with an average playtime of about 10 minutes.

Procedure

Before the study started, all participants got an explanation of the standard mechanics to control the game (walking, looking around, shooting, etc.). Some participants changed the mouse sensitivity to feel more comfortable with the game. As a help, the controls and key assignments were printed on a sheet of paper and placed next to the computer. Participants of the non-control groups were fitted with the Moto360 on the right or left wrist depending on their preference and subsequently familiarized with the tactile feedback. As demonstration of the tactile feedback the vibrations corresponding to 100, 50 and 10 health points were applied to the participants for five seconds each and the respective values of the vibrations was explained. As a very short test, the vibrations matching 75 and 30 health points were applied and participants were asked for the corresponding values.

All participants were instructed to focus on the experience of the system and not to feel pressured by taking as little damage as possible. Immediately after finishing the level, the game was minimized and the participants were asked to report the number of health points they think they had in the last instance.

4.1.5 Results

Intuitivity and Recognition of Hit Points

Introduced to the system, participants were quickly (within 2 minute warm-up phase) able to handle *LifeTact*, with a reasonable accuracy in identifying their hit points. Both VT- and T-Group had a mean deviation between reported and actual hit points of about 10 HP (VT-group 9.5 (SD 7.23) and T-group 7.6 (SD 7.8)) in the introduction. During the actual game, all participants felt certain about the remaining hit points. When asked

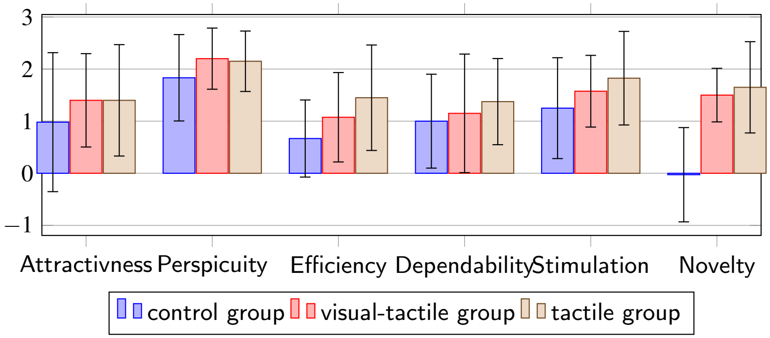


Figure 4.4: Mean and Standard Deviation of the UEQ separated by C-Group, VT-Group and T-Group. The scale ranges from -3 (worst) to 3 (best).

how certain they felt about their hit points during the game on a scale from 1 (not at all) to 7 (very certain) participants of VT-group had a mean of 5.0 (SD 1.33) and participants of T-group had a mean of 5.6 (SD 1.7).

Vibration Perception

The intensity of the vibrations was perceived positively although several participants criticized the vibration intensity as too low. When asked what they felt wearing the smartwatch in the game one participant of T-Group described the vibration as *"enjoyable and not disruptive"*, while five participants described it as *"funny", "very good" and "enjoyable"* but wishing for more intense and clearer vibrations, especially in low-health, high-pulse and tense situations. When asked the same question, participants of VT-Group gave more critical feedback as compared the T-Group. One participant described the vibrations as *"clearly noticeable"*, four participants as *"slightly too weak", "too weak"* and *"[I] only felt the vibration when focussing on it"*. One participant felt *LifeTact* was *"distracting when the vibration rate is changing"*. One participant criticized the system as *"making the game too real"* and making the participant nervous.

Comfortable Wearing

The opinions about comfortable wearing during gaming varied. Three participants (two VT and T-Group each) stated annoyance by wearing the smartwatch when asked what they disliked. One participant (T-Group) attributed the discomfort to wearing the smartwatch on the 'mouse-hand' and the caused interference when using the mouse ("[It's] annoying when using the mouse") The other participants (VT-Group) attributed the discomfort to being unfamiliar with the feel of the watch and usually not wearing a watch. The remaining participants of VT- and T-Group either didn't mention the comfort at all (4T, 4VT) or described it as comfortable (2T, 1 VT), not distracting (1T, 1VT), not uncomfortable (2 T) or only slightly feeling the smartwatch (1 VT).

User Experience and Immersiveness

The results of the UEQ suggest that both groups with tactile feedback evaluated the system more positively than the control group, in particular in the dimension *Novelty* (see Figure 4.4). These results are supported by the qualitative feedback of the participants who stated that the system *"Works (as it should)"*. Six (3T, 3VT) participants stated that the vibrations did distract them from the game.

About half of the participants stated that *LifeTact* made the game more realistic by increasing suspense and tension and thus improving the immersion into the game. Participants using *LifeTact* described it as *"making the game more real"*, *"being more integrated into the game"* or that the *"pulse increases the excitement"*. Only two participants stated that the vibrations did distract them from the game. This result points to the positive impact of the tactile feedback in giving the players an *"further kick"* and *"expanding the game with another sensory perception"*. 90% of VT- and T-Group participants reported that they would like to use a system like *LifeTact*, provided they already owned a smartwatch. Some of them restricted the intended use to single-player and non-competitive games.

4.1.6 Discussion

LifeTact shows the possibility and feasibility of a tactile feedback system using off-the-shelf hardware in gaming to enhance the immersion and gaming experience. Study participants using *LifeTact* were able to estimate remaining hit points with reasonable accuracy and felt certain about their HP during the game. This could indicate, that while the participants may not know their exact HP, they know enough to to feel certain about their HP to play accordingly. *LifeTact* was well received by the majority of participants and the concept was recognized as being innovative and having a positive influence on the gaming experience.

LifeTact or a similar system has a lot of potential in story- and experience-driven single-player games to enhance the players gaming experience with already existing hardware. *LifeTact* could be adapted to indicate the remaining HP in games like *Fallout 4* or values equivalent to HP like *Sanity* in *Amnesia: The Dark Descent*. *LifeTact* could also fit very well with projects like *Immersive HUD* for Fallout 4, which allows players to disable the HUD or reduce the information shown on the HUD to allow a more immersive experience playing the game. Combined with the trend in FPS games to indicate low HP by blood splatters on the screen [134] *LifeTact* could help to create immersive UIs that use the technology the player has at hand – like smartwatches or fitness trackers. Although the *LifeTact* system currently does not scale well, this issue could be improved if game developers or modders include values like Hit Points in the existing game APIs.

By virtue of the fact, that the large majority of participants were interested in using the system for personal use, it can be stated, that the system has a positive influence on the gaming experience. The results can be attributed to the improved immersion and the intuitive way to communicate hit points. Whether this comes from the improved immersion that the system provides, or whether it is due to the supported perception of health in games, can not be determined clearly and has to be investigated further.

4.2 Drive by Maintenance

Attribution

The work presented in this chapter is is a collaboration of Andrei Miclaus and Erik Pescara. The individual contributions can be divided up as follows. Andrei Miclaus was responsible for the Motivation and the industrial application part of the work, as well as being main author on the resulting published paper [77]. The contributuion of Erik Pescara consisted of the design and implementation of the wearable as well as the design, implementation and evaluation of the user study.

4.2.1 Motivation

Although automation is the backbone of the modern industrial complex, humans remain the indispensable shepherds of the machine park. One operator may be responsible for several machines which need to run continuously. Unfortunately, the complexity of the machines and processes increased faster than the improvement in the corresponding interaction technologies. In the paper I co-authored with Andrei Miclaus we propose a multi-modal adaptive human computer interface system for the modern industry that relies on position, activity and other relevant contextual information, in order to provide a more flexible interaction in industrial scenarios. Information about the machine, is transmitted to the worker using a vibrotactile display on his wrist whenever the line of sight is broken. The context in which the user and the machine currently reside in, are determined by software artefacts (Apps). We evaluate transmitting arbitrary information via vibrotactile displays and come to the conclusion that such a system is feasible in industrial settings and may be beneficial as it has a very low distraction rate. Andrei Miclaus observed at modern manufaturing plants, that optimization is primarily focused on the processes directly generating revenue (automation, flow optimization etc.) and not the communication interfaces between humans and machines [77]. While there has been progress in the interfaces, there are many advanced interaction technologies that could be leveraged in order to accelerate human machine interaction. Currently, user interfaces and wearables are mostly static touch screens and scanner gloves. This leads to sub-optimal interaction in the work environment. Improving the interaction has several advantages like improved efficiency, effectiveness and job satisfaction (less stress, more situational awareness). Most importantly it may lower errors and improve safety[101].

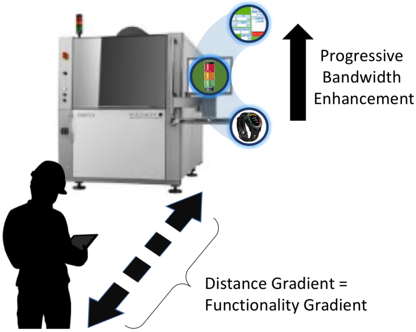


Figure 4.5: Improving the user experience with gradual enhancement of the human machine information bandwidth based on contextual data.

In the most striking observation Mr. Miclaus witnessed during an on-site requirements analysis phase, was a maintenance worker taking a coffee break during his normal work shift. Because the machines must run 24/7, no downtime is allowed. Therefore, breaks are always connected to a small risk of unintended production stops due to unexpected machine failure. As the coffee and lunch room was situated behind a corner, there was no direct line of sight towards the machines the worker had to monitor. This visibly increased the workers anxiety levels while his coffee was brewing, as he was constantly peeking behind the corner toward the machines. The view was additionally obstructed by cables and other paraphernalia. One can imagine that physiologically motivated breaks may induce an even larger amount of stress.

By leveraging the context of the user in such situations, vital information can be condensed and then transferred via on body vibrations in such a way as to confer a state of constant monitoring without direct proximity. This is exemplified in Figure 4.5. As the user approaches a machine the information richness increases. Vice versa, when the user changes his context (e.g. breaking the line of sight due to a break) the information gracefully degrades to the point where only vitally important information is presented (e.g. status light or on body vibrations).

There are two major challenges that need to be surmounted when considering the introduction of human machine interaction technologies in industrial scenarios. The first issue is the low acceptance and willingness to invest in interaction technologies with no clear or immediate return on invest. Therefore, gathering requirements becomes difficult and field testing is only possible in select cases and with a mature product [77].

The second issue is the production level deployment of the software system (machine and human data acquisition, context processing algorithms etc.). In certain cases, a specific piece of software might take months until it can be deployed, especially if it has never been used in that company before. Some software may never get the green light due to infrastructure inadequacies. To solve this, we proposed using a modern App based eco-system platform on the manufacturing shop floor that works in parallel with the existing IT infrastructure [77].

The two issues mentioned above are show stoppers for adaptive work environments. This chapter provides a potential solution and will describe the continuous wearable tactile display in this section.

The simplified scenario is illustrated in Figure 4.5 where an instance of the system performs the activity recognition (distance and line of sight) and modulates the richness of information and the medium with which it is received.

The scenario is further detailed in Figure 4.6. A medium switch has to take place between the modes of notification and interaction, in order to prevent overloading the user with information (lamp goes red, watch/band vibrates, headphones ring etc.). The system modulates the information bandwidth in the following manner:

In close proximity to the machine Full display of all on-monitor controls and widgets but no watch notifications.

Distance increases - line of sight intact Switch to an on-screen status light and very large labels. Wearable vibrotactile notifications are sent periodically (machine status and raw material level).

Distance increases further - line of sight broken Wearable notifications are fully enabled, vibration patterns deliver constant feedback. Optionally a panic button is activated and put on standby in case of emergencies.

The on-body vibrations give the user an augmented sense for the machines when they are not in sight. By replacing the smart watch with more complex vibrotactile interfaces, more information can be transmitted in a context-dependent, user friendly manner.

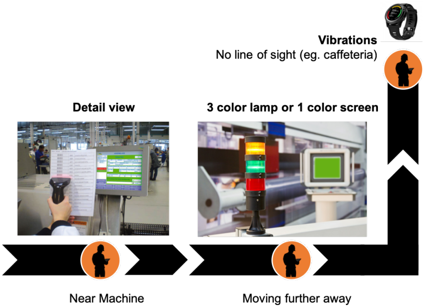


Figure 4.6: Close proximity to the machine configures the screen to show detailed information. Moving farther away, the worker will still see a status indicator on the screen (similar to a three color lamp). Breaching the line of sight activates the wearable vibrotactile display.

4.2.2 Wearable Vibrotactile Display

A common smart watch has only 1 vibration motor. For displaying more complex patterns, a vibrotactile display has been developed that allows for more fine grained vibration pattern control (information bandwidth). This in turn can be integrated in functional clothing and allows for spatially separate vibrations to occur.

The design of the wearable relies on existing literature [38]. The wearable design must not endanger the user during the primary task by being negligibly small and fitting inside the users proxemic hull[37]. Additionally, it must allow all and any movement the user has to perform.

The wearable used in this work consists of a forearm sleeve equipped with 8 pancake vibration motors arranged in two rows, as seen in Figure 4.7. It is made out of soft fabric and can be closed with a hook-and-loop fastener. The actuators are placed on the outside with a spacing of 5 cm between the motors and 6 cm between the rows. The Arduino board can be controlled over Bluetooth Low Energy (BLE) or serial over USB.

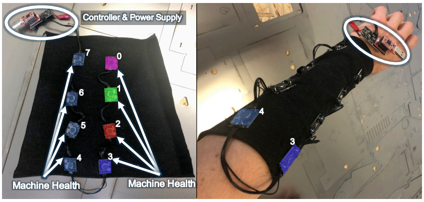


Figure 4.7: Wearable display developed for vibrotactile communication using 8 vibration motors controlled by an Arduino chip

4.2.3 Communicating Information Through Vibration

The vibration pattern requirements are the following:

Intuitive The vibration patterns should be self-explanatory and intuitive. The user should understand it with minimal effort [130].

Non-Disruptive The user should not be annoyed by the continuous vibrations.

Responsive The system should be responsive to actions that happen in the environment.

When using tactile interfaces to communicate machine states, the tactile interface has to be flexible enough to communicate multiple states for multiple machines. As the line of sight is broken tactile patterns have to be linked to a machine and not be confused with patterns of other machines. This can be achieved in multiple ways, either through spatial or temporal differentiation of the associated patterns. Therefore the tactile wearable has to be flexible enough to allow for spatial and temporal differentiation. The wearable used in this work satisfies these conditions, it has enough actuators to allow spatial differentiation and each actuator can be controlled separately via BLE so that different vibration patterns can be programmed.

As an example two different vibration patterns that could be used for two different machines were implemented.

Pattern 1 communicates four different states with four different vibration actuators (see Figure 4.8). Pattern 1 is diverse in spatial and temporal information to increase redundancy.

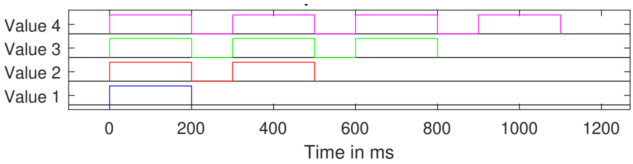


Figure 4.8: Pattern 1 uses different motor positions for the different values and also different numbers of vibrations to increase redundancy and ease of interpretation. Each vibration is 200 ms long with breaks of 100 ms length. The colors describe the motor number, e.g. value 1 on motor 3, see Figure 4.7.

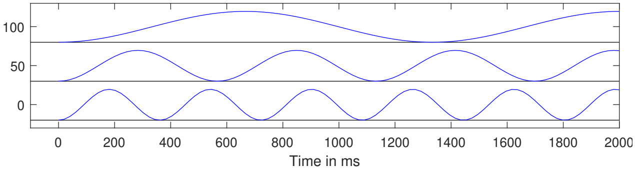


Figure 4.9: Pattern 2 uses a wave-like heartbeat to represent values from 0 to 100. The values 0, 50 and 100 are shown as an example.

Pattern 2 communicates integer values between 0 and 100 (see Figure 4.9). The pattern is based on the concept of a vibrotactile heartbeat that was already discussed in this chapter. [92].

Both patterns are suited monitoring the KPIs (Key Performance Indicators) of machines: *Pattern 1* communicates a machine state (working/idle/broken down) while *Pattern 2* communicates a numerical value between 0 and 100 (raw material level, fuel, process parameters etc.).

4.2.4 Evaluation

An evaluation of the entire system using factory personnel in their daily working environment is something that would be optimal. However, due to strong work guidelines in German factories studies with employees are difficult. Thus there was no possibility during this work to secure an in-field evaluation due to reasons such as system maturity and the possibility of process interruptions as well as privacy issues.

Therefore, a lab study was conducted as an alternative to an evaluation in a factory.

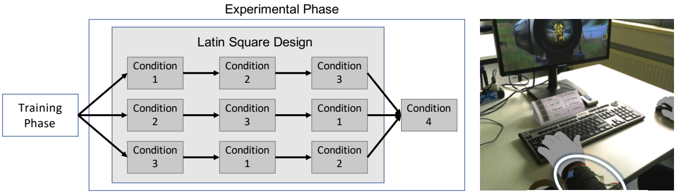


Figure 4.10: Study Design: Condition 1,2 and 3 are carried out in a latin square deign, condition 4 is carried out last.

The lab study required users to identify the information transferred to their wrist while being distracted by the video game ARMA 3 (Bohemia Interactive [55]). ARMA 3 is a „tactical shooter“ game in which the player has to quickly react to auditory and visual stimuli to prevent harmful actions against the player character and further the goals of the player. The video game therefore creates an environment for the participant in which the participants is under cognitive load and needs to engage with the game to prevent harmful actions against the virtual player character and fulfill the goals of the game. This simulates distracting activities that the worker is performing while away from the assigned machines. These can include coffee breaks or helping colleagues with more complex tasks.

Methodology

24 participants (all male, aged between 18 and 33, mean M = 23) took part in a within-subject study. All participants had basic knowledge about the controls of computer games.

During the experiment, participants had to play the game ARMA 3 and play through several courses (parkour) in the game with some running and shooting at targets while wearing the wearable (see Figure 4.10). They were receiving constant vibrotactile information through the vibration patterns. Four different conditions were tested during the experiment (see Table 4.1): Condition 1, 2 and 3 were tested in a latin square design and Condition 4 was tested afterwards (see Figure 4.10). Each participant started with a training run without vibrations to accommodate themselves with the distraction task. This was performed mainly to clarify the game and the controls.

Condition	ARMA 3 Parkour	Pattern 1	Pattern 2
Condition 1	Parkour 1	Yes	No
Condition 2	Parkour 1	No	Yes
Condition 3	Parkour 1	Yes	Yes
Condition 4	Parkour 2	Yes	Yes

Table 4.1: Design of different Conditions.

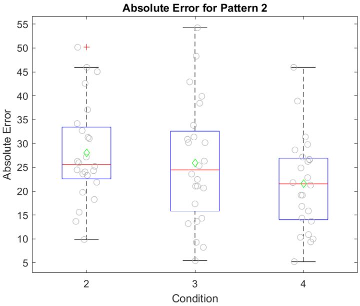


Figure 4.11: Absolute Error for Pattern 2 in Condition 2, 3 and 4.

Procedure

For the experimental phase, multiple triggers were placed in the parkour, when stepping on the trigger a graphical interface would pop up and ask the participants to enter the information they were currently receiving through the vibrotactile patterns. For *Pattern 1* they had to enter a number between 1 to 4 and for the *Pattern 2* between 0 and 100. The whole study took around 45 minutes per participant. Only the information of one pattern was asked for at a time, during condition 3 and 4 both pattern 1 and 2 were asked for equally often. The vibration motors 0-3 were used for *Pattern 1* and motor 5 for *Pattern 2* (see Figure 4.7).

4.2.5 Results

As the recognition of *Pattern 1* is essentially a classification task, confusion matrices are used to evaluate the recognition accuracy of *Pattern 1*. The confusion matrices for

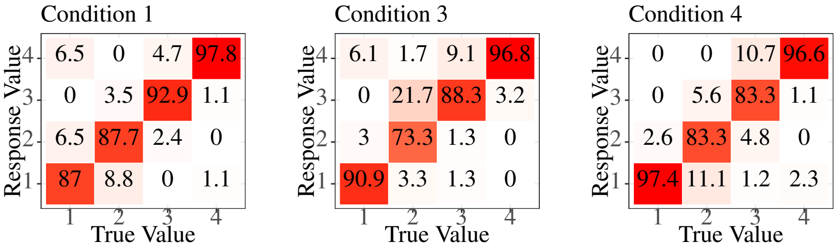


Figure 4.12: Confusion matrix for Pattern 1 during Condition 1, 3 and 4.

Pattern 1 in condition 1, 3 and 4 can be seen in Figure 4.12. Overall, participants were able to identify *Pattern 1* values with an accuracy of 90.27 % (SD 14.01) throughout the whole experiment with no statistically significant differences between the conditions. This suggests, that displaying both pieces of information (Pattern 1 & 2) at the same time does not influence the accuracy. Looking at the recognition accuracy per participant over the different steps of the experiment, no significant change could be found with a one-way ANOVA, indicating no improvement or learning effect.

To evaluate *Pattern 2* the mean absolute error is used to determine how good participants could identify the numerical value. The results of *Pattern 2* can be seen in Figure 4.11 show no significant differences between the different conditions regarding mean absolute error. Interestingly, condition 3 (25.91) performed better than condition 2 (28.05) and Condition 4 had the best mean absolute error (21.53). The absence of a significant difference in recognition error seems to suggest, that there is no negative impact of displaying both information. This is relevant for an industrial use case where different pieces of information for different machines is communicated through the wearable tactile display.

4.2.6 Discussion

The system presented is designed to communicate arbitrary synthetic data originating from industrial machines such as raw material levels or status through vibrations. Using a vibrotactile display, it was shown that data can be reliably transferred to the user without needing a direct line of sight or visual display based devices. The vibrotactile display has the added benefit of not being intrusive or hindering other verbal or visual communication. The evaluation of the wearable device has been carried out in a laboratory setting using video games as distraction. Designing and refining in non-industrial environments and at a later stage transferring the technology to the shop floor could allow researchers to introduce a high degree of novelty. The results suggest that it is feasible and robust to display industrial KPIs with a wearable even if the user is distracted by other tasks and does not have any visual information about the KPIs and the corresponding machine. In the prototypical implementation two different patterns were implemented for two different use-cases, *Pattern 1* communicates discrete information such as machine states while *Pattern 2* communicates a value between 0 and 100. With an overall accuracy of 90.27 % *Pattern 1* is sufficiently accurate to inform the user about the corresponding machine state, even though the accuracy is not 100% this should not be a problem due to the continuous repetition of the patterns. Even if a pattern is not correctly recognized in the first attempt, it can be recognized in the next repetition. Although the accuracy for *Pattern 2* is not good enough to recognize a specific value, it is good enough to have an approximation and to recognize trends. It is also encouraging that the recognition accuracy of *Pattern 2* and *Pattern 2* didn't significantly change when both patterns were displayed and suggests that displaying multiple tactile patterns on the body is possible.

4.3 Conclusion

This chapter presented two continuous wearable tactile displays, both were developed with gaming and leisure in mind but can also be deployed in other circumstances. *LifeTact* is a a continuous smartwatch-based tactile hit point display for games. *LifeTact* shows the possibility and feasibility of a tactile feedback system using off-the-shelf hardware in gaming to enhance the immersion and gaming experience. Study participants using *LifeTact* were able to estimate remaining hit points with reasonable accuracy and felt certain about their HP during the game. This could indicate, that while the participants may not know their exact HP, they know enough to to feel certain about their HP to play accordingly. *LifeTact* was well received by the majority of participants and the concept was recognized as being innovative and having a positive influence on the gaming experience. Distinct potential for *LifeTact* or the tactile wearable used in the Drive By Maintenance project can be seen in story- and experience-driven single-player games to enhance the players gaming experience with already existing hardware as well as serve as continuous wearable tactile display in real world scenarios. Drive By Maintenance showcased an improved interaction environment for the manufacturing domain based on modulating the information bandwidth between workers and the machines they operate. This chapter demonstrates the opportunity in using continuous wearable tactile feedback in video games and real world applications.

The results presented in this chapter lead to several implications that inform the contributions of this thesis in the areas of creating vibrotactile patterns, learning vibrotactile patterns and the spatial stability of vibrotactile patterns.

As already seen in chapter 3 vibrotactile pattern design plays an out-sized role for the whole tactile wearable. In this chapter two different design approaches for the vibration patterns were taken. *LifeTact* and Pattern 2 of the Drive By Maintenance wearable (see Figure 4.9) utilized the tactile representation of a heartbeat or something akin to a heartbeat to communicate a value on a spectrum, this approach of vibration pattern design can be called heartbeat-approach. Pattern 1 of the Drive By Maintenance wearable (see Figure 4.8 communicated states with four distinct vibration patterns, similar to the approach already discussed with *RüttelFlug* and can be called Morse-approach. During evaluations it became clear, that the two different approaches are well suited for different tasks and requirements. The heartbeat-approach is well suited to generate emotional connections, as seen in *LifeTact* where participants felt the game was “more real” and is well suited to communicate rapid changes as also seen in *LifeTact*. However, the heartbeat approach is not well suited to communicate exact values, as also seen in this chapter. The Morse-approach is opposite to that, legibility of the patterns comes at the cost of speed and with a reduced number of values that can be clearly communicated. With this insight it becomes clear that automatic generation of vibration patterns is a promising approach for Morse-like patterns. Optimizing recognition accuracy and detection speed is something generative models are very well suited for. With this information in mind the automatic generation of vibrotactile patterns discussed in chapter 6 will focus on the automatic generation of Morse-like patterns.

Regarding the need that the user has to learn the vibration patterns and their associated meanings this chapter hones in on the findings of chapter 3. Once again it shows the importance of easy access and easy learning and makes the case for learning the patterns and their meanings passively. This chapter also shows the futility to learn heartbeat-like patterns, as too many very similar patterns with only the very slightest of variations exist in these pattern sets. As an example the *LifeTact* pattern for 50 health is a vibration pattern with a 80ms vibration, followed by a 210 ms pause, followed by a 90ms vibration and a 455ms pause. In comparison to this the pattern for 51 health is 80ms vibration, 219ms pause, 90ms vibration and 461.5ms pause. In total there is difference of less than 10ms between the patterns. Any reasonable observer can see that telling these to patterns apart with any hope of accuracy is unfeasible and should not be tried. Therefore chapter 7 will focus on Morse-like patterns.

As with chapter 3, looking at the wearables and tactile displays with the lens of reference frames and body movement reveals the importance of thinking about the optimal way to display spatial information in regards to the wearable and its surrounding. The health status information displayed by *LifeTact* does not have a spatial component, but the information displayed by the Drive By Maintenance wearable could very well have a spatial component. As the Drive By Maintenance system is intended to fully activate when the line of sight to the machine is broken, it is not a stretch to imagine also a spatial component of the wearable to inform the user which machine where shows which key performance indicators. This begs the question again how spatial information should be displayed, as wearable technology has evolved to include Inertial Measurement Units to compute the orientation of the wearable and even indoor navigation technologies - needed for a system like Drive By Maintenance - has seen dramatic improvements in the last years. The question how spatial information should be displayed will be discussed in the next chapter and a deeper dive into it will follow in chapter 8.

5 Exploration of Continuous Wearable Tactile Displays in Business and Dashboard Environments

The last two chapters discussed and explored continuous tactile feedback as a modality to communicate abstract information like velocity or hit points in a game. This chapter discusses and explores continuous tactile feedback in dashboard environments. The thesis explored two different approaches to incorporate continuous tactile feedback into dashboard and business environments. The first approaches mirrored works already discussed in the last chapters by using tactile feedback to communicate graph data [91] and stock data [95]. While this is interesting, it's contribution isn't very different from the contributions made in the last two chapters, furthermore communicating absolute values with tactile feedback is not feasible as it would require a massive tactile alphabet. The second approach was to utilize continuous tactile feedback as a tool to help users to shift attention and awareness. Attention and awareness are key resources to managing and monitoring large cyber-physical systems where simple auditory cues are not sufficient anymore. This chapter presents a user study with 24 participants to investigate continuous tactile attention support systems and compare temporal tactile patterns with spatial tactile patterns regarding their capability to quickly and accurately inform users

Figure 5.1: The control room at the Rheinhafen steam plant in Karlsruhe.

about events in large dashboard environments. As an exemplary design this chapter also presents the wrist-worn vibrotactile wearable *VibrAid* (Figure 5.3) that was specifically designed for use in monitoring environments and developed in collaboration with power plant operators. The content of this chapter was published in Proceedings of the 12th ACM International Conference on Pervasive Technologies Related to Assistive Environments in 2019 [94].

5.1 Related Work

The role of control room operators in a power plant is vital, not just during emergencies and abnormal situations, but also during normal operating conditions the operators are key figures in monitoring the situation, detecting warning signs of problems yet to come and taking steps to prevent situations from escalating [81]. In order to display all necessary information, control room environments have to have a certain complexity. As seen in Figure 5.1, the control room of a power plant - in this case a steam plant - has lots of different screens to monitor different components of the power plant. These systems typically follow a standardized set of functional and visual rules for supervision of large industrial systems, called SCADA (Supervisory Control and Data Acquisition) [15]. SCADA includes standards for event-driven communication, interfaces, trend-analysis and logging/reporting as well as ensuring scalability, extensibility and redundancy of the system [30]. SCADA systems are widely used in power plants, industrial production systems and research facilities such as the Large Hadron Collider.

The scope of these systems makes it impossible for the operators to constantly monitor every detail. To counter this flood of information, systems often automatically prioritize, summarize and abbreviate alerts before showing them to the operator. To ensure that the most severe alerts are not missed, modern systems typically employ auditory alerts [30]. A different, more personalized approach, is using vibrotactile cues to guide the attention of the user [66]. This is especially useful when certain alerts should only be noticed by one user. While it is possible to wear a wearable tactile display nearly everywhere on the body [137], the effectiveness of tactile displays on the forearm it is usually highest when it is attached to anatomical points of reference like the wrist or the elbow [23]. Especially in very noisy environments or environments with certain privacy needs, continuous wearable tactile displays can play an important role[51].

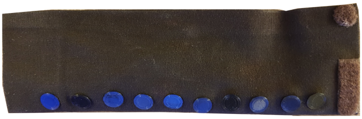


Figure 5.2: *VibrAid*, closed.

5.1.1 Dashboards and Attention Guidance

A recent topic of research is dashboards and their capabilities [136]. In the ever increasing flood of information generated in organizations and businesses today, dashboards are expected to manage and curate information for the user to enable the user to make better decisions. Although dashboards are usually mostly visual, using a multimodal approach to convey information generally results in a higher amount of information transferred [79]. Especially in large scale dashboards like shown in Figure 5.1, it can be beneficial to guide the users attention. Attention is often defined as "selectively processing incoming sensory information with limited capacity and reactive and deliberate processes" [7]. With that in mind, attention can be seen as a finite resource with which should be dealt as efficiently as possible by guiding the user to important aspects of their situation. Although some research suggests that reacting to a directional haptic cue comes with a reduced reaction time compared to a visual cue [83], this finding is debated elsewhere [100], taking the approach that a multimodal interface with haptic and visual cues has the most benefits [100]. To guide attention in interfaces Tan et al. used a 3x3 grid of vibrotactile actuators mounted to the back of a chair to significantly decrease reaction time in a change detection task [122]. Spatial vibrotactile cues can help directing the visual attention of the driver to important events or information [50] or help pilots during long flights keeping the aircraft in balance [19]. Other recent research shows the viability of spatial tactile cues in large scale control room environments to shift attention towards important situations [120].

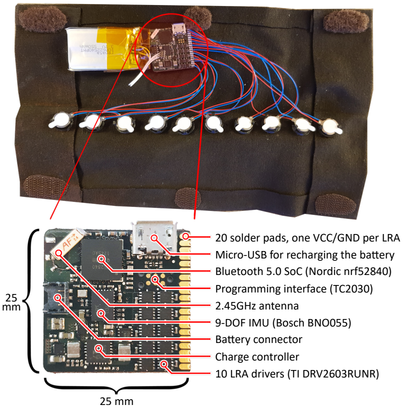


Figure 5.3: *VibrAid*, open.

5.1.2 Tactile Interfaces in Monitoring Tasks

There is already a good body of research how tactile interfaces can be integrated into monitoring tasks ([22], [123], [100]). Tchakouté et al. studied 30 tactons - applied to the sole of the left foot - on their viability to communicate risk levels and selected six which were easily differentiable and improved their recognition rate significantly with repetition [123]. Cauchard et al. applied tactons through a smart-watch to inform users about their progress while performing stationary as well as physical activities such as cycling or running [22]. The use in stationary activities shows the viability of these tactons in monitoring tasks often performed in control room environments although the answer time (signal to recorded reaction) of 18 seconds should be improved when used in potentially critical situations [22].

Component	Size (mm) (WxLxH)	Weight (g)	Power Consumption	BOM Cost ($)
LRA motors	8.0x8.0x2.5	1.0	28mA (1.2V, full vibration)	10 x7.1$
Central Board	25.0x25.0x2.0	5.2	PCB (1mm FR4), 0A	68.2$
			nRF52840-QIAA, 0.7μA idle, 14.8mA TX (+8dBm), 9.6mA RX	4.5$
			DRV2603, max. 2.5mA quiescent current	10 x1.5$
			BNO-055, 12.3mA@100Hz sample rate, 0.4mA low-power mode	10.5$
			MAX17048, 3μA hibernate, 23μA active	2.0$
			LTC3567, 0 A (consumes energy only when charging)	7.7$
Battery	25.5x39.5x4.0	12.0	550mAh (capacity, 3.7-3.9V)	16.0$
Cable	N/A	1.0	-	0.1$
Total	N/A	16.2	Measured: 2mA idle, 52mA normal use, 314mA max. load	195.0$

Table 5.1: Overview of all electrical components of the *VibrAid* wearable.

5.2 System Design

5.2.1 Hardware Design

The hardware design used in this chapter was developed by Vincent Diener during his Software Campus Project in 2017. Figure 5.2 shows the assembled system in a closed state, with all internals being hidden inside. Figure 5.3 shows the opened system. Table 5.1 shows an overview of all components used in the system.

Main board

All electronic components were put on one PCB, including 10 LRA driver modules and the ultra-low-power BLE 5.0 Nordic nRF52840 system-on-chip with a Cortex-M4F CPU. This approach greatly reduces the required wiring, which can be very time-consuming.

The main goal on the hardware side was to create a design that was small enough to fit in a wristband but could also be used in a wide range of wearables. To this end, the 0201 package (imperial) was chosen for the components. This made it possible to fit all components in a relatively small area (25x25mm).

A Bosch BNO55 9-axis absolute orientation IMU (inertial measurement unit) was included in the design. It was not used in this study but it is included in the firmware and was used for experiments in a later chapter.

Actuators

Precision Microdrives C08-00A 8mm diameter linear resonant actuators were chosen for this wearable due to their low current consumption and faster reaction times when compared to ERM-type (eccentric rotating mass) actuators.

Power Consumption

In regards to battery size, the aim was to support at least one full working day (7-8 hours). A total average power consumption of 0.2W to 1.06W was measured, depending on the number of active actuators (1 vs. 10). Besides the actuators, BLE communication was the second biggest contributor to power consumption. Assuming normal usage of *VibrAid* (0-3 actuators activated at all times on average), the 550 mAh battery leaves on average at just over 8 hours operation time. Micro-USB is used for charging.

Thermal Aspects

Apart from user feedback, the components were measured with the highest current flow, the actuators, using an IR camera (see Figure 5.4). The measurement in the figure show the actuators turned off, under full load for 1 minute, 10 minutes and for 10 minutes with the wearable closed as it would be worn by the user. Using the vibration patterns designed for the study (spatial and temporal), the maximum temperature of the closed wearable never exceeded 32 °C (see Figure 5.4, E and F), which is considered safe according to EN ISO 13732-1 and well within the range or normal skin surface temperatures (30-35 °C).

5.2.2 Wearable Design

The main design goal here was to create a tactile wearable that could be discretely worn at a workplace without causing any discomfort, as informed by the general wearable

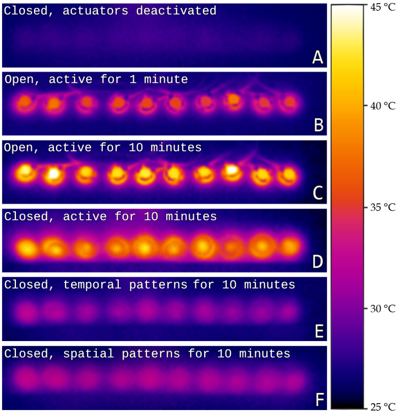


Figure 5.4: Thermal map of the actuators when deactivated (A), active for 1 minute (B, max. 37.9 °C), active for 10 minutes (C, max. 44.8 °C) and closed after 10 minutes (D, max. 40.7 °C). E and F show the wearable closed after repeating all possible temporal patterns (E, max. 31.3 °C) and spatial patterns (F, max. 30.9 °C) for 10 minutes.

design guidelines by Gemperle et al. [38]. The small electronic design gave a lot of freedom in the finding a good form language. At just 16g total weight (including actuators), the electronics could easily be integrated anywhere on the body without being noticeable. The *wristband* form factor was chosen because of its inconspicuous character and ease of access (e.g. when compared to wearables worn on the back). This makes it easy to quickly put it on and take it off, recharge it even when in use or perform maintenance. Slightly stretchable fabric was used, so the wearable fits a range of regular wrist-sizes. When closed, no electronic parts are exposed, as shown in Figure 5.2.

The main board and battery are attached inside the wearable using Velcro tape. For the actuators, 3D-printed small clips firmly hold them in place. The clips themselves pierce through the fabric to directly deliver the full vibration to the skin, effectively bypassing the vibration attenuation that would inevitably be caused by the layer of fabric.

Considering usability, the wearable was designed by Vincent Diener to be usable without any user input. Once the battery is connected, no further user input is required.

5.3 Evaluation

The aim of this study was to evaluate if and to what degree a dashboard-based monitoring task could be supported using vibrotactile cues and to evaluate the wearable for use in a realistic monitoring work environment.

Specifically the following hypotheses were tested:

- **(H1)** Support from spatial patterns provides a significant advantage in task completion time.
- **(H2)** Support from spatial patterns makes participants more confident in their choices.

The critical part of this research was creating a study setup and environment that would closely represent what a real modern monitoring system looks and feels like. To gain the knowledge required to properly design a realistic environment, Vincent Diener reached out to the Rheinhafen steam plant in Karlsruhe. They agreed to support this project by giving Vincent Diener and me a detailed tour of their monitoring facilities (pictured in Figure 5.1) and letting us conduct extensive interviews with employees responsible for monitoring and controlling the power plant. This allowed us to get valuable insights in how these systems are structured, what visual representations are used and what the typical tasks are. From this, we developed a visual dashboard environment and four small tasks that roughly abstract and summarize typical monitoring tasks as described by the monitoring staff. The visual setup can be seen in Figure 5.7 and is explained in more detail in the following section.

5.3.1 Overall Experimental Design

The basic idea of the study was to have participants do a series of simple dashboard-based tasks with and without the support of our wearable while recording various parameters. Later on those parameters would be evaluated to see how using the wearable changed the interaction with the dashboard systems and whether or not it provided a significant advantage.

Participants

24 right-handed participants (5 female, 19 male) were invited to the lab, all but one (age 55) between the age of 22 and 31 (mean age 26.79, SD 6.41). All subjects were graduate students or Ph.D. candidates. The students who participated did so mostly out of interest in the technology. No incentive was provided for study participation.

Before starting with the study, participants were asked to fill out a Multidimensional Mood State Questionnaire (*MDMQ*, orig. German *MDBF*, *"Mehrdimensionaler Befindlichkeitsfragebogen"* [119]) to assess their current mental state. This was done to screen out participants who were tired or in an otherwise undesirable mental state that could potentially affect their attention or ability to concentrate in the experiment. Since the ability to discern colors was important for this study, participants were also screened for color vision deficiency using Ishihara test charts [45].

Experimental Procedure

The study was conducted in a lecture room at TECO over the span of two weeks, as pictured in Figure 5.5. Distracting factors such as unwanted background noises were minimized during the study. To ensure participants wouldn't be able to hear the vibration and to further create a realistic work environment, participants wore headphones playing ambient office noise for the duration of the study.

The study was conducted with a within-subject design with the following conditions:

- **No Wearable** – Without support from wearable.
- **Temporal** – With support from wearable (temporal patterns).
- **Spatial** – With support from wearable (spatial patterns).

To mitigate learning effects and possibly decreasing participant motivation in the recorded data, the condition order for each participant was counterbalanced according to a Latin Square design.

Each condition consisted of 36 small tasks, coming to a total of 108 tasks per participant. Completing all tasks took participants roughly 35 minutes on average.

The study setup with the participant wearing the *VibrAid* wearable is pictured in Figure 5.5. The wearable was worn on the left wrist in order not to possibly obstruct participants when using the mouse. Figure 5.7 shows a detailed view of the three screens as

Figure 5.5: Study Setup. A: Participant wearing the *VibrAid* wearable on his left arm, B: Eye-tracker, C: Headphones playing office noise.

seen by participants. After putting on the wearable, participants were then explained the study scenario. They were to play the role of employees at a power plant, responsible for monitoring important systems. The central screen showed a list of alerts sent from the plant. New alerts would pop into that list in groups of four, each one with a severity level (color coded) of either *low* (yellow), *medium* (orange) or *high* (red). Of those four, participants were told to only solve the single alert with the highest severity and afterwards wait for the next group of alerts to appear.

Each alert included a number (1-4), corresponding to the system that caused the alert. Each of the four systems was represented as a window containing a small task on the left or right screen (see Figure 5.7. The tasks were to be solved as follows:

- **1** – Align all white handles with the black handles.
- **2** – Select the graph with the highest average.
- **3** – Turn on the green ventilation units. Turn the red ones off.
- **4** – Select the boiler with the highest temperature.

Due to a technical limitation of the eye-tracker, the windows on the left and right screen could only cover roughly half of its width.

For the first 12 tasks, participants had 15 seconds to solve each one. For the next 12 tasks, the time was lowered to 10 seconds and finally 5 seconds for the last 12 tasks.

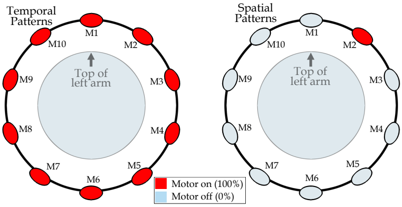


Figure 5.6: Visual representation of the vibration patterns used in the study.

This was done to see how participants would react under pressure and when given barely enough time to finish the tasks.

Participants were told that if they were unable to solve a task in time, they should ignore it and move on to the next.

After finishing the 36 tasks in one condition, participants would move on to the next and after that to the final one. After each condition, participants were asked to fill out a NASA TLX (Task Load Index [47]) questionnaire to assess the experienced workload.

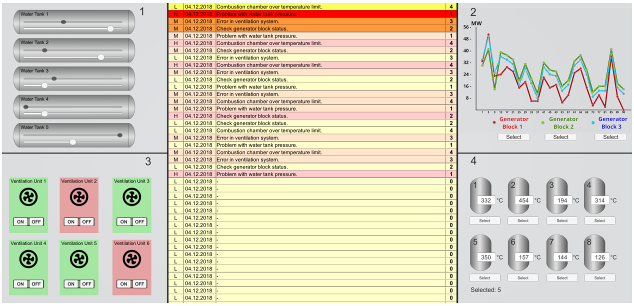
Before each of the two conditions utilizing the wearable, the patterns were briefly explained and shown to the participant. The following two patterns were used (Figure 5.6):

- **Temporal** – All 10 vibration motors vibrate X times, where X is the ID of the window with the highest alert severity. Vibrations lasted for 150ms with 100ms breaks in between.

- **Spatial** – Only one vibration motor vibrates. The motor indicates the direction of the window with the highest alert severity (top left, top right, bottom left, bottom right). Vibration lasted for one second.

5.3.2 Data Collection and Analysis

All data was automatically collected by the study application and written to a CSV file. Eye-tracking was employed to track the subject's attention and navigation when interacting with the application. For this, a Tobii 4C eye-tracker [124] was mounted at the bottom of the middle screen (see Figure 5.5, B). The following data was recorded: head movement, eye-position (x/y screen coordinates of gaze), focus element (gaze), mouse-



L	04.12.2018	Combustion chamber over temperature limit.	4
H	04.12.2018	Problem with water tank pressure.	1
M	04.12.2018	Error in ventilation system.	3
M	04.12.2018	Check generator block status.	2
M	04.12.2018	Problem with water tank pressure.	1
H	04.12.2018	Combustion chamber over temperature limit.	4
M	04.12.2018	Check generator block status.	2
L	04.12.2018	Error in ventilation system.	3
H	04.12.2018	Combustion chamber over temperature limit.	4
M	04.12.2018	Error in ventilation system.	3
L	04.12.2018	Check generator block status.	2
L	04.12.2018	Problem with water tank pressure.	1
M	04.12.2018	Error in ventilation system.	3
M	04.12.2018	Combustion chamber over temperature limit.	4
M	04.12.2018	Problem with water tank pressure.	1
H	04.12.2018	Check generator block status.	2
L	04.12.2018	Check generator block status.	2
L	04.12.2018	Combustion chamber over temperature limit.	4
M	04.12.2018	Error in ventilation system.	3
L	04.12.2018	Problem with water tank pressure.	1
M	04.12.2018	Combustion chamber over temperature limit.	4
M	04.12.2018	Error in ventilation system.	3
L	04.12.2018	Check generator block status.	2
H	04.12.2018	Problem with water tank pressure.	1
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	0
L	04.12.2018	-	

Figure 5.7: The alert list and task windows 1-4 as seen by the participants (slightly scaled to fit). The list in the middle shows four active alerts, the second from the top being the most urgent.

position (x/y screen coordinates of cursor), focus element (mouse) and task completion times. Using this data, the following features were calculated:

- $\mathbf{t_{task}}$ – Average task completion time for each condition (Table 5.2).
- $\mathbf{r_{task}}$ – Average task completion rate for each condition (Table 5.3).
- $\mathbf{t_{focus}}$ – Average time taken to focus gaze on correct task after task has been shown in the list (Table 5.4).
- **Gaze Length** – Average distance of gaze-path (in meter) on screen for each condition (Table 5.5).
- **Mouse Length** – Average distance of mouse-path (in meter) on screen for each condition (Table 5.5).
- **Focus Element** – Average gaze focus times for each element (task 1-4, task list and off-screen) (Table 5.6).

The significance threshold was $\alpha = 0.05$.

Condition	Female [s]	Male [s]	Both [s]
No Vibration	6.39 (0.46)	6.35 (0.74)	6.36 (0.69)
Temp. Patterns	6.41 (0.23)	6.11 (0.60)	6.17 (0.55)
Spat. Patterns	6.08 (0.50)	5.61 (0.62)	5.70 (0.62)

Table 5.2: Mean task completion times t_{task} in seconds (with SD) by condition. Overall mean and split by sex.

Condition	Task Completion Rate r_{task} [%]
No Vibration	73.21 (8.29)
Temp. Patterns	76.79 (6.38)
Spat. Patterns	79.40 (6.79)

Table 5.3: Mean task completion rate r_{task} (and SD) by condition.

5.3.3 Discussion of Results

Table 5.2 shows the average task completion time for each condition. Evaluation of the data revealed that, as expected, the choice of vibration pattern is critical when supporting dashboard tasks. For the task given in the study, the spatial patterns allowed for a natural mental mapping from the perceived pattern to the correct window. This is reflected in the significantly lower task completion times when comparing the conditions *No Wearable* and *Spatial Patterns* (H1, $p = 0.001$). The same can not be said for the temporal patterns: when comparing them to the *No Wearable*, no significant change could be found ($p = 0.31$).

The task completion times of the female participants appeared to be higher on average when compared to male participants, but this difference did not meet the significance threshold (H3, $p = 0.064$). Due to the low number of female participants (5 of 24), statistical comparisons between male and female participants may not be meaningful and no definite conclusion can be drawn from this.

The eye-tracking data was further analyzed to find the cause of this time-gain (see Table 5.4). As expected, the time saved when using spatial patterns is due to participants finding the correct window faster. To show this, we calculated the mean time it took participants to focus their gaze on the correct window after the task had been started. We accepted a window as correctly *focused* once it had been directly looked at by the par-

Condition	**Focus Time t_{focus} [s]**
No Vibration	2.60 (0.61)
Temp. Patterns	2.62 (0.69)
Spat. Patterns	2.06 (0.48)

Table 5.4: Mean focus time t_{focus} (and SD) by condition.

Condition	**Gaze Length [m]**	**Mouse Length [m]**
No Vibration	80.02 (13.89)	24.70 (4.94)
Temp. Patterns	81.42 (14.68)	24.46 (3.98)
Spat. Patterns	71.76 (14.11)	23.86 (2.88)

Table 5.5: Mean gaze and mouse travel distance length (with SD) by condition.

ticipant for one second. This focus time t_{focus} is significantly lower when comparing the conditions *No Wearable* and *Spatial Patterns* (H1, $p = 0.001$), with participants saving 0.54 seconds on average. This roughly accounts for the 0.66 seconds lower task completion times when using the spatial patterns. For the temporal patterns, no significant change in t_{focus} was found ($p = 0.90$).

As a quantitative measure of how confident participants were in their choice of the correct window, we looked at the general eye movement data. We expected the spatial patterns to shorten the time needed to scan the screen for the correct window. Furthermore, once the window had been found, the participants wouldn't have to double-check by looking back at the list. To analyze this, we calculated the average length of the gaze-path on the screen for each condition (see Table 5.5). There is a significant decrease when using the spatial patterns (H2, $p = 0.046$), but not when using the temporal patterns ($p = 0.74$).

H2 is further supported by the significant increase in task completion rate when comparing the *No Wearable* (73.21% correctly solved) and *Spatial Patterns* (79.40% correctly solved) condition ($p = 0.007$, see Table 5.3). When comparing the *No Wearable* condition to the *Spatial Patterns*, no significant increase in r_{task} could be observed ($p = 0.102$).

This is supported by the self-reported NASA TLX results, as seen in Figure 5.8. Participants reported experiencing less frustration when using the spatial patterns, both

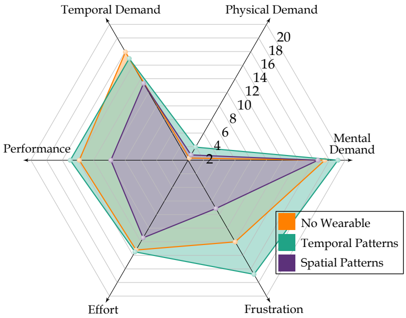


Figure 5.8: Mean NASA TLX scores. Note that a the *"Performance"* scale goes from *"Perfect"* (0) to *"Failure"* (20), so a lower score is preferable here as well.

Condition	**List [%]**	**Wind. [%]**	**Off-Scr. [%]**
No Vibration	21.55 (15.76)	61.90 (10.58)	16.55 (7.72)
Temp. Patterns	21.01 (16.98)	62.76 (12.32)	16.23 (6.58)
Spat. Patterns	21.92 (17.76)	60.82 (11.41)	17.26 (9.25)

Table 5.6: Percentage of total gaze focus time (and SD) for each element.

when comparing them to the *No Wearable* and the *Temporal Patterns* condition. Compared to the *No Wearable* condition, frustration decreased using the spatial pattern (H2, $p = 0.0002$) but increased when using the temporal patterns ($p = 0.0001$). Participants also scored higher on the *Performance* dimension ($p < 0.0001$), required slightly less effort ($p = 0.0005$, TLX dimension *Effort*) and felt less rushed ($p < 0.0001$, TLX dimension *Temporal Demand*) when using the spatial patterns.

As with the gaze path length, we looked at the average length of the mouse cursor path. We did not expect to see any significant differences here as participants would only move the mouse cursor once the correct window had been identified. The data didn't show any differences for either the spatial patterns ($p = 0.47$) or the temporal patterns ($p = 0.85$).

Lastly, we looked at the mean focus times for the elements on screen (see Table 5.6). We did not expect or find any significant differences here when comparing the conditions.

A short interview was conducted with each participant after the main part of the study.

Both patterns were described by participants to be very easy to discern. Most participants did not voice a clear preference for either pattern before the study, while after the study the majority (21 participants) felt that the spatial patterns generally helped them maintain an overview and aided them in finding the correct window faster. 3 participants did not think either pattern helped them. All but one participant reported wearing the wearable as feeling either *comfortable* or *neutral*. Here, the pattern did not make a difference.

Several participants voiced concerns about the directions of the spatial patterns not matching the actual window directions all the time due to them subconsciously moving/rotating their arm with the wearable. This is hard to avoid without specifically concentrating on it and breaks the mental mapping. A possible solution to this would be automatically adjusting the patterns according to the current arm position, which would be possible to implement using our current hardware (BNO-055 orientation sensor).

When asked for their strategies, most participants revealed that they did not feel comfortable relying solely on the wearable when identifying the active window, even when they were confident they had correctly discerned the pattern. One popular strategy (reported independently by 7 participants) was to first look at the number as soon as a new alert appeared, then look to the window according to the perceived pattern. Finally, the participants would check whether or not the window number matches with the number they just saw on the list. Using this strategy allowed them to combine the confidence of visual confirmation with the natural intuitiveness of directional vibration cues.

5.4 Conclusion and Implications

This chapter described *VibrAid*, a tactile attention guidance system for control room environments. It described the wearable and hardware design of *VibrAid* and what design choices were made. Interviews were conducted with control room operators to inform the tactile design and the conducted user study. *VibrAid* was evaluated in a small dashboard environment and compared the usage of temporal and spatial cues with the standard visual attention cues of the control room environment we observed. Participants performed significantly better (self reported and measured) and were significantly less frustrated when the spatial vibrotactile cues were applied as compared to temporal tactile cues and the visual cues. The better task completion time when spatial cues were applied can be explained by the significantly decreased focus time (time needed between the attention cue and focus on the right task), while the time it took to solve the task once it was focused remained the same. This chapter demonstrates the opportunity in using continuous wearable tactile feedback to aid in control room environments and contributes to our knowledge how spatial cues on the wrist should be designed.

As with chapter 3 and chapter 4, this chapter can also be viewed through the three different lenses of generating vibrotactile patterns, learning vibrotactile patterns and spatial aspects of vibrotactile patterns to inform the contributions of this paper.

Regarding the need to craft vibration patterns that fulfill the requirements of the application they are used in is once again made clear. VibrAid compared spatial tactile patterns with temporal tactile patterns on how their capabilities of attention guidance in dashboard environments were. The spatial tactile patterns used in this study vastly outperformed the temporal tactile patterns, even to the point where the visual cues of the control group performed as well as the temporal cues. The fault in the temporal patterns can be pinpointed to the length of the tactile patterns and the ambiguity of the pattern during transmission. Even though the vibration bursts of the tactile patterns are comparatively short with only 150ms per burst, the pattern as a whole can be between 150ms and 900ms long and the meaning of the pattern con not be finally determined until the pattern is completely finished - hence the ambiguity. Compared to the spatial pattern in which the direction is clear as soon as the placement of the vibration is clear to the user. A better approach to pattern design should factor in reaction time as an optimization variable. While the approach of automatic tactile pattern generation discussed in chapter 6 does not utilize reaction speed as an optimization variable, it is very possible to build models that do this to optimize temporal patterns for attention cueing.

Learning vibration patterns easily is once again an important point as this chapter stresses again, as already chapter 3 and chapter 4 did. Although the temporal patterns didn't perform well, passive haptic learning could be used to rehearse and reinforce motions to be executed after the tactile cues. However, for the purpose of this thesis, correctly interpreting the temporal tactile cues is key and chapter 7 will look into this further.

The most important angle to look at this chapter concerns the spatial stability of the tactile display. When designing a tactile display that tells the user where to shift his or her attention, the natural movement of the body needs to be at least be consciously dealt with in the design process. In this chapter the tactile display was independent from the movement of the user, so when there is arm movement by the user still the same actuators are activated as if the arm is not moved, making this display a display based on a egocentric reference frame. The opposing idea is a display in which the tactile display shifts the activation during arm movement to the actuator that is the closest match to the intended direction in space, basing the tactile display on an allocentric reference frame. In chapter 8 this thesis will discuss allocentric and egocentric reference frames on the wrist and evaluates them in terms of reaction time and mental load when answering spatial cues.

6 Interactive Generation of Personalized Vibration Patterns

As seen in chapter 3, chapter 4 and chapter 5, creating new expressive vibration patterns is a challenge. Although there are some guidelines (see [16; 38; 130; 131]), every new wearable tactile display is different and for all tactile presented in the chapters before the process of creating the tactile patterns was long and with lots of trial and error. Creating expressive vibrotactile patterns was especially important for *RüttelFlug* discussed in chapter 3, due to the tactile system using distinct vibration patterns that needed a high degree of discernability to be useful to paraglider pilots. Typically vibration patterns are hand crafted by experts and then evaluated in laboratory and field studies. Hand crafting and evaluating is a long process with one set of patterns as the result and the resulting pattern is not adapted to the specific user but a compromise solution that needs to satisfy ever user at once. The typical process of creating vibration pattern therefore comes with two drawbacks, first the patterns need to be manually created and tested and secondly the resulting patterns are compromise solutions and not adapted to the specific user. In chapter 3 the vibration pattern played a key role in communicating vertical velocity to the paraglider pilots and the process of creating good patterns was hit and miss. For *RüttelFlug* it worked quite well, although tinkering with the vibration patterns and a second field study was needed to confirm the effectiveness of the vibration patterns in the field. Whereas the 6-Channel Tactile Variometer Cuff was based on the idea of a vibration "moving around" and had more problems in designing a fitting and expressive vibration pattern. Although the 6-channel variometer worked and was more or less successfully evaluated in the field, the different vibration modes, the different speeds of the vibrations moving around the arm and the complicated assignments to the vertical velocity didn't help the tactile display in being easy to read. In retrospect, the 6-channel tactile variometer was not enough optimized towards legibility. Examples of the difficulty to design expressive vibration patterns can also be found in chapter 5 where the vibrations of the temporal patterns were too long to be competitive with the spatial pattern or even the control group, a further optimization towards legibility and reaction time would have been necessary to be competitive with the spatial patterns.

To restate this once more, almost all tactile interfaces that use vibration patterns as means of communication run into the problem of designing said vibration patterns. These patterns are usually handcrafted universal vibrotactile patterns and are based on prior trials. The dominant way to evaluate these patterns is to test them out in user studies. However, as research into tactile perception has shown, human individuals show a considerable variety in how they experience tactile stimulation. For example, the perception of frequency differs and cultural expectations influence the interpretation of rhythm [125]. Further, Ferguson et al. showed that the polarity and magnitude of a data concept mapped to vibrations varies considerably between individuals [36]. Even when looking only at one subject, thresholds for vibration recognition highly depend on the contact area, frequency, stimulus duration, waveform, attention, and age of the subject [58]. All of these different factors make crafting a set of vibrotactile patterns for a specific application challenging, as the researcher or practitioner must incorporate the target user group and their demographic, as well as the application and the information that has to be transmitted. Another direction could be to generate personalized sets of vibrotactile patterns that fit the specific user and the specific application and is optimized towards predefined metrics like accuracy, pleasantness or reaction time. However, there has been very little research done into generative and personalized modes of vibrotactile communication.

In this chapter the aim is to explore interactive generation of vibration patterns and to test the feasibility of this alternative approach to generate vibration patterns. Furthermore requirements for a generative approach to the creation of vibrotactile patterns are proposed, as it has to navigate a non-linear and multi-objective solution space, converge in an acceptable time to a solution, and needs to operate with no or limited prior knowledge. To this end an interactive generation system of vibration patterns called GenVibe was designed, implemented and evaluated. The content of this chapter was published in the Proceedings of the International Augmented Humans Conference 2020 [97].

6.1 Related Work

Mobile phones are especially important applications for tactile pulses and present a clear application case [60] they also describe rhythmic patterns with music notes. While there are concepts to increase effectiveness of notifications by increasing their intrusiveness (see [43]), the existing research mostly focuses on non-intrusive methods to increase effectiveness of notifications. Increasing the number of possible values for a dimension results in a higher expressiveness of a mapping but with more values to choose from, differentiation becomes more complicated as well. Therefore, a balance between recognition and expressiveness is key to high information transmission.

An analysis of existing works in the field suggests non-linear optimization for this problem because input parameters are not correlated to outputs in a linear manner. Luzhnica et al. showed that the sensitivity of the cutaneous sense is complex and does not behave linearly to input values in general [71]. In their work, the user could have three different mental models of vibration intensity: 1) linear, 2) power, 3) log [71]. Steven's law [118] defines a non-linear relationship between the physical intensity and the perceptive magnitude. These insights suggest the need for a non-linear optimization algorithm.

In contrast to discriminative models classifying chunks of data, generative models are capable of creating synthetic data. With the rise of modern machine learning approaches like deep neural learning, Goodfellow et al. introduced Generative Adversarial Networks (GAN) in 2014, a game theory inspired approach of two networks playing against each other [39]. These methods usually operate on random input variables drawn from a distribution such as a uniform distribution. A conditional approach generates outputs of a specific class instead of random noise – a selection with added randomness to an initial condition. In order to follow these data-driven methods for algorithmic generation of samples from existing data, distribution needs to be available. Currently, no structured data sets are mapping between vibrations and their perception, although multiple research groups described evaluations of vibrations. Seifi et al. developed a tool called VibViz, which connects keywords and impressions of participants to vibrations [105]. Nevertheless, some generative models have been utilized to generate a vibration pattern. Ujitoko et al. employed a GAN, generating vibrations based on textures [128]. Participants interacted with a tablet through the use of a custom-made stylus, the stylus imitating the properties of the texture shown on the screen of the tablet. Abdulali et al. applied a radial basis network for surface-based interaction and generation of vibration-based on textures [3]. Luzhnica and Veas optimized an alphabet encoding for skin reading by optimizing the distributions of vibrotactile patterns on multiple vibration actuators [70]. The approach proposed by Luzhnica and Veas is different from the approach proposed in this chapter by optimizing one alphabet encoding on several vibration actuators, while the approach proposed here is for one actuator and several, personalized encodings.

6.2 Design

6.2.1 Requirements

An adaptive generation algorithm needs to fulfill a set of requirements to fit into the described domain of vibrations. The main objective of this approach is resilient, fast recognition of vibrotactile patterns by the user as well as a pleasant vibrotactile pattern. Additionally, the approach should not cause any discomfort to a user, which could ultimately result in a rejection of the new approach. The following section describes these needs.

Non-Linear, Multi-objective Solution Space

The approach has to find a **set of vibration patterns** representing a spectrum rather than a single optimal solution. Each pattern in the set should have a high **recognition accuracy**, as well as a high **pleasantness** rating. Because correctly identifying a vibrotactile pattern is a recognition task, recognition accuracy is defined by the proportion of correct identifications among all vibration patterns displayed. The user should correctly identify a pattern and not confuse it with a different pattern. **Pleasantness** is defined by how much the user likes the patterns and finds them pleasant. Therefore, this approach needs to solve a a multi-objective problem which may require the usage of a Pareto-Front, where no solution can improve performance on one objective without degrading another objective. Interactivity is essential to this approach as this approach tries to take advantage of user feedback for the creation of patterns. Therefore, the proposed approach needs to incorporate user feedback for optimizations. This can be achieved through a request-response pattern where the algorithm plays a pattern to a user who subsequently provides feedback about that pattern. Based on the given scoring, the algorithm adapts the parameters used for the generation of patterns.

Fast Convergence

User engagement has certain drawbacks, mainly user fatigue and loss of concentration. In addition, a lengthy setup process is not in the interest of the user. User fatigue occurs on extended evaluation sessions that require a high degree of concentration by a user. When concentration begins to wane, a break and context switch is necessary to regain some of this resource. As a result, fast convergence is emphasized to minimize the needed concentration resource.

No Existing Data

Naturally, it is challenging to balance between exploration and exploitation of a solution space. An algorithm might follow one successful trait to a local optimum without exploring the residual solution space for a global optimum. In the past, most approaches to vibrotactile pattern generation is driven by an expert's decision, relying on previous study results. As of yet, research groups have not collected or provided reusable data sets, which are essential to the training of data-intensive approaches like deep neural networks, making it unfeasible to employ any of these techniques without data collection. This approach therefore needs to work with low demands of data or no existing data.

Later on, collected data might be used to build the previously described user estimator to reduce the number of needed user evaluations. Another objective might be a static analysis like absolute differences between patterns of a set. Static measures could help to generate a more diverse set of vibration patterns and convergent faster to a solution.

In conclusion, this approach needs to investigate interactivity for fast convergence in a non-linear, multi-objective solution space with no existing data. Based on the requirements discussed, this approach pinpointed genetic algorithms with a human-as-a-function to be the best means for the optimization of this problem.

6.2.2 Vibration Pattern

In previous works, researchers used music notes to describe the vibration rhythm [17; 125]. GenVibe borrows terms from the music domain to simplify the understanding of clustering and encoding. A vibration pattern consists of one or more notes. An intensity level describes a note as a percentage and duration is described in milliseconds. For

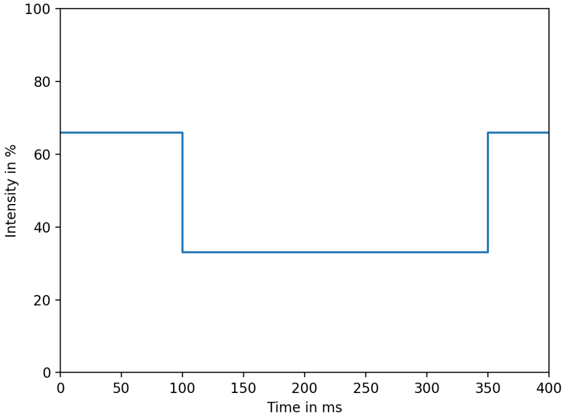


Figure 6.1: Example pattern with three notes. The pattern is described by the following tuple: [(66%, 100ms), (33%, 250ms), (66%, 50ms)]. The first note has a duration of 100ms and 66% intensity, the second note is 250ms long with an intensity of 33% and the last note is 50ms long and 66% intensity.

example, a note with an intensity of 50% and a duration of 500 ms activates an actuator for 500 ms with the consistent intensity of 50%. Figure 6.1 visualizes an example pattern with three notes, each note consists of a tuple holding intensity and duration. Pauses in this context are tuples with a given length but 0% intensity. In the future, other features of a note might include waveform or roughness.

6.2.3 Evolutionary Algorithm

Evolutionary algorithms (see Figure 6.2) encode solutions to a problem in a genetic code to apply evolution-inspired methods. First a population of individuals is initialized, in this case a population of vibration patterns. An individual vibration pattern contains data and fitness used by the evolution strategy. The data of an individual vibration pattern consists of a list of notes consisting of length and intensity. As the human tactile perception has a low resolution for vibrations, a high granularity in the encoding has only small benefits, which is why this approach follows the note-like encoding discussed earlier. On creation, the data field - defining the structure of the vibrotactile pattern - is necessary

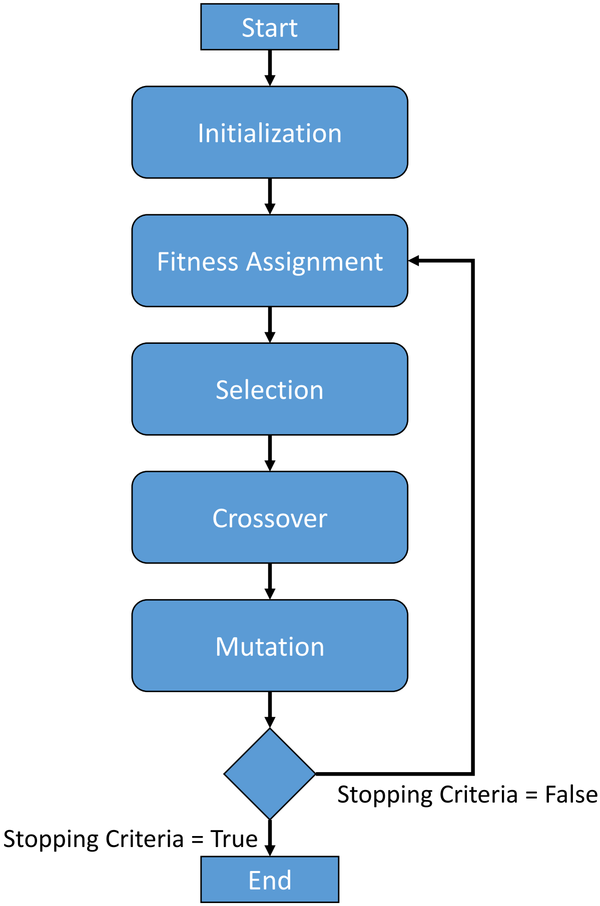


Figure 6.2: Flowchart of an generic evolutionary algorithm.

and needs to be filled, while the fitness of an individual is assigned later. A population represents a group of individuals. A generation holds a population with individuals, an assigned number, and any submitted scoring of that generation. A participant submits a score as an evaluation of the tested pattern. There can be multiple scores to a pattern if evaluated multiple times, but there is only one fitness value assigned to the individual.

In the next step *Fitness Assignment* the *Fitness Function* is compounded from recognition results, confidence, and pleasantness for each individual:

$$\phi = 2 * \chi * \omega + \pi$$

where ϕ is the fitness, χ is either 1 for correct or -1 for incorrect, ω is the confidence of choice, and π is the pleasantness. As discussed earlier it is a weighted sum, multi-objective approach. The recognition result, confidence and pleasantness is gathered by presenting the individuals to a user and asking the user to correctly identify an individual vibration pattern, ranking how confident the user was is identifying the individual and ranking how pleasant the vibration felt.

Afterwards evolution-inspired methods are utilized, consisting of selection, mutation, and crossover. In selection, the algorithm selects individuals from a set for the next steps of mating and mutation. Crossover and mutation are the sources of change in genetic algorithms. Thereby, the crossover is the operator for the exploitation of the solution space, while mutation is the operator for exploration.

Selection is achieved by tournament selection, the size of the tournament is set by the parameter ts. For each position in the population of the current generation, tournament selection selects the better performer from a set of ts randomly drawn individuals. An individual is better than another if its fitness value is in sum higher. The selected individual can be part of mutation in the next step or stay unaltered. After selection, crossover, and mutation, there might be empty spots in a population, to keep the population size constant high-performing individuals of past generations fill these slot. Crossover of two individuals is a one-point crossover. A random point between index zero and the shorter length of the two individuals is chosen and used as a slicing pivot. After slicing individuals into two parts, individuals exchange halves. The joined halves form two new offspring. The probability of crossover between two individuals in a population is set by the parameter cx and can be between 0 and 1. The probability of mutation is set by the parameter mt and can be between 0 and 1, if an individual is selected for mutation, the bit mutation decides over the mutation of each gene of the individual. Bit Mutation of a note is set by the parameter *bmt* and can be between 0 and 1, the mutation replaces the current note with a new randomly drawn note having no context with the replaced note. The optimization of patterns can potentially take place in two different moments in the process: after each evaluation of a pattern or after evaluation of all patterns. GenVibe applies genetic operators to the solutions after the evaluation of all patterns in a generation.

After the genetic operators are applied the algorithm checks if the stopping criteria is met, if yes the algorithm stops, if the stopping criteria is not met another round of evaluation and applying the genetic operators follows.

In the process of starting the genetic algorithm, there needs to be an initial population of individuals. This seed consists of randomly generated individuals with random notes. The following constraints apply to the generation:

- Intensity can be 0%, 50% or 100%
- Note length needs to be between 50 ms and 600 ms
- Minimum accumulated length of the whole pattern needs to exceed 800 ms
- Patterns can not start or end with a note with intensity level 0%

6.3 System

While the genetic algorithm used in GenVibe could run on any platform and an a multitude of haptic devices and wearables, a smartphone use-case is used to evaluate the system in the context of today's smartphone generation. Therefore dummy smartphone was used as the physical platform to conduit the vibrations. The dummy smartphone was used due availability issues in 2019 with real smartphones that had the capability to adjust vibration amplitude at the time of the study. When writing this thesis these issues are subsiding with Android smartphones entering the market that can utilize the *createWaveform* method with amplitude.

Figure 6.3: The dummy smartphone with the electronic components inside.

6.3.1 Case

As a case for the prototype a 6 inch smartphone was chosen due to their popularity and relevant dimensions. Additionally to a relatable height, width, and depth, the dummy weighs 194 g and has rounded edges. A close look and feel to a smartphone favors a transformation of knowledge between test setting and the real world. Unfortunately as a result of using breakout board components inside the case, it was not possible to work with a case as thin as a smartphone; instead, the thickness of the dummy increased from 8.3 mm to 20 mm, see the resulting case in Figure 6.3.

6.3.2 Hardware

A *HUZZAH32 – ESP32 Feather Board* micro-controller was utilised on a breakout board manufactured by Adafruit [5]. The main purpose of the board is to connect to the haptic driver DRV2605L by Texas Instruments [54], which is provided on a breakout board by Adafruit [4]. The driver supports ERM and LRA actuators, is controlled through I2C, and has multiple modes. The I2C interface sets the intensity level of the vibration. The microcontroller connects to the driver through I2C, voltage supply, and one GPIO pin. The vibration actuator is directly soldered to the connectors on the driver.

As a vibration actuator, the dummy smartphone uses a C10-100 by Precision Microdrives [78]. It's a LRA actuator with a diameter of 10 mm, a resonance frequency of 175 Hz and an amplitude of 1.5 g. A LRA actuator was chosen due to higher expressiveness than an ERM. A variety of devices use such actuator, including cell phones, game controllers, and virtual reality hardware. After setting a new level, the chip will drive the actuator with the specified intensity as long as no reset occurs. Additionally, the driver operates in a closed-loop manner, handling the acceleration and braking of the actuator automatically.

6.4 Evaluation

6.4.1 Algorithm Benchmark

An algorithmic benchmark was performed to check if the implementation of the evolutionary algorithm performs as expected and could be compared to other implementations. As an algorithmic benchmark, the algorithm was run against the One Max optimization problem instantiated with individuals holding 15 notes. In its essence the One Max problem asks the question of what the maximum sum is of a bitstring with only 1s and 0s. For the algorithmic benchmark the definition of note was changed from a tuple holding length and intensity to just a bit that could be either 1 or 0. Initially, individuals were seeded with a random combination of zeros and ones. The convergence of this implementation shows consistent results when compared to other implementations. Figure 6.4 and Figure 6.5 show average fitness values of a generation for different hyper-parameters. In Figure 6.4 crossover probability is 60%, mutation probability is 10%, bit mutation probability is 5%, tournament size of three, population size of 100, and 100 generations. The used operators make it impossible to reach an average fitness value of one, due to randomness. Usually, an algorithm terminates if it reaches a certain threshold of mean fitness or if it finds an individual with a fitness value higher than a threshold. In the above configuration, the algorithm needed at least 35 generations to return one individual with a fitness value of only ones. Figure 6.5 shows a more appropriate set of hyper-parameters for the vibration optimization problem with the configuration of 90%

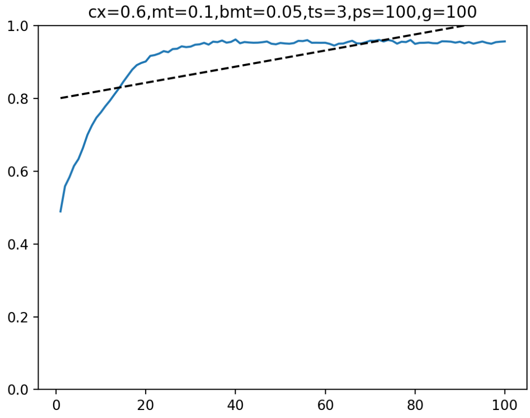


Figure 6.4: Full Benchmark.

crossover probability, 10% mutation probability, 10% bit mutation probability, tournaments size of three, and ten generations. The algorithmic benchmark showed, that the implementation of the evolutionary algorithm behaved as expected and could solve standard problems like the One Max problem.

6.4.2 Preliminary Study

Before the main user study, a preliminary study was conducted to analyze the first samples and generally test the setup. Participants were encouraged to give qualitative feedback during the study.

Participants were recruited from the lab.Each session lasted for approximately one hour and included a briefing and familiarization with the graphical user interface. In conversation with participants, three statements emerged:

- Comparing duration is difficult
- Comparing intensity levels is easier than duration
- Comparing intensity levels is more difficult than rhythm

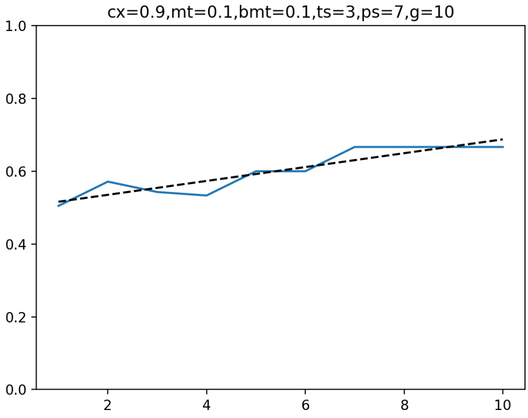


Figure 6.5: Reduced Benchmark.

Furthermore, it seemed to be easier to recognize patterns with constant pulses than slopes of multiple intensity levels. Participants reported that some patterns are impossible to tell apart, although these patterns were technically different. The algorithm ensured to have only distinct patterns in a generation. Participants reported less confidence over time, due to the high amount of newly learned vibrations. Also, confidence drops within one evaluation round, as the time between training and testing increases. The order seemed to be important as well. Playing two similar patterns after each other makes it easier to compare them. Participants described patterns as "more distinguishable over time" and a more diverse population in later generations of the algorithms. It was also possible to decrease the likelihood of further occurrences of unpleasant patterns by rating them as unpleasant. In addition to recognition results and interview notes, participants submitted their personal notes. Three types of personal notes emerged: adjectives, music notes, and intensity lines. Participants report difficulties when responding to a test without their notes. By observing the samples, it became clear that participants would not answer without looking at the notes first. In discussions with participants, two cases emerged: more confident selection result in higher pleasantness, but also more pleasant patterns are easier to remember. Due to the difficulty of our participants to create a mental model of the generated vibrations we decided to incorporate the notes also in the main study to help our participants and get insights into how their mental model of the vibrations worked.

6.4.3 Main Study

For the evaluation, 11 participants were invited to the lab (8m, 3f) with an age range from 22 to 35. Participants gave their consent to store and process their data, including information about gender and age. The total duration of a session was between 48 min and 75 min, depending on the participants individual performance and if and how long breaks were.

6.4.4 Procedure

The genetic algorithm was initialized as follows:

- Individual Vibration Patterns per Generation: 7
- Number of Generations: 10
- Crossover probability: 90%
- Mutation probability: 10%
- Bit mutation probability: 10%
- Tournament size: 3

At the beginning of every session the participants were briefed about the study and the interface, next they were free to test the user interface to familiarize with it. The initial test run aimed to minimize learning effects of the interaction during the actual run. Participants wore earphones with white noise played to mask the sound emitted by the vibrations, they were asked to adjust the volume to avoid hearing any vibration noises during the study. Participants took the test on a clear desk without any distractions, see Figure 6.7. Notes are on the right, while the participants hold the device in their left hand. Due to the complicated and lengthy task of the study participants needed a high amount of concentration, participants were encouraged to take breaks and regain concentration if they felt their concentration was waning.

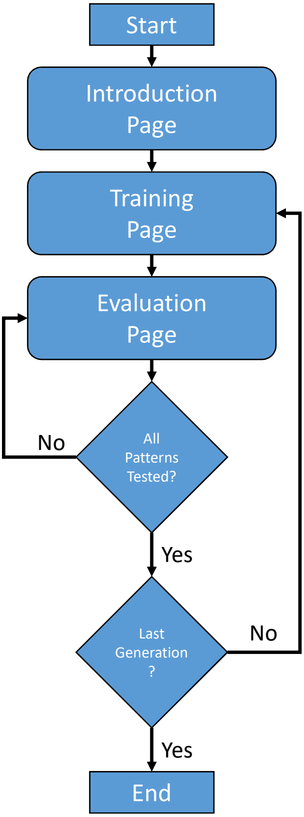


Figure 6.6: User Flow during the main study.

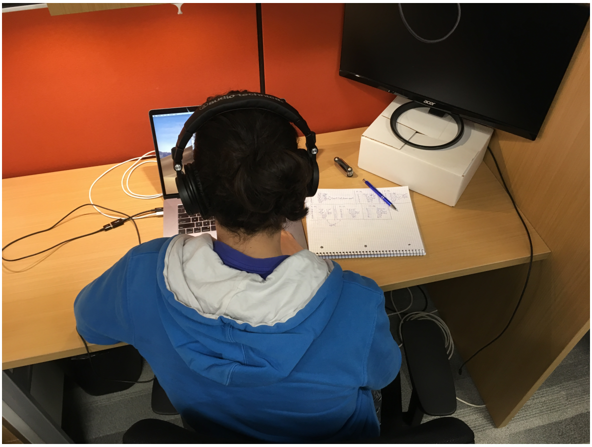


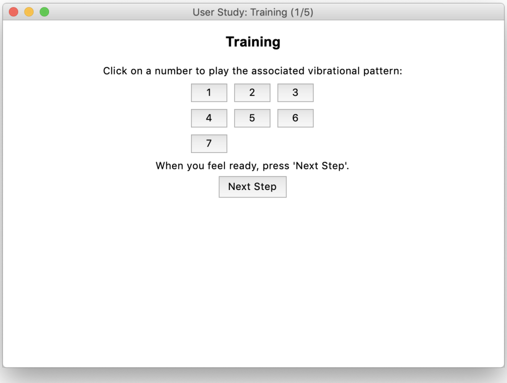
Figure 6.7: Setup for the user studies.

The study itself consisted of three steps seen in Figure 6.6. First a short introduction to the study with an introduction to the experiment and all instructions for the following steps.

On the training page (see Figure 6.8), participants learned all patterns by clicking on the presented numbers. A click on a number would play the pattern on the actuator. When ready to proceed, participants would click on the ‘Next Step’ button. Initial user testing uncovered rushed skipping of training. As a solution, the final version contained a confirmation pop-up, which has to be clicked before proceeding to the evaluation page.

On the evaluation page (see Figure 6.9), a participant could press ’Play’ multiple times to play the pattern on the actuator. A participant was asked to identify the played vibration pattern by clicking on the corresponding number, learned on the training page. In addition, participants were asked to rate their confidence and pleasantness on a 10-point scale each. After submission of an evaluation result, a user would either be shown a new test page, indicating more patterns to be played or a training page with the next generation patterns. In each generation each pattern would be tested three times, testing order was randomized for each generation.

Throughout the multiple rounds of training and evaluation, the number of patterns per generation would not change, but rather be always 7 patterns.

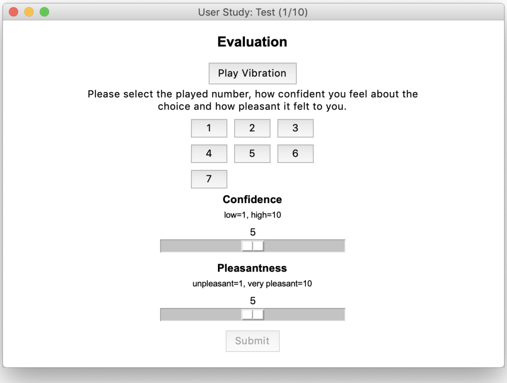

User Study: Training (1/5)

Training

Click on a number to play the associated vibrational pattern:

When you feel ready, press 'Next Step'.

Figure 6.8: Training page for the user study.


User Study: Test (1/10)

Evaluation

Please select the played number, how confident you feel about the choice and how pleasant it felt to you.

Confidence

low=1, high=10

5

Pleasantness

unpleasant=1, very pleasant=10

5

Figure 6.9: Evaluation page for the user study.

6.4.5 Notes

During the training phase of a generation, each participant made notes about the vibrations that was experienced. These notes helped to distinguish between the different patterns. It also gives clues about the cognitive model of a vibration for the user and helps to understand the user. Three methods of note-taking were found to be used: written adjectives, music notes, and lines. Line-based notes were the most common among participants, while music notes were rare. In this way, a line indicates the changing intensity levels during the play of a vibration. In later generations, participants stopped making notes for each pattern but only noted changing patterns. Usually, a dominant pattern group emerged, consisting of 2-4 patterns with very distinguishable features. Therefore, participants recognized them quickly. At the end of a session, participants could compare their notes with the actual plots of the patterns.

6.4.6 Results

Accuracy

Figure 6.10 shows results for recognition. In the first generation, the mean recognition rate is 73.6 % with a standard deviation of 11.9 %. In the last generation, the mean is 84.0 % with a standard deviation of 11.9 %.

There is a significant improvement of the recognition rate over the course of the study between the first and the last generation (paired t-test, $t(10)= 2.6312$, $p<0.05$) with a large Cohen's d effect size of 0.87. Also, Figure 6.10 indicates an increasing trend over time. These results are comparable to prior works, for example Ryu et al. uses seven tactons and achieves recognition for 53 % [104]. In addition, the recognition results show a trend towards higher values in the last generations of a session. This indicates a successful adaptation of the vibration patterns to the individual vibrotactile perception of a participant.

Confidence

As shown in Figure 6.11, confidence has a significant change over time. In the beginning, mean is 69.6 % with a standard deviation of 15.1 %, while in the end, mean is 77.9 % and a standard deviation of 11.1 %.

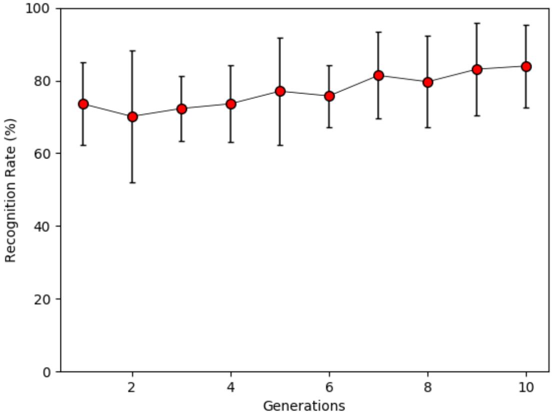


Figure 6.10: Recognition in Percentage through the ten generations of the user study.

There is a significant improvement of the confidence over the course of the study between the first and the last generation (paired t-test, t(10)= 2.7616, p<0.05) with a moderate Cohen's d effect size of 0.62. The increase in confidence over time suggests two outcomes: participants are more familiar with vibrations at the end of a session, and patterns are easier to distinguish. Participants make more confident decisions about vibrations generated by GenVibe.

Pleasantness

As can be seen in Figure 6.12, there are no significant changes in pleasantness (paired t-test, t(10)= 0.70557, p>0.05) with a small Cohen's d effect size of 0.26. In the first generation average pleasantness is 57.1 % with a standard deviation of 10.0 %, while in the last generation mean is 59.5 % and standard deviation 7.9 %. In conversation with participants, they reported difficulties to quantify pleasantness and effectively compare patterns based on pleasantness.

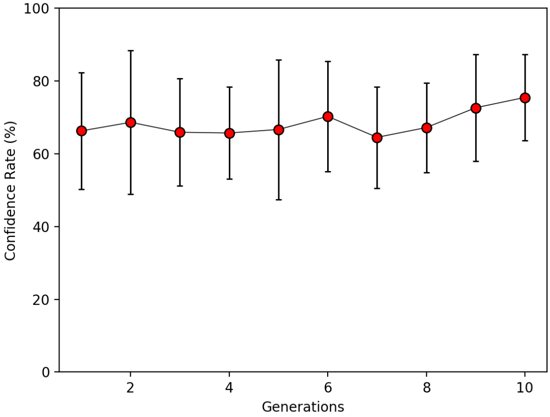


Figure 6.11: Confidence in Percent through the ten generations of the user study.

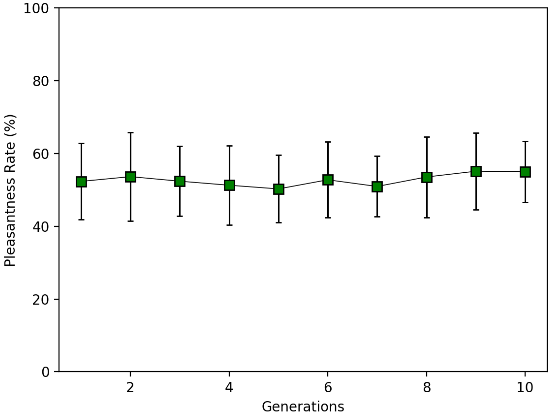


Figure 6.12: Pleasantness in Percent through the ten generations of the user study.

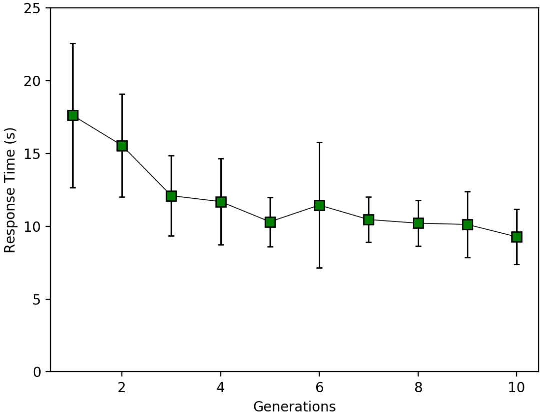


Figure 6.13: Response Time in Seconds through the ten generations of the user study.

Response Time

During the user study, participants took breaks resulting in wrong response times. Figure 6.13 shows changes in response time over the ten generations. The starting mean is 17.6 s and standard deviation is 5.2 s. The final mean is 9.3 s and standard deviation is 2.0 s. There is a significant reduction in response time over the course of the study between the first and the last generation (paired t-test, t(10)= 6.2009, p<0.05) with a very large Cohen's d effect size of 2.12.

Figure 6.14 plots the average amount of times a participant played a vibration pattern on the evaluation page (see Figure 6.7). In average participants played every pattern 4.1 times with a standard deviation of 2.7 in the first generation. In the last generation, participants played vibration patterns 2.7 times with a standard deviation of 0.9. There is no significant change in plays over the course of the study between the first and the last generation (paired t-test, t(10)= 2.0544, p>0.05) although is has a moderate Cohen's d effect size of 0.74.

The response time (see Figure 6.13) and amount of plays suggest a substantial improvement in reaction. In the last generation of a session, participants responded almost twice as fast, with only $\frac{2}{3}$ of the plays. This improvement suggests that these populations

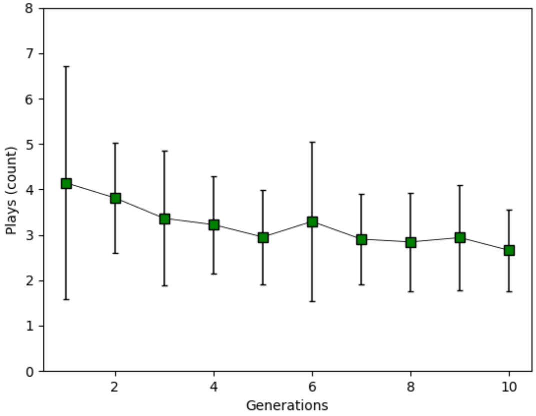


Figure 6.14: Average plays of a pattern through the ten generations of the user study.

are easier to recognize for the participants. The individually optimized vibrations show quick recognition.

Personal Vibrations

As the vibrotactile patterns are personalized by a generative model the patterns differ between the participants, therefore it is hard to compare the patterns in their structure between participants.

Three different sets of vibration patterns in the last generation can be seen in Figure 6.15, Figure 6.16 and Figure 6.17, the sets were genereated by one participant each. Each plot compares the total duration with the number of changes in a pattern. A change describes a switch between two intensity levels. For example, a break as part of an otherwise monotonous pattern means two changes. In comparison, all three participants show a different set of patterns in the last generation.

The first example set of patterns has roughly the same length vibrations with different amount of changes (see Figure 6.15). In the second example set of patterns, each vibration has a minimum length of approx. 800 ms (see Figure 6.16). The third example set offers a wider range of vibration lengths, containing very short vibrations as well (see

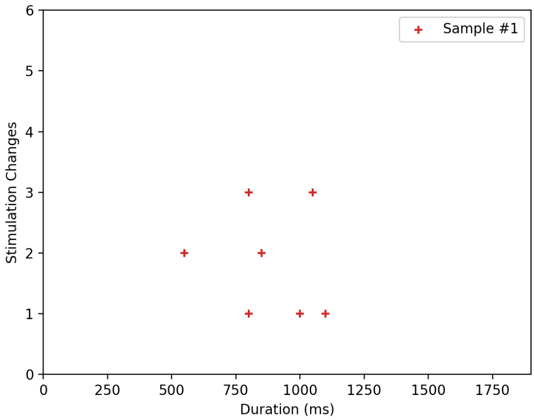


Figure 6.15: Example Set 1. Vibrotactile patterns after the last evolutionary generation of one participant.

Figure 6.17).

The diversity of results for the last generation suggests the importance of individual differences in tactile perception and individual choices during the generation process. GenVibe selected the best performing patterns for each participant. Thereby, each participant has preferences regarding patterns.

6.5 Conclusion

In prior works, researchers mostly utilized existing expert knowledge or random guessing for the generation of vibration patterns and tested said patterns with an audience without any individual modifications. This chapter explored a novel approach to answer the question of how vibration patterns can be created. GenVibe uses an instance of genetic algorithms, during multiple evaluation rounds, a population of vibration patterns adapts to individual preferences of a particular user. In this way, GenVibe exploits the personal differences in the cutaneous perception of a human. Differences are not only limited to the sense but also the mental model of vibrations and originate from differences in gender, age, culture, and activity. Although genetic algorithms are known for

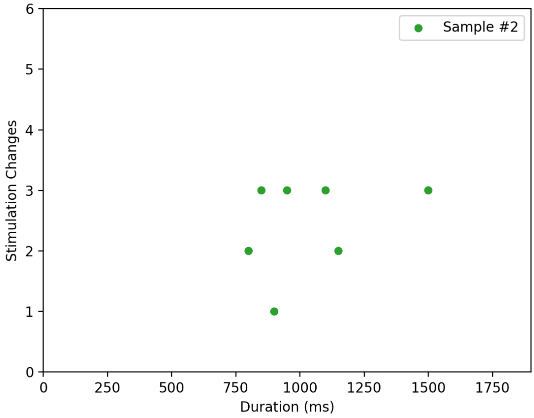


Figure 6.16: Example Set 2. Vibrotactile patterns after the last evolutionary generation of one participant.

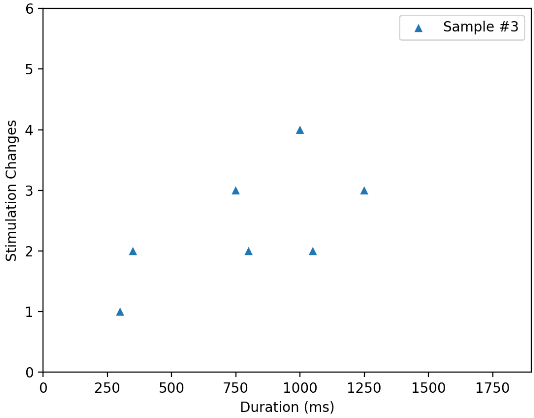


Figure 6.17: Example Set 3. Vibrotactile patterns after the last evolutionary generation of one participant.

a slow convergence to an optimal solution, this work utilises an evolutionary algorithm due to the lack of prior data and the ability to of a genetic algorithm to start with very limited data. Many evaluations drain concentration of participants leading to user fatigue ultimately, so this approach stopped after ten generations, and even that might have been too long. However, the results are promising as there is indication that the evolutionary algorithm adapted differently to different participants and thus a personalisation of vibration patterns happened. During the study, improving performance of the participants could be witnessed by the increase in accuracy and confidence as well as a reduction in response time could be measured. In future work a reduction in training time should be the primary goal, possible solutions could be an estimator to the system that learns from prior evaluations and can be used to train the genetic algorithm. A deep neural network estimating fitness values for individuals could enable the model to train partially without user input and thus lead to a faster convergence.

7 Passive Haptic Learning for Stimulus-Stimulus Associations

The exploration chapters discussed the necessity to learn new vibration patterns and their associated meanings. Information is encoded into vibrotactile patterns and the user has to decode that information. Although tactile patterns or tactons are universal on principle [16], as the meaning of a specific tactile pattern is fixed and understandable in all languages, the correct decoding of the tactile pattern still has to be learned. Learning the correct encoding of vibrotactile patterns can be compared to learning new vocabulary, the user has to learn the new vocabulary initially to later profit from the new knowledge. However, learning a new vocabulary can be rather boring and thus can become an obstacle for the spread of wearable tactile interfaces. Learning a new vocabulary passively or without much attention would certainly be very helpful for users when learning a new set of tactile patterns. Passively accumulating knowledge is a well known phenomenon and in recent years researchers were able to teach simple piano melodies with a process called Passive Haptic Learning. Passive Haptic Learning has since then been expanded to teaching Morse Code with several papers demonstrating the possibility of teaching Morse Code with Passive Haptic Learning [108; 110]. Learning a new tactile vocabulary without voluntary attention or focus would mean a great improvement for the ease of learning and could very well lower the barrier of entry for new users. chapter 7 investigates Passive Haptic Learning and its capability to teach stimulus-stimulus-associations, the experiment conducted by Seim et al. in 2016 was recreated and conditions which prevented implicit and explicit active learning were added to better understand the phenomenon.

Haptic interfaces may enhance various learning processes. There are a variety of applications in development [28; 112; 59]. This chapter focuses on Passive Haptic Learning (PHL) which is the "phenomenon of acquiring motor skills without active attention"[53]. Recently the concept has been expanded to non-motor skills, for example to teach Morse

Code passively (see [108]). This is an important distinction, while Passive Haptic Learning was used to acquire motor skills in earlier works, the expansion into teaching non-motor skills is very intriguing as it would mean one could potentially learn new informations and new associations without paying active attention. Therefore Passive Haptic Learning for non-motor skills could be beneficial for the adoption of continuous tactile wearable tactile displays with vibration patterns due to the passive nature of learning the vibration patterns and their associated meanings. Tactile patterns or tactons are abstract vibration combinations and their associated meanings have to be actively learned before the system is ready to use. If a paraglider would just put on a tactile variometer like the RüttelFlug without learning the vibration patterns and their associated meanings he or she would be very confused in the air. This in fact happened at one point of the development of RüttelFlug when a paraglider wanted to test out the system but was very rushed at the take-off point so there was no time to do a short training for the patterns. When the paraglider was back on solid ground the feedback was mostly confusion due to the multiple patterns and the inability to correctly interpret them. With Passive Haptic Learning this could be at least partially ameliorated and the user could learn the tactile patterns and their associated meanings passively. Passive Haptic Learning of Morse Code has been found to be a highly successful means of learning in two studies by Seim et al., the first one using Google Glass as vibrotactile actuator [108], the second using a smart watch [110]. These studies suggest that PHL for non-motor learning tasks is viable and could solve the problem with investing time and active attention to learn the associations. However, close reading of the paper led to the presumption, that the training and testing procedures which were used leaked information about the learned patterns to the participants on additional channels aside from PHL, and that the additional learning significantly improved performance. To measure the effect of the additional information and the learning score that can be achieved with only PHL without any other information, a 50 participant user study was conducted where 5 different groups' PHL performance was compared. The results of this user study are presented in this chapter and were published as a long paper in the Proceedings of the 2019 International Symposium on Wearable Computers (21% acceptance rate for long papers) [96].

7.1 Related Work

The field of haptic interfaces in passive motor learning is a continuation of research concerning haptic feedback in motor learning ranging from applications in sports, like rowing [9], snowboarding [113], or climbing [35] to motor learning in rehabilitation tasks [6; 57]. It has been shown repeatedly that haptic feedback can improve active motor learning significantly [28; 59; 76; 112].

The term Passive Haptic Learning (PHL) was first coined in a series of projects by Huang et al. [52] that investigated teaching piano melodies using a device called Piano Touch [52]. It consists of a vibrotactile fingerless glove that indicates what finger is used to play the current melody note that the participant is listening to through headphones. In a subsequent within-subject study by Kohlsdorf and Starner[63], the same system was used to examine in how far the distraction task makes a difference in learning through PHL. Seim et al. developed a system to incorporate two gloves to teaching chorded melodies and tested PHL for piano songs [107]. Each of the mentioned studies reported increased playing performance when incorporating PHL.

Seim et al. first tested the teaching of typing skills on a non-standard, eight-button keyboard [111] to test the general feasibility and was later used in a study investigating the use of PHL in Braille typing [106]. Results showed that the PHL group significantly improved their typing performance in contrast to the control group that did not receive tactile information. Seim et al. expanded the concept of text input to number typing in two studies in 2017 [109] by teaching users to type on a number pad with randomized layout, so users need to learn which finger to use to push each button. The PHL group showed stronger decrease in number of times looking at the keypad (determined using an eye tracker) than a control group that did not receive the PHL training [109].

A new direction in the exploration of the possibilities of PHL was developed 2016 in a study by Seim et al. [108] by teaching participants Morse Code with PHL. This is a departure from the earlier research in PHL for motor learning tasks by focusing on PHL for non-motor learning tasks. This approach was expanded upon by Seim et al. [110] by teaching morse code with PHL on a smartwatch and Luzhnica et al. [72] by teaching skin-reading with PHL.

Using PHL for non-motor learning tasks such as learning Morse Code is intriguing, because the process of learning a cognitively demanding skill differs from learning a motor skill. Psychological research indicates that different human long-term memory systems are involved in these two learning tasks. Motor sequences are stored in procedural memory - an implicit memory systems which does not require much attention for recalling information. Procedural memory is created through procedural learning, i.e., by repeating an activity over and over again until all of the relevant neural systems work together to automatically produce the activity. In contrast, stimulus-stimulus associations (as Morse code) are represented in declarative memory - an explicit memory system that requires attention during acquisition (i.e., learning) and retrieval. An addition to experimental evidence, this theoretical distinction has been supported by neuroscientific findings [40; 26; 114]. PHL of Morse Code would require learning associations in declarative memory through procedural learning.

This work also looks into some design choices in earlier studies, such as leaking information during tests [108; 110] and therefore tried to repeat and extend the already published work by Seim et al.. Seim et al. themselves noted in their work, that it is unclear how far the results can be accounted to active learning processes.

7.2 Study Design

Based on the previous work of Seim et al. a between-subjects user study to evaluate specific aspects of Passive Haptic Learning of Morse Code was conducted.Similar to previous studies the experiment consisted of participants sitting in front of a computer and using a wearable with vibrotactile actuators. A wrist band was chosen for simplicity, easy wearability and because its vibration is almost inaudible in comparison to e.g. a head band. Furthermore, the wrist has also previously been used to teach Morse Code with PHL using a smartwatch by Seim et al. [110]. For the duration of designated PHL training sessions, participants repeatedly felt patterns displayed to them by the wrist band and at the same time they heard the corresponding character spoken to them through headphones. After each training session, a test was conducted how much the participants had learned so far. In contrast to Seim et al., more intermittent tests but no repeat tests per training session were done (Seim et al.'s recall tests were repeated three times per test session). After the study the participants were given a list of statements which they were asked to rate on a five point Likert scale (agree, rather agree, neutral, rather disagree, disagree) to inquire about the participants' experience of the tactile display, of the game and their self-assessment of their learning performance.

Study	Letters	Total training time	Training per letter
Seim et al. [108]	26	160min	6,2min
Seim et al. [110]	10	24min/48min	2,4min/4,8min
This study	10	60min	6min

Table 7.1: Comparison of training times between previous studies and this study.

7.2.1 Code and Pattern

Seim et al.'s first PHL Morse Code study [108] used the whole morse alphabet as training set and taught it in eight 20-minute-sets. Including the tests, Seim et al.'s study took around four hours. Seim et al.'s second PHL Morse Code study [110] used 10 letters as training set and taught it in 24 or 48 minutes (depending on the group). In this study 10 patterns were used to reduce the training time. As in Seim et al.'s first study, training was divided into 20-minute-sets. Instead of eight training sets for the 26 patterns, three training sets for the 10 patterns were done. The training times are also compared in Table 7.1.

Ten patterns were chosen at random for each participant, so every participant had a different pattern set and participants that already knew some Morse code did not have an advantage. The patterns were taken from Morse code and were selected as such, that each participant got the same amount of patterns regarding length and complexity, so that the pattern sets were equally difficult to memorize for each participant. Length was defined as the number of dots or dashes in the pattern and complexity was defined as the number of dash-dot-transitions and vice versa, for example •• has the same complexity and length as – – (complexity of zero), while • – has a complexity of one. Table 7.3 compares the training patterns used in Seim et al.'s studies and our study. The length and complexity distribution that were used can be seen in Table 7.4. The distribution of length and complexity of Morse Code was emulated as close as possible (see the parentheses in Table 7.4). Each pattern then was randomly assigned a unique number from 0 to 9 to represent the pattern to the participant. So in effect, even if a participant knew a bit of Morse Code, the meaning of the patterns were unknown and thus the connection from pattern to symbol had do be relearned. An example pattern can be seen in Table 7.2. This effort was undertaken to make sure each participant was taught a pattern set that was smaller than the set taught by [108], but was equal in memorization difficulty and complexity.

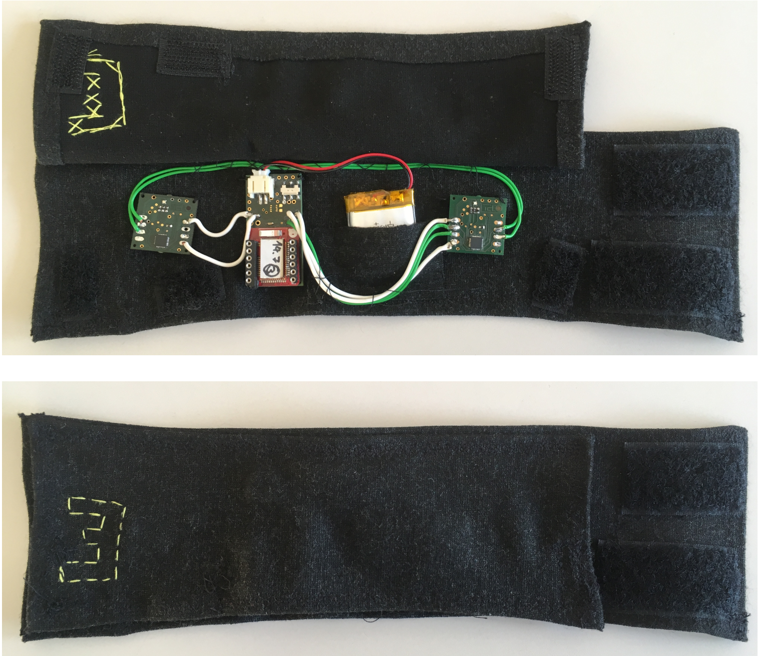


Figure 7.1: Wearable device, opened and closed with velcro tape.

Digit	Pattern	Corresponding Morse Letter
0	• – •	R
1	– • •	D
2	•	E
3	– • • •	B
4	• •	I
5	• –	A
6	– – • –	Q
7	• – – •	P
8	– – –	O
9	• • • –	V

Table 7.2: Example pattern like the ones used in the study. Only the digit-pattern combination is learned.

7.2.2 Wearable

The design of the wrist-worn wearable (see Figure 7.1) was informed by Gemperle et al. [37] in being lightweight, small and worn on the skin. As technical platform the previously used system of Diener et al. [31] was chosen, using vibration actuators by Adafruit (Product ID 1201) driven by TI TLC5971 drivers. The frequency of the vibration actuators is 121 Hz as described by Diener et al.. The wearables vibrated with both actuators for 500ms for a dash ($-$) and for 200ms for a dot ($\bullet$), pauses between dashes and dots were 300ms long, these lengths were taken from Seim et al. [108]. In training, pauses between patterns were 5 seconds long and are slightly longer than what Seim et al. used in 2018.

7.2.3 Training

Similar training duration as Seim et al. were used, three sets of 20 minutes each (see Figure 7.5). Each set was divided into four training sessions, which consist of five minutes of training followed by a test. In the five minutes of training, every five seconds, a pattern was shown and its digit announced audibly. This means that per training session, 60 patterns were shown. For the first two training sets only five patterns were taught, each individual pattern was therefore repeated twelve times. For the last training set, all ten patterns were taught, and each pattern was repeated six times. The patterns were organized in a random sequence that got repeated twelve/six times to simulate how Seim et al. used repeating words to teach in their study [108].

7.2.4 Tests

Participants underwent two tests after each training session, a recognition test and a recall test. No initial test as Seim et al. did in their studies [108; 110] had to be performed,

Study	Letters	Average complexity	Average length
Seim et al. [108]	26	1.12	3.15
Seim et al. [110]	10	0.8	2.9
This study	10	1.0	3.0

Table 7.3: Comparison of training patterns between previous studies and this study.

as participants couldn't have had previous knowledge of the patterns and their assigned numbers - even if participants had some knowledge of Morse Code.

Recognition Test

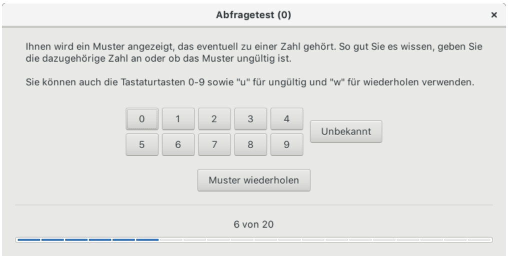
In the recognition test, vibration patterns were presented on the wrist band and the corresponding digit was asked for. To inhibit active learning, no feedback was given. To inhibit being able to determine patterns by rule of elimination, ten additional invalid patterns that did not correspond to a learnable digit were included, so there were twenty patterns in total that were shown to the user during the recognition test. These invalid patterns were chosen for each recognition test from the remaining 16 patterns the same way as the valid patterns (with the same length distribution, see Table 7.4). The participants were informed in a way so that they didn't know which patterns occurred, how often, or if a pattern occurred at all. Users could answer the test by selecting one of the digits 0 to 9 or that they didn't know the answer. Users were allowed to repeat vibration patterns and the number of repeats was recorded as well. An example of the recognition test can be seen in Figure 7.2.

Recall Test

In the recall test, the user heard a digit and were prompted to answer with the pattern. If they knew the pattern belonging to the spoken digit, they entered it to an input box as dots and dashes, if they did not, they could leave it empty. No correction was allowed. Feedback was given depending on the treatment. In each test, all ten digits were tested in random order. An example of the recall test can be seen in Figure 7.3.

Length	0 Transition	1 Transition	2 Transitions
1	1 (0.1, 0.08)	0 (0, 0)	0 (0, 0)
2	1 (0.1, 0.08)	1 (0.1, 0.08)	0 (0, 0)
3	1 (0.1, 0.08)	1 (0.1, 0.15)	1 (0.1, 0.08)
4	0 (0, 0.04)	2 (0.2, 0.15)	2 (0.2, 0.23)

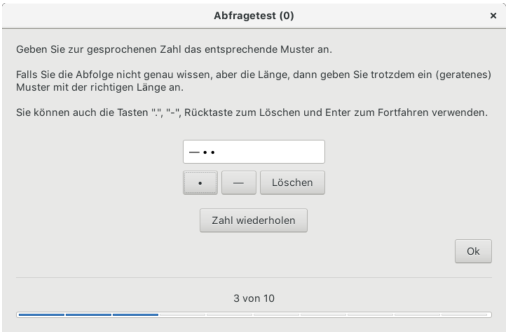
Table 7.4: Number of patterns with length and transitions used in a training set for the study (In Parentheses, the first number is the frequency in our Code, the second is the frequency in Morse Code).



Ihnen wird ein Muster angezeigt, das eventuell zu einer Zahl gehört. So gut Sie es wissen, geben Sie die dazugehörige Zahl an oder ob das Muster ungültig ist.

Sie können auch die Tastaturtasten 0-9 sowie "u" für ungültig und "w" für wiederholen verwenden.

Figure 7.2: Screenshot of the recognition test in german.



Geben Sie zur gesprochenen Zahl das entsprechende Muster an.

Falls Sie die Abfolge nicht genau wissen, aber die Länge, dann geben Sie trotzdem ein (geratenes) Muster mit der richtigen Länge an.

Sie können auch die Tasten ".", "-", Rücktaste zum Löschen und Enter zum Fortfahren verwenden.

—••

Figure 7.3: Screenshot of the recall test in german.

7.2.5 Treatments

The study consisted of five test groups (see Table 7.5). Every group got the same kind and the equal duration of haptic training and they each completed the same tests surveying their knowledge. The differences between the groups were in their distraction tasks and the interaction design of the tests (see Table 7.5). All participants (with exception of the control group) were told to focus solely on the distraction task as their only objective.

Distraction Task

The *Distraction Task* was either **Easy** or **Hard**. The **Easy** distraction task was the open source game "Gweled" [44] (see Figure 7.4, left), which is a similar connect-three game as the one used by Seim et al. in their study. The difficulty of the game was kept constant

Distraction	no-Feedback	with-Feedback
Easy	Easy-no-Feedback	Easy-with-Feedback
Hard	Hard-no-Feedback	Hard-with-Feedback
None	Control	

Table 7.5: Overview of groups for study and their naming scheme.

Figure 7.4: Left: Easy distraction task: Gweled. Right: Hard distraction task: Open Hexagon

throughout the experiment.

The **Hard** distraction task was the open source game “Open Hexagon” [49] (see Figure 7.4, right). A second and harder distraction task was chosen, because the connect-three genre of games may have been too easy for a distraction task. Open Hexagon requires constant attention and quick reaction time so that the user will supposedly be more constrained from focusing on the PHL training. Some graphical elements of Open Hexagon were removed or reduced (spinning background, color change) to not cause nausea. While the game usually increases in difficulty through increasing game speed, the speed and therefore difficulty was kept constant during the duration of the experiment.

Interaction Design

The *Interaction Design* of the tests were either **no-Feedback** or **with-Feedback**.

With-Feedback was an *Interaction Design* similar to the design used by Seim et al. in

Group	Size (#m, #f)	Mean Age (SD)
Control	10 (7 m, 3 f)	27.3 (13.2)
Easy-no-Feedback	10 (7 m, 3 f)	28.9 (13.0)
Hard-no-Feedback	10 (7 m, 3 f)	25.1 (1.9)
Easy-with-Feedback	10 (6 m, 4 f)	24.2 (3.0)
Hard-with-Feedback	10 (6 m, 4 f)	24.1 (2.7)

Table 7.6: Group Demographics.

their paper. During the recall test the users were informed about the corresponding digit to the pattern they just entered. In case the participants entered a pattern not corresponding to a digit the user was shown an error message. Seim et al. noted in their paper, that this interaction design “facilitate some active learning” [108].

No-Feedback was a *Interaction Design* that eliminated the remaining feedback in the recall test. No feedback about the pattern entered in the recall test was given.

Control

As control group (Group Control) there was no distraction task and participants were told to exclusively focus on the haptic/auditory training. This served as a baseline for how much learning is possible at maximum under active haptic learning conditions (vibrotactile armband and spoken digits, no-Feedback interaction design). The outcome that was expected was very high, close to perfect learning rates after one or two training sessions.

7.3 Study Procedure

Participants.

50 participants, 17 female and 33 male, aged between 18 and 54 were recruited. The majority of participants (41 out of 50) were students, aged between 18 and 28. The participants were randomly divided in the five study groups of ten participants each in a way that the age and gender distribution is similar between the groups (see Table 7.6).

The study consisted of four parts (see Figure 7.5): setup, training and test sessions and a survey after the study.

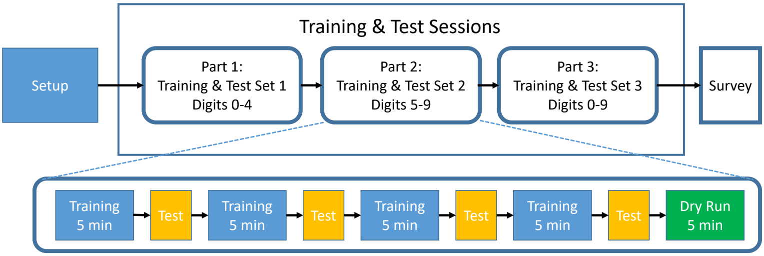


Figure 7.5: Study Procedure.

Setup

Participants were randomly assigned to one group. Wristband and earplugs were put on and wristband functionality was tested. Participants were then familiarized with the game they were about to play and had 30 seconds to try it out. The task (playing the game) and the objective (getting a high score in the game, explicitly not focusing on the digits and patterns) were explained and stressed. The study began afterwards.

Training & Test Sections

The study was split up into three sets of four training and test sessions each, plus one dry run in which participants only play the game without PHL stimulation (no dry run for the control group). In the first set the digits 0 to 4 were taught, in the second set the digits 5 to 9 were taught and in set 3 all digits (0 to 9) were taught (see Figure 7.5). A training session was 5 minutes long.

Survey

A short survey was conducted after the study, inquiring about the participants' experience with the tactile display, of the game and their self-assessment. The participants were also asked about their attention during the game.

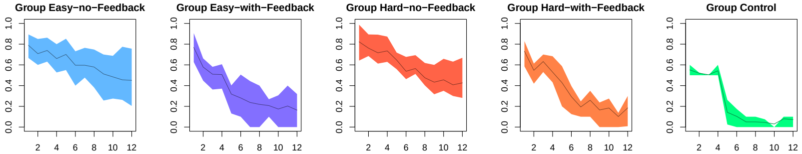


Figure 7.6: Recognize test results using mean error rate metric for each test. Horizontal axis is the training session, vertical axis is the error rate. The colored areas around the mean line show the section between upper and lower quartile.

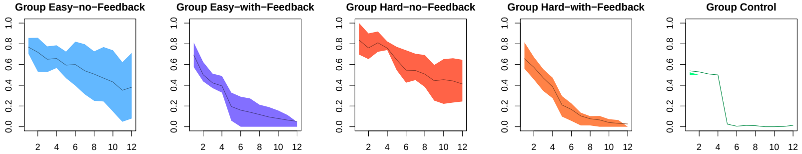


Figure 7.7: Recall test results using mean error rate metric for each test. Horizontal axis is the training session, vertical axis is the error rate. The colored areas around the mean line show the section between upper and lower quartile.

7.4 Results

To evaluate learning results, an error rate metric was used. The error rate metric calculates the Levenshtein distance of the participants' answer and the correct answer and normalizes it by dividing through the pattern length and capping the value at 1 for maximum error rate.

For example if the correct answer is — • — and the participant enters — — —, the error rate will be $\frac{1}{3}$. If they entered • — — •, the error rate is 1. Thus, an error of 0 means a correct answer, an error of 1 that every Morse letter of the pattern was wrong (for example if they left the input box empty) and everything in between indicates a fraction of how many Morse letters were wrong.

In the recognition test, the results of the invalid questions from this evaluation were excluded.

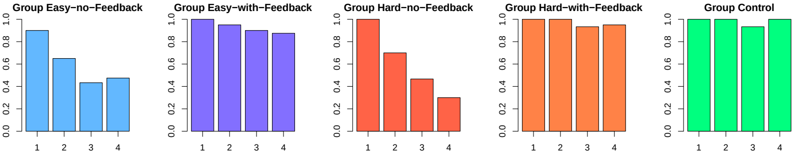


Figure 7.8: Percentage of learned patterns (determined by final recall test) by pattern length. Horizontal axis is the pattern length, vertical axis is the ratio learned.

7.4.1 Recognition and Recall Test

Group Control

Group Control is the measurement of what the best possible active haptic learning score can be - without feedback in the recall test. Very high learning rates are reached even after the first training session (see Figure 7.6 and Figure 7.7). As participants only learn the first five patterns in the first four training sessions, the best score obtainable in either recall and recognize after session 4 is 0.5 (apart from lucky guesses). The mean error in the last recognize test is 0.0725.

This result shows that the chosen teaching modality is very capable and that active memorization of the patterns is a comparably easy task that is repeatedly achieved with very high accuracy after only one five-minute training session for five patterns. The recall test shows that some patterns from the first set can be forgotten during the second set but in the final set where all digits were repeated, they were remembered again. More fluctuation is present in the recognize test and perfect scores were not guaranteed once all patterns were learned (which was after one training session for most participants, according to the recall test). It can be assumed that this might be due to the test being more difficult as it includes needing to sense the pattern correctly, needing to remember whether it is a known pattern and lastly, identifying it. Nevertheless, recognition scores were still close to perfect.

Groups Easy-no-Feedback and Hard-no-Feedback

Regarding the recognize error rates of groups Easy-no-Feedback and Hard-no-Feedback, there is a significant improvement over the course of the study for both groups between the first and the last test-session of the study (recognize error rate, paired t-test, same test as used in Seim et al. [108], Easy-no-Feedback: (t(9)=3.341, p<0.01), Hard-no-Feedback: (t(9)=4.993, p<0.01)). The same significant improvement can be seen in the recall tests of both groups between the first and the last test session of the study (recall error rate, paired t-test, Easy-no-Feedback: (t(9)=3.893, p<0.01), Hard-no-Feedback: (t(9)=4.583, p<0.01)). Mean error in the last recognize test was 0.4508 for group Easy-no-Feedback and 0.4267 for group Hard-no-Feedback, mean error in the last recall test was 0.3816 for group Easy-no-Feedback and 0.4125 for group Hard-no-Feedback. However there is large fluctuation for the recognize error as well as the learning performance. In the recognize test after the first training session the inter-quartile distance is 0.2271 for group Easy-no-Feedback and 0.3458 for group Hard-no-Feedback. This fluctuation seems to increase over time to the point that in the end group Easy-no-Feedback has an inter quartile distance of 0.5521 and group Hard-no-Feedback has one of 0.3875. The inter-quartile distances of error rates of the recall tests behave similarly, after the first test it is 0.1521 for group Easy-no-Feedback and 0.3042 for group Hard-no-Feedback, after the last test it is 0.6334 for group Easy-no-Feedback and 0.4021 for group Hard-no-Feedback.

When regarding the pattern lengths of successfully learned patterns (which was measure by whether a pattern was answered correctly in the final recall test), both groups Easy-no-Feedback and Hard-no-Feedback only learned the shorter patterns successfully (see Figure 7.8). This means that the informational value of what was learned is less than the previously mentioned mean error rates.

Groups Easy-with-Feedback and Hard-with-Feedback

Regarding the recognize error rates of groups Easy-with-Feedback and Hard-with-Feedback, there is a significant improvement over the course of the study for both groups between the first and the last test-session of the study (paired t-test, same test as used in Seim et al. [108], Easy-with-Feedback: (t(9)=12.205, p<0.01), Hard-with-Feedback: (t(9)=5.192, p<0.01)). The same significant improvement can be seen in the recall tests of both groups between the first and the last test session of the study (recall error rate, paired t-test, Easy-no-Feedback: (t(9)=10.447, p<0.01), Hard-no-Feedback: (t(9)=11.313, p<0.01)). Mean error in the last recognize test was 0.1633 for group Easy-with-Feedback and 0.1850 for group Hard-with-Feedback, mean error in the last recall test was 0.0516 for group Easy-with-Feedback and 0.0267 for group Hard-with-Feedback. There is less fluctuation than in the non-feedback groups. In the recognize test after the first training session the inter quartile distance is 0.2792 for group Easy-with-Feedback and 0.2437 for group Hard-with-Feedback. This fluctuation seems to increase slightly over time to the point that in the end group Easy-with-Feedback has an inter quartile distance of 0.3188 and group Hard-with-Feedback has one of 0.2917. The inter quartile distances of error rates of the recall tests behave differently: after the first test it is 0.2375 for group Easy-with-Feedback and 0.2542 for group Hard-with-Feedback, after the last test it is 0.0458 for group Easy-with-Feedback and reaches 0.0 for group Hard-with-Feedback.

Group Comparison

Recognition Test. A two-way ANOVA was run on the data of the last recognition test (excluding the control group), using interaction designs (no-Feedback vs. with-Feedback) and distraction task (Easy vs. Hard) as between-subject factors. The main effect of interaction design was significant, $F(1,36) = 10.00$, $p = 0.003$, indicating that participants recognized more patterns when feedback was provided during the test. The difficulty of the distraction task did not effect the learning, $F(1,36) < 1$, and the interaction between interaction design and task difficulty was not significant, $F(1,36) < 1$.

Recall Test. Similar results were observed in the recall test. Again, a two-way ANOVA was run on the data of the last recall test (excluding the control group), using interaction design (no-Feedback vs. with-Feedback) and distraction task (Easy vs. Hard) as between-subject factors. The main effect of interaction design was significant, $F(1,36) = 25.43$, $p < 0.001$, indicating that participants recall more patterns when feedback was provided during the test. The difficulty of the distraction task did not effect the learning, $F(1,36) < 1$, and the interaction between interaction design and task difficulty was not significant, $F(1,36) < 1$.

Control Group Comparison. When comparing the final results of the control group to either group Easy-with-Feedback or group Hard-with-Feedback the similarity is evident, and also the dissimilarity to groups Easy-no-Feedback and Hard-no-Feedback (see Figure 7.6 and Figure 7.7). There is a significant difference between the last recognition tests of group Control when compared with the corresponding tests of group Easy-no-Feedback and Hard-no-Feedback (recognition error rate, Welch Two Sample t-test, group Control vs. group Easy-no-Feedback: (t(10.352)=3.41, p<0.01), group Control vs. Hard-no-Feedback: (t(11.294)=4.073, p<0.01)). The same significant difference can be seen in the recall tests between group Control and groups Easy-no-Feedback and Hard-no-Feedback in the last session of the study (recall error rate, Welch Two Sample t-test, group Control vs. group Easy-no-Feedback: (t(9.161)=3.41, p<0.01), group Control vs. Hard-no-Feedback: (t(9.255)=4.636, p<0.01)). There is no significant difference when applying a t-Test to the last recall and recognize tests of group Control and comparing them with their corresponding data of groups Easy-with-Feedback and Hard-with-Feedback.

There was also a strange phenomenon in the tests of the fourth session (the last session of the first part, see Figure 7.5). As only half of the patterns are taught but all patterns are tested, the best obtainable error rate should be 0.5 at this point in the study. In the recall test (see Figure 7.7) the control group has a mean error rate of 0.5 and groups Easy-no-Feedback and Hard-no-Feedback are significantly worse than group Control in both tests (Welch Two Sample t-test, group Control vs. group Easy-no-Feedback: (t(9)=2.422, p< 0.05), group Control vs. group Hard-no-Feedback: (t(9)=5.341, p<0.01)). Surprisingly, groups Easy-with-Feedback and Hard-with-Feedback perform *significantly better* than the control group in the recall test (Welch Two Sample t-test, group Control vs. group Easy-with-Feedback: (t(9)=-2.789, p<0.05), group Control vs. group Hard-with-Feedback: (t(9)=-2.606, p<0.05)) with a mean difference of -0.105 for group Easy-with-Feedback compared to group Control and a mean difference of -0.115 for group Hard-with-Feedback compared to group Control. This means both groups Easy-with-Feedback and Hard-with-Feedback learned on average one pattern more than they should have, this can only be explained by the interaction design *with-Feedback*. This stems from the fact that although only half of the patterns are taught, but all patterns are tested. In a study design without information leakage only the the information already presented to the user can be successfully retrieved without guesswork, in this case the correct association of pattern and number. Information leakage in this study happens in the **with-Feedback** treatment of the *Interaction Design* independent variable. As participants could enter any combination of dots and dashes during the recall test (see Figure 7.7) chances are high a combination of dots and dashes was entered that was in the pattern set but not yet taught by the study. In the *not-Feedback* Interaction Design no feedback was given and thus participants weren't able to learn a pattern not yet taught. However in the *with-Feedback* Interaction Design feedback was given and due to this participants could learn patterns not yet taught by the study.

7.4.2 Game scores

For groups Easy-no-Feedback, Easy-with-Feedback, Hard-no-Feedback and Hard-with-Feedback the dry runs without PHL stimulation were compared with the game scores of the training session directly before and after it and found no significant differences (paired, two-sided t-tests). This leads to the conclusion that for both game groups the PHL stimulation did not significantly affect the game play. Moreover, all groups show significant learning effects that resulted in performance gains over time, so it can be concluded that participants were at least somewhat invested into playing the game well.

7.4.3 Survey Results

Testing whether the self-assessment and the actual recall and recognize scores are correlated using Spearman's rank correlation coefficient is affirmative ($\rho_{\text{recognize}} = 0.59, \rho_{\text{recall}} = 0.68$), which suggests that participants were well aware of their performance and learning rate - in spite of the missing feedback in the tests.

7.4.4 Comments from participants

Additionally to the survey, participants were interviewed after the study by asking how they felt about the learning and what they noted about their experience.

Even though explicitly told to not focus on the patterns and audio cues, eight of the twenty participants from groups Easy-no-Feedback and Hard-no-Feedback noted that the many tests made them feel under pressure to produce a good result, so it made them focus on the patterns involuntarily. Participants felt inadequate needing to answer that they don't know a pattern repeatedly in the tests. As consequence, it can be hypothesized that the frequent testing artificially increased the participants' scores. This may be a general problem with our study design, as the only way to fully remove that subjectively felt pressure would be to remove the intermittent tests and only do a single test at the end of the study that the participants do not know about before starting the PHL training. However, that would also reduce the information gathered about the learning process.

Six participants from the non-control groups pointed out that they felt increasingly tired over the course of the study due to focusing on the game for a long time. Future studies should investigate different distraction tasks, however it may be difficult to find a suitable task that is mentally straining enough to distract the user from the PHL training yet does not cause fatigue when done for a longer period of time.

7.5 Discussion and Limitations

The study has shown that PHL for Morse Code without any active feedback only induces a marginal learning effect. However, only by including minimal feedback in the recall test, the learning success is significantly improved and at times even better than the control group. This suggests that in previous studies, the study design was flawed and that a major amount of actual learning was dependent on active learning. In comparison to full active learning (control group), PHL is according to this study orders of magnitude slower and less consistent. Using PHL without any active feedback, even after one hour, only half the patterns are learned - the shortest ones - by about half the participants

The results of the Interaction Design *no-Feedback* groups (Easy-no-Feedback and Hard-no-Feedback) seem to be consistent with the pilot study of Luzhnica et al. [72] where they only found 72% of the information learned. The patterns of the Luzhnica et al. study are very short patterns with one or two vibrations, so this is consistent with the results of group Easy-no-Feedback and Hard-no-Feedback where the shorter patterns were better learned than the longer ones (see Figure 7.8). However it is difficult to compare the two studies directly as they have different interfaces, patterns, training procedure and amount of information.

Future studies about PHL need to pay special attention towards their design and system not to put participants under pressure to perform well. Even though participants were explicitly told to not focus on learning and that the test result is irrelevant, the participants still had an expectancy to what their performance should be like. The limitations of PHL that were found might only apply to Morse code learning on the wrist. Other haptic letter representations like the one that Luzhnica et al. taught using PHL [72] may be more capable. It would be advisable to perform comparisons of other methods instead of just focusing on Morse code.

In a broader sense, it is still unclear how “passive” the learning from PHL is. The phenomenon may very well be due to divided attention and incidental learning. Exploring this however requires measuring attention and mental workload which is a nontrivial task. To get specific numbers, future studies about PHL could explore whether recording and analyzing brain activity during PHL training could be a feasible way of detecting whether participants focus on the PHL stimuli or on the distraction task.

7.6 Conclusion

This chapter studied and reevaluated Passive Haptic Learning of Morse code. The user study which was conducted showed significant improvements of recall and recognition in all groups over the study duration. However, the study also showed only low learning rates when the PHL design explicitly excluded all form of active learning compared to the much higher learning rates of the groups with active learning components which were successfully replicated from previous PHL studies. Finally, drawing the line around what PHL is capable of is very difficult. Drawing from the experience that was gathered, it seems unlikely that there will be haptic devices that can passively teach complex non-motor skills without any active attention. Passive Haptic Learning therefore does not offer an easy solution to the problem of pattern learning. However, small chunks of stimulus-stimulus data can be learned at least somewhat passively, this keeps the door open for some limited background learning.

8 Influence of Reference Frames for Spatial Tactile Stimuli

When designing tactile wearables a factor that is critical is the natural movement of the body when wearing and using the wearable. This is especially important when actuator locations correspond with spatial information. In the previous chapters several continuous wearable tactile displays were afflicted by the body movement, *RüttelFlug* and *VibrAid* both are influenced by the arm movement of the user as the vibration patterns they use have a spatial component. *RüttelFlug* indicates upwards or downwards velocity not only with different vibration patterns but also through different actuators. The spatial patterns of *VibrAid* indicate quadrants by the position of the vibration actuator on the wrist. The question with both wearables is, how does movement and the reference frame utilized by the wearable influence the perception and interpretation of the vibration patterns. In the case of *RüttelFlug*, depending on how the paraglider grips the brakes the wrist is oriented in a different way. With the actuator for upwards movement being positioned on the outside of the wrist and the actuator for downwards movement positioned on the the wrist, there is an implicit assumption that the user will hold the brakes with the wrist fully pronated, meaning the palm is facing downwards. However, there are also other common grips that paragliders can utilize which come with different wrist orientations and thus the orientation of the actuators don't necessarily match with the intended direction. The same issue arises with *VibrAid* when the user pronates or supinates the wrist and the direction of the actuators aren't lined up with the intended direction anymore. chapter 8 investigates how reference frames influence the perception and interpretation of spatial tactile stimuli.

Never before were digital screens as prevalent as they are today. Be it while driving a new car, taking a walk or at work – the sheer flood of primarily visual information that users are confronted with poses an enormous challenge to the ability to filter and process information selectively. Tactile displays allow communicating spatial information without further contributing to the already overloaded and heavily demanded visual system. This thesis already discussed several applications for continuous tactile displays that incorporate spatial tactile information in chapter 3 and chapter 5. In chapter 3.2 *RüttelFlug* the direction of the vertical velocity is indicated in two ways, first which actuator is activated - outside of the wrist for upwards and inside of the wrist for downwards - and the vibration pattern that is displayed [89]. In chapter 5 the relationship of the tactile cues and their directionality were explored and directional cues were compared to temporal cues. The directional cues heavily outperformed temporal cues in this work in regards to reaction time and mental demand. Both examples shown here utilized an egocentric reference frame to indicate the spatial component of the signal. For example, *RüttelFlug* indicates upwards with one actuator and downwards velocity with another actuator. The reference frame *RuettelFlug* uses therefore is egocentric to the wrist of the user, if the user turns the wrist in one direction or another, the tactile signal changes position but still communicates the original meaning. Even if the wrist is turned by 180° and the actuator for „upwards“ is now facing downwards, the meaning of the signal is still „upwards“. No matter where a wearable is located on the body, chances are that the limb is not in line with the body's natural posture, causing ambiguous interpretations of tactile stimuli when spatial cues are utilized.

This poses an interesting question: Given that spatial cues outperform temporal cues in indicating directions, how does the natural movement of the body influence directional tactile cues and what design considerations can be derived from this? Active research into reference frames for vibrotactile interfaces aims to synthesize spatial mappings of corresponding events onto tactile cues. The main objective is to provide frameworks that are intuitive and easy to understand when building tactile displays. Therefore understanding different reference frames and their effects on the user gives valuable insights into designing real-world tactile applications, such as monitoring applications for time critical systems [94]. As humans tend to move and stretch even sedentary positions, incorporating the natural movement of the user into tactile displays is very important [38].

This chapter presents a controlled lab study with 20 participants to evaluate two reference frames in terms of their reaction time, accuracy and cognitive load in spatial localization tasks using a wrist-worn vibrotactile bracelet. The first reference frame encodes spatial coordinates with respect to a wrist-centered frame of reference, while the second reference frame is set in an allocentrically anchored coordinate system to represent spatial directions. The results of the study presented in this chapter were published in the the Proceedings of the 2021 International Symposium on Wearable Computers [98].

8.1 Related Work

Research into haptic and tactile displays often aims to expand the perception of our subjective reality. Whether the expansion is encoding visual information into tactile stimuli [10], or encoding information into stimuli that humans would otherwise not be able to experience [99; 127].

Although some research suggests that reacting to a directional haptic cue comes with a reduced reaction time compared to a visual cue [83], this finding is debated elsewhere [100], taking the position that a multimodal interface with haptic and visual cues has the most benefits [100]. Spatial vibrotactile cues can help pilots during long flights keeping the aircraft in balance by decreasing the attention needed to perform specific tasks like maintaining an aircraft's altitude and take corrective action when the autopilot goes off bound [19]. Tan et al. used a 3 × 3 grid of vibrotactile actuators mounted to the back of a chair to significantly decrease reaction time in a change detection task. Particularly wrist-worn devices, such as vibrotactile bracelets, have been developed to assist with attention guidance and navigation. For example, a system was evaluated with respect to the ability to guide a user's attention towards certain panels of a large dashboard using vibrotactile spatial cues [94]. However, task complexity drastically increases once the tactile display is not aligned with the visual reference frame, which according to Heed and Azañón tends to dominate other senses during spatial remapping [48]. Panëels et al. have taken a first step towards using vibrotactile feedback for mobile navigation, where the system was evaluated in both a wrist-centered and allocentric reference frame with almost unrestricted freedom in arm movement. Performance, measured through response time and accuracy, was found to be better when cues were presented in a wrist-centered frame of reference [87]. An interesting aspect of tactile cues is how "spatial remapping" occurs from tactile sensation to the actual location on the body [85]. For example, crossing hands results in higher response time to tactile stimuli, which suggests that anatomical remapping according to body posture has to be performed [48; 85; 86].

Using cross-modal stimulation techniques, Ley et al. advanced the theory that the brain assigns different weights to both somatotopic and external representations of the body surface [67]. According to their observations, both representations appear to be active in parallel [67]. The idea of weighted internal representations has already been suggested by Volcic et al. in 2009, wherein an experiment subjects had to assess the parity of two objects located in various spatial locations by exploring them with different hand orientations using a bimanual rotation task. Results indicated that the wrist-centered reference frame plays an important role in haptic mental rotation tasks. In contrast, they found that for visual mental rotation, an allocentric reference frame appears to dominate [133]. To determine the effects of a directional bias during horizontal reaching tasks, Pennel et al. conducted a study where participants were only shown a live video feed of their arm with alternating camera angles, while direct vision of their arm was blocked, effectively limiting the control of arm movement over the video stream. It was observed that there is no clear preference towards either of the two reference frames, however, they furthered the speculation that the allocentric reference frame is of greater potential [88]. Similar observations were already made in a study by Attneave and Reid, where participants had to name slopes of shown lines under head rotation [8].

The research presented in this chapter ties in with the aforementioned works by exploring and testing how spatial tactile cues on the wrist map to secondary locations on a smartphone screen and if aligning the location of sensations to the display reduces mental effort. As there is still no clear consensus in the literature on allocentric or egocentric reference frames perform better, it is fruitful to investigate this and compare them.

8.2 Methods

8.2.1 Framework

A wrist-worn tactile bracelet was used for this study, it consisted of ten Precision Microdrives LRAs 10mm in diameter spaced evenly around the wrist for vibration output. In order to ensure a good fit for most wrist sizes, an elastic jersey fabric (with an approximate stretch ratio of 2) was used and tightly fit to most wrist sizes around 18 ± 1.5cm. A Bosch BNO055 inertial measurement unit was included to measure the wristband's orientation in terms of roll. Two different frameworks to communicate a spatial tactile cue to the participant were utilized:

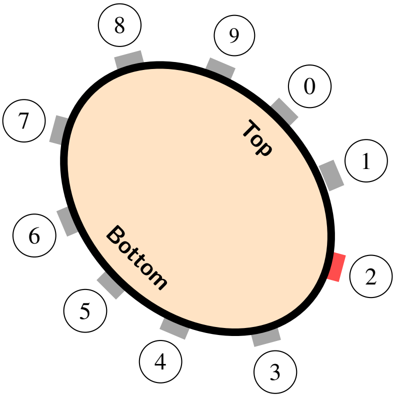


Figure 8.1: Cross section of the wrist rotated by 45 degrees with actuator (2) vibrating.

- **allocentric**: Spatial directions are encoded in an allocentric reference frame. Depending on the orientation of the wrist, different actuators are used to communicate the same direction.
- **wrist-centered**: Spatial directions are encoded in a wrist-centered reference frame. Therefore every actuator always represents the same spatial direction, irrespective of wrist rotation.

An illustrative example is given in Figure 8.1, where the wrist is rotated by 45 degrees clockwise. Equal spacing of motors allowed us to divide the surface of the wrist into ten circular sectors, each covering approximately 36 degrees. Depending on reference frame, wrist rotation, and vibrating motor, the spatial direction represented by the active motor can be calculated, in this case motor (2). For the wrist-centered condition, the vibration mapped to $2 \cdot 36^\circ = 72^\circ$, while the allocentric representation also accounts for wrist rotation, therefore mapping to $2 \cdot 36^\circ + 45^\circ = 117^\circ$.

8.2.2 Experimental Procedure

20 participants (19 male, 1 female) were invited to the lab (mean age 23.95 ± 2.29 years) from which two were left-handed and 18 right-handed. After welcoming the participant, explaining the experiment's concept and getting their informed consent, the bracelet was

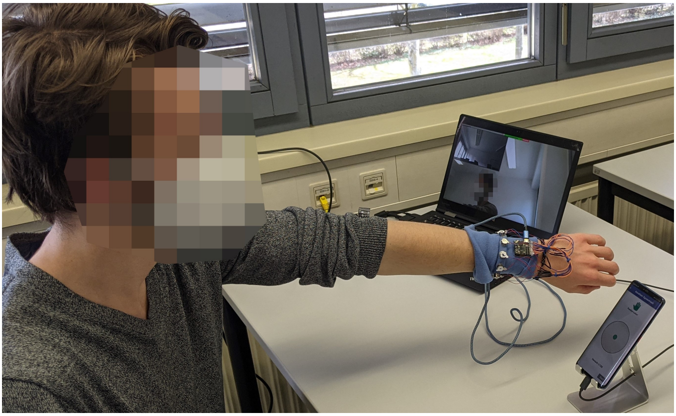
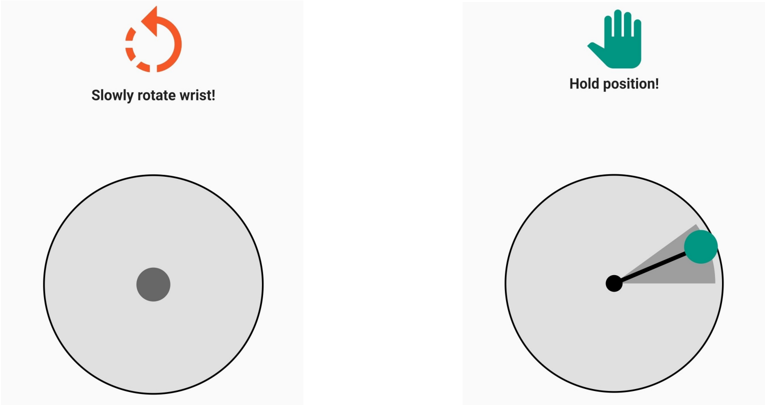


Figure 8.2: Study setup showing a participant wearing the bracelet on the non-dominant hand and a smartphone fixed within reach to enter associated vibration direction

fit onto the participant's non-dominant arm and several tests were performed to make sure that every actuator fit correctly and was equally perceptible by conducting a short pretest. The study was conducted in a lecture room at the TECO lab over the span of approximately four weeks. Figure 8.2 shows the setup which was designed to accurately measure response time and accuracy and imitate movement patterns of the arm suitable for sedentary activities in desktop environments. The study was conducted with a within-subject design with the two presented output frameworks –wrist-centered and allocentric – as conditions. To mitigate carryover and learning effects, each participant was assigned to one of two groups, where the order of conditions was varied according to a 2×2 Latin-Square-Design. After the completion of each condition, participants were asked to fill out a RawTLX questionnaire [46]. Each condition consisted of 120 subsequent spatial localization tasks, where all participant were confronted with the same combinations of wrist rotation and activated motor in randomized order to ensure equal data distribution among participants. Each trial started with participants rotating their wrist to the previously determined position as seen in Figure 8.3 (a). Once the wrist had been rotated, the previously determined actuator was activated and participants were asked to enter the direction by performing a directional movement of the center dot on the smartphone screen. Participants were explicitly told beforehand to respond as quickly as possible but as slowly as necessary to maintain a reasonable level of accuracy.



(a)

(b)

Figure 8.3: (a) Participants first rotated their wrist until the arrow slowly faded towards a green color to then respond by performing a directional movement from the center to the edge of the outer circle (b)

8.2.3 Hypotheses

The study aimed to evaluate both wrist-centered and allocentric reference frames whilst rotating the wrist. The experiment was conducted to test the following hypotheses:

(H1) Performing tasks with the wrist-centered condition results in lower accuracy compared to the allocentric condition. While this hypothesis is backed by Pagel et al.[86], opposite results were observed by Panëels et al.[87].

(H2) Performing tasks with the wrist-centered condition results in higher response time compared to the allocentric condition. It can be argued from the existing related work (see [48; 85; 86], that shifting visual and wrist-centered reference systems causes confusion and, therefore, greater cognitive load, leading to higher reaction time.

(H3) Increasing deviation from a fully pronated forearm during the wrist-centered condition results in increased response time compared to the allocentric condition. This hypothesis was derived through pilot studies and [121].

(H4) Increasing deviation from a fully pronated forearm with the wrist-centered condition results in lower accuracy compared to the allocentric condition. Again, this hypothesis was derived through observations in the pilot study and [121].

(H5) A steeper learning curve can be observed for the wrist-centered condition compared to the allocentric condition, as participants are likely to associate recurring directions with the same spatial directions after some trials (see [88]).

(H6) The allocentric condition is mentally less demanding and therefore more intuitive than the wrist-centered condition.

8.3 Results

A significance level of $\alpha = 0.05$ was used for all statistical tests.

8.3.1 Reaction Time

When comparing both conditions with respect to response time (see Figure 8.4), a statistically significant difference ($Z = -12.59,\ p < 0.001$) with low effect size ($d = 0.271$) was found using a paired Wilcoxon signed-rank test. While response time averaged $2169.4 \pm 840.1\,\text{ms}$ for the wrist-centered condition, the allocentric condition was slightly faster averaging $1929 \pm 734.8\,\text{ms}$. This supports **H2**.

8.3.2 Accuracy

A paired Wilcoxon signed-rank test indicated that there was no statistically significant difference ($Z = -1,\ p = 0.318$) for accuracy between both conditions. With the wrist-centered condition, participants were able to achieve an average accuracy of $84.1 \pm 15.2\,\%$ (or abs. angular error of $28.5 \pm 27.3\,\text{deg}$) and similarly $85.1 \pm 12.5\,\%$ (or abs. angular error of $26.8 \pm 22.5\,\text{deg}$) during the allocentric condition. Therefore **H1** is not supported by data.

8.3.3 Learning Effect

Linear regression was used to measure a learning effect for both conditions using trial number to predict reaction time, see Figure 8.5. No statistically significant evidence

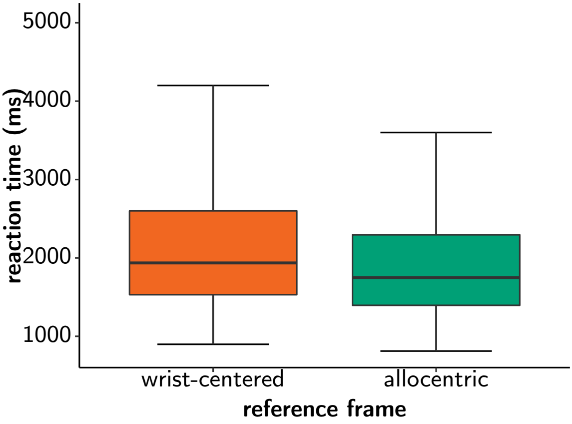


Figure 8.4: comparison of response time by reference frame

was found for the wrist-centered condition for reaction time ($R^2 = 0.00116,\ F_{1,2069} = 2.4,\ p = 0.12$), however there was a statistically significant decrease in response time for the allocentric condition ($R^2 = 0.01474,\ F_{1,2115} = 31.65,\ p < 0.001$). Nonetheless, **H5** is not supported.

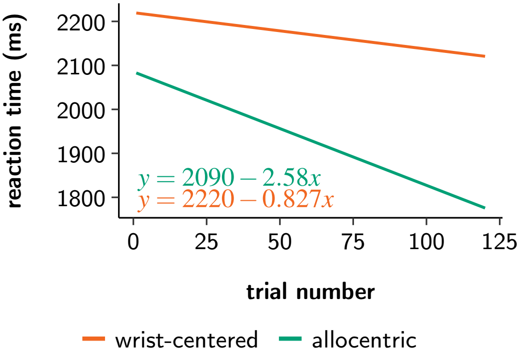


Figure 8.5: Linear regression analysis of reaction time by condition using experiment progress as predictor.

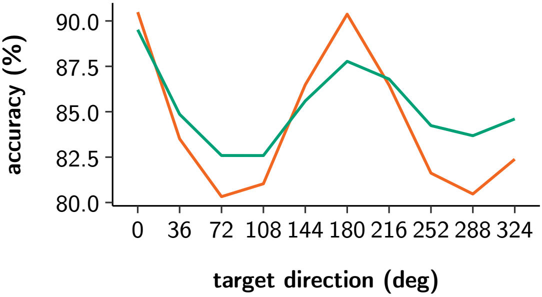


Figure 8.6: Effect of target direction on accuracy. Accuracy was highest for both 0 and **180**° and decreased for intercardinal directions.

8.3.4 Directional Analysis

When examining the effects of both wrist rotation and target direction on performance for both conditions the following analyses were conducted[1].

Target Direction

In order to examine how target direction affected accuracy, a Kruskal-Wallis test was conducted for each condition separately using target direction as the group. Results indicated a statistically significant difference between target directions for both the wrist-centered ($\chi^2_{9,2071} = 264.36,\ p < 0.001$) and allocentric ($\chi^2_{9,2117} = 149.36,\ p < 0.001$) condition. Therefore a post-hoc pairwise Wilcoxon signed-rank test with Bonferroni correction was conducted for each condition which yielded no statistically significant differences between both 0 deg and 180 deg for both conditions, which is clearly visible in Figure 8.6. However, accuracy dropped towards east and west directions, which is supported by the statistically significant differences between 0° and $72, 108, 252$ and 288° in both conditions.

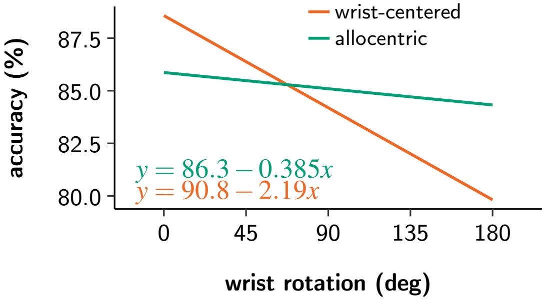


Figure 8.7: Linear regression analysis of the impact of wrist rotation on accuracy. Increasing wrist rotation negatively impacts accuracy in the wrist-centered condition.

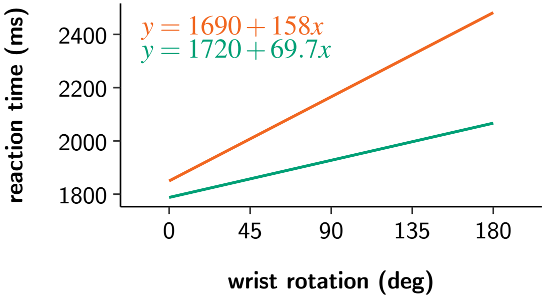


Figure 8.8: Linear regression analysis of the impact of wrist rotation on response time. Increasing wrist rotation negatively impacts accuracy in the wrist-centered condition.

Wrist Rotation

Linear regression analysis using wrist rotation as the predictor was used to examine how rotational deviation from normal position affected reaction time and accuracy in both conditions respectively, as seen in Figure 8.7 and Figure 8.8. For the wrist-centered condition, the regression analyses were found to be statistically significant for both reaction time ($R^2 = 0.06,\ F_{1,2069} = 123.17,\ p < 0.001$) and accuracy ($R^2 = 0.03,\ F_{1,2069} = 70.75,\ p < 0.001$). This supports **H3** and **H4**.

8.3.5 Cognitive Load

To analyse the cognitive load the data collected by the RawTLX questionnaires was investigated to analyze how the participants mental demand was affected under both conditions. The RawTLX was separately evaluated for each dimension as seen in Figure 8.9. The allocentric reference frame yielded better results in all dimensions. Paired Wilcoxon signed-rank tests indicated statistically significant differences in every dimension with low effect sizes, except for a large effect size in mental demand ($Z = -3.13,\ p < 0.001,\ d = 0.532$) and moderate effect size in performance ($Z = -2.66,\ p < 0.001,\ d = 0.41$) and effort ($Z = -2.26,\ p < 0.001,\ d = 0.303$). This finding supports **H6**.

8.3.6 Subjective Feedback

Besides from an analytical standpoint, participants gave a substantial amount of feedback and made some interesting observations after the experiments. During the wrist-centered condition some participants closed their eyes while the vibration was occurring. When asked, one participant argued that he found it easier to perform the mental rotation without the influence of vision. Instead of closing their eyes, some participants also used the first three fingers to represent the coordinate system to then imitate the rotation of the wrist in order to better allocate the vibration spatially. Some participants could also be observed looking at their wrist after the vibration. It was argued that it is easier to visualize the vibration on the skin before assigning a direction. During the demo phase, a majority of participants expected the fixed-on-wrist condition to be much more demanding. After the experiment however, some participants revised their initial statement and

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[1] Only data from the last 8 participants could be used to perform analysis with the wrist fully pronated (0 degrees rotation). This was caused by a bug in the study software that was only fixed for the last 8 participants.

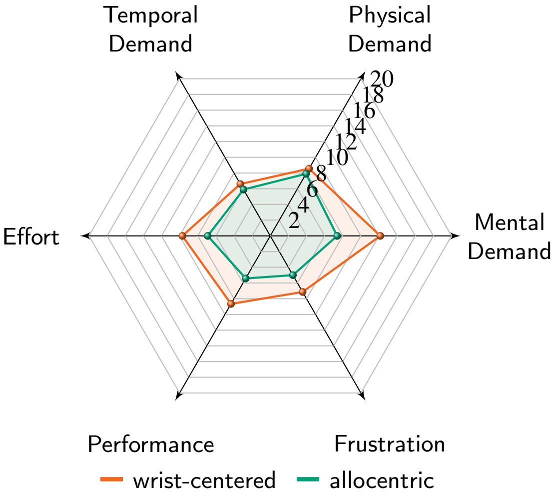

Figure 8.9: Average RawTLX values for both reference frames, the allocentric reference frame being less demanding in every dimension.

concluded that the fixed-on-wrist condition was mentally indeed more demanding, but overall they overestimated the difficulty in the beginning.

These observations could not be made during the fixed-in-space condition.

We of course also received some critical feedback concerning the wearable and the application. During trials, the second motor made some noise for some participants because the snap fastener was not tight enough. They argued that it was easier to localize the direction knowing the exact position of the actuator and wrist rotation. However this is not reflected in the data. Despite the flexible fabric, the device almost did not fit the wrist of two participants. Another participant criticized the size of the circular input. We initially considered the use of a tablet, but due to technical problems we stuck with the smartphone, which worked well for every other participant.

8.4 Conclusion

The experiment was conducted to asses two reference frames in the context of somatosensory spatial localization under wrist rotation with regards to the aspects accuracy, reaction time and cognitive load. The study was designed to be conducted contactless due to the ongoing Covid-19 pandemic. Analysis of the experiment results could show no significant difference in accuracy between the allocentric reference frame and the wrist-centered reference frame. The experiment could show that participants were slightly but significantly faster in identifying spatial cues displayed in the allocentric reference frame than in the wrist-centered reference frame. A directional analysis revealed that the allocentric reference frame is mostly robust against wrist rotation while the wrist-centered reference frame performed worse the more the wrist was rotated. Apart from quantitative measurements, one of the more notable findings to emerge from the study is that the allocentric reference frame is far less mentally demanding compared to the wrist-centered reference frame. This was not only derived by the evaluation of the RawTLX questionnaires, but most importantly by subjective feedback, where participants described the egocentric reference frame to be far less intuitive and more demanding. The findings regarding the learning effect during the experiment were surprising. Contrary to the initially stated hypothesized position that the reaction time during the wrist-centered condition would improve during the experiment, only little improvement with the wrist-centered reference frame could be observed and substantial improvements in reaction time within the allocentric reference frame could be observed. These results are somewhat contrary to previous work of Panëels et al., which indicated that a wrist-centered reference frame might be beneficial regarding accuracy and reaction time in a mobile setting. However, results might be less contradictory when considering the yet comparatively small difference in reaction time between both conditions. Nonetheless, being only limited to wrist rotation, it is yet to establish how different postural changes affect performance. Despite of its limitations, the study certainly contributes to our understanding of how spatial cognitive processing is affected by reference frames and how they can be utilized to achieve better performance in tactile localization and control tasks or even mobile navigation.

9 Conclusion and Future Work

This thesis explored continuous wearable tactile displays in three different application areas: outdoor sports, gaming and dashboard environments. Applications in outdoor sports for continuous tactile wearable displays were explored through the lens of paragliding and continuously communicating critical information like vertical velocity through tactile means to the paraglider pilot. This thesis presents design and evaluation of two wearables to communicate vertical velocity to paraglider pilots. Contributions were made in the exploration of the design space of wearable tactile variometers and the continuous communication of important information through repeating structured vibration patterns. Wearable tactile variometers were evaluated in a lab study with 11 participants and two field studies with 4 and 2 paraglider pilots.

Applications in gaming were explored through continuous display of valuable information to the user, examples for this were provided in chapter 4 and include a smartwatch-based continuous tactile display for hit-point in the game "Half-Life 2" and a tactile feedback system for industrial applications evaluated in the game "ARMA 3". Contributions in the area of continuous tactile feedback for video games presented in this thesis are the exploration of continuous tactile feedback with off-the-shelf hardware, the design and implementation of a continuous tactile feedback system with off-the-shelf hardware and the 29 person between-subject user study. This thesis presents evidence of the possibility and feasibility of a tactile feedback system using off-the-shelf hardware in gaming to enhance the immersion and gaming experience.

Applications in dashboard environments were explored through continuous tactile cues on the wrist for attention guidance. Visual cues and spatial and temporal tactile cues for attention guidance with a wrist-worn wearable were compared in a 24 person within-subject user study. Participants were significantly faster and significantly less frustrated when reacting to the spatial tactile cues compared to visual cues and temporal tactile cues. Adding spatial tactile cues can help to support monitoring tasks and bring new modalities to situations in which fast and decisive reactions are necessary. This work opens up possibilities of incorporating tactile displays into large cyber-physical monitoring systems.

Three challenges for continuous wearable tactile displays could be identified through the exploratory approach:

- Generation of Vibration Patterns
- Learning of Vibration Patterns
- Body Movement and Spatial Tactile Stimuli

This thesis aimed at providing answers for each challenge in chapter 6, chapter 7 and chapter 8.

To address the challenge of manually generating vibration patterns this thesis explored interactive automatic generation of vibration patterns to personalize vibration patterns during their creation. An interactive evolutionary algorithm was designed, implemented and tested with a 11 person user study. This thesis presents evidence, that an interactive generation of vibration patterns is possible and leads to distinct personalized vibration patterns that are on par with vibration patterns found in the literature. Participants improved their performance in correctly and quickly identifying the generated vibration pattern throughout the study.

To address the challenge of users needing to actively learn a new set of vibration patterns and their corresponding associations, passive haptic learning of vibration patterns was investigated and existing research reevaluated. In a 5 group user study with together 50 participants passive haptic learning of vibrotactile patterns was tested. The user study presented in this thesis in chapter 7 found that previous studies in passive haptic learning of stimulus-stimulus-associations (like learning Morse code with PHL) leaked information in their testing protocol and therefore produced better results as would be possible with passive haptic learning alone. An essential contribution of this is, that unfortunately passive haptic learning of stimulus-stimulus-associations like vibration patterns is only feasible in very short patterns.

To address the challenge of body movement with wearable tactile displays this thesis investigated reference frames for spatial tactile cues on the wrist with a 20 participant within-subject user study. Allocentric and egocentric reference frames were compared. This thesis presents evidence that allocentric reference frames on the wrist outperforms egocentric reference frames on the wrist for spatial localisation tasks while keeping accuracy stable. Reaction time and frustration were significantly lower with the allocentric reference frame compared to the egocentric reference frame.

The road for continuous tactile wearables is far from over with lots of interesting questions to be answered in the future.

Integrating continuous wearable tactile feedback into SCADA systems to support monitoring tasks seems like a fruitful venture to bridge the gap between research in tactile displays and the real world. Singling out specific indicators in dashboard environments and communicating these indicators through tactile wearables can be a good way to improve dashboard environments and reducing mental load on the operators and if necessary enhance reaction times if critical situations arise.

As discussed in this thesis, the design and generation of vibrotactile patterns is currently mostly done manually for one set of patterns for the intended application. Automatic generation or personalisation of vibration patterns as displayed in this thesis is only in its infancy. Powerful generative black-box models could help future researchers to create vibration patterns faster and give consumers the tools to easily personalize vibration patterns depending on their personal need.

Passive Haptic Learning although not feasible for learning stimulus-stimulus associations can be a powerful tool in the future for learning or rehearsing motor skills. Research already indicates that Passive Haptic Learning has a positive impact on the long-term retention of the learned motor skill. There is yet much research to be done, but the phenomenon of Passive Haptic Learning is stable and needs to be utilized. Application areas could be assistance technologies like exoskeletons for care workers or disabled persons. Passive haptic learning could be used to teach motor skills needed to interact with exoskeletons passively.

Continuous wearable tactile displays also have a high utilisation potential in giving biofeedback of the user to a single user or giving biofeedback of a group of people to single user. There is already research that shows that applying a tactile feedback on the body has the ability to influence the human autonomic nervous system and with it the parasympathetic nervous system and the sympathetic nervous system. This can be utilised in creating systems to help regulate and self-regulate bodily functions of the wearer, for example by helping the user calm down before sleeping or helping the body to wake up after sleep. This could also be applied to groups of people by applying tactile heartbeats or rhythms to group members to help groups be more synchronized which could help in group activity or connect an audience that is usually passive to an active performance.

All in all continuous wearable tactile displays offer a multitude of possibilities to extend the perception of our reality and help the wearer experience new senses. The wearable aspect is core in this as it allows practitioners and researchers to seamlessly integrate new devices into already existing clothing or new clothing and extend the boundaries of the human sensory apparatus.

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