NEAR-BODY INTERACTION

FOR WEARABLE INTERFACES

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DOCTORAL THESIS

Near-body Interaction

for Wearable Interfaces

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Near-body Interaction for Wearable Interfaces
Doctoral dissertation

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ULM UNIVERSITY

Abstract

Faculty of Engineering, Computer Science and Psychology
Institute of Media Informatics

Doctor rerum naturalium (Dr. rer. nat.)

Near-body Interaction for Wearable Interfaces

by David DOBBELSTEIN

Smart devices and mobile interfaces are getting evermore pervasive and available to users, so that nowadays information access is possible almost anywhere and anytime. With the frequency of mobile interactions increasing, access time and always availability are becoming more and more important. As a result, interfaces are moving closer to the user's body. While smart phones enabled users to access and interact with information with reach from the user's pocket, wearable devices such as smart eyewear and smart watches are further advancing this trend. By being able to always display information within or near the user's field of view, a faster access time to information can be enabled. When it comes to interaction with wearable interfaces, however, no interaction techniques could be established as state-of-the-art yet. Building on that, this thesis contributes to the field of human-computer interaction (HCI) by investigating important properties for near-body interaction with wearable interfaces. For user input, novel concepts for near-body touch techniques are introduced, using the user's body as an interaction delimiter. The body of research includes social implications of wearable interaction techniques and the internal perception of unobtrusiveness, the input expressiveness of touch gestures in mobile contexts, and suitable on- and off-body input locations. For user output, current modalities for wearable devices are mostly limited to visual and haptic feedback. In this thesis, the capabilities of haptic feedback are extended to positional feedback, using not only the temporal domain of vibrational feedback, but also positional continuous feedback by self-actuation. Furthermore, the concept of scent-based feedback is explored by introducing a wearable olfactory display that can emit multiple scents as an emotional channel for mobile notifications.

UNIVERSITÄT ULM

Zusammenfassung

Fakultät für Ingenieurwissenschaften, Informatik und Psychologie
Institut für Medieninformatik

Doctor rerum naturalium (Dr. rer. nat.)

Near-body Interaction for Wearable Interfaces

von David DOBBELSTEIN

Intelligente mobile Benutzerschnittstellen sind immer weiter verbreitet und verfügbar, so dass heutzutage fast jederzeit mobil auf Informationen zugegriffen werden kann. In diesem Zusammenhang wird eine schnelle Zugriffszeit und stetige Verfügbarkeit durch die häufige Nutzung von mobilen Interaktionen immer wichtiger. Dies kann unterstützt werden indem Schnittstellen näher am Nutzer positioniert werden. Während Smartphones es ermöglichen aus der Hosentasche heraus auf Informationen zuzugreifen und mit diesen zu interagieren, gehen tragbare Benutzerschnittstellen wie Smartwatches und Smartglasses noch weiter. Durch die Möglichkeit Informationen direkt im Sichtfeld des Nutzers anzuzeigen, kann die Zugriffszeit deutlich reduziert werden. Betrachtet man jedoch die Interaktionsmöglichkeiten von tragbaren Benutzerschnittstellen, konnten sich bisher noch keine Interaktionstechniken als Stand der Technik etablieren. Hierauf aufbauend, beschäftigt sich diese Arbeit mit wichtigen Eigenschaften von Interaktion mit tragbaren Benutzerschnittstellen. Für Nutzereingaben werden neuartige Interaktionsmöglichkeiten vorgestellt, bei denen sich die Toucheingabefläche nahe am Körper befindet. Hierbei werden wissenschaftliche Fragestellungen der sozialen Implikationen und der internen Wahrnehmung von Unaufdringlichkeit, der Expressivität von Eingabegesten in mobilen Kontexten, sowie geeignete Positionen für die Nutzereingabe adressiert. Für die Nutzerausgabe bei tragbaren Benutzerschnittstellen sind derzeitige Modalitäten auf visuelles und haptisches Feedback beschränkt. In dieser Arbeit werden die Möglichkeiten von Haptik auf positionsbasiertes Feedback erweitert. Statt nur die temporären Eigenschaften von haptischem Feedback als Benachrichtigung zu nutzen, kann die Position einer sich-selbst aktuierenden Benutzerschnittstelle als kontinuierliche haptische Ausgabe agieren. Des weiteren wird das Konzept von duft-basiertem Feedback exploriert, indem ein tragbares olfaktisches Ausgabegerät vorgestellt wird das mit Hilfe unterschiedlicher Düfte es ermöglicht mobile Benachrichtigungen um eine emotionale Komponente zu erweitern.

Acknowledgements

Working on this thesis has been one of the most exciting and challenging parts of my life and I am deeply grateful to all the people that supported me. First of all, I want to thank my supervisor **Enrico Rukzio** for supporting me and my work already from the very early days in Essen -even before pursuing a PhD- up to this point of writing my dissertation. You sparked my interest in HCI research, provided a flourishing work environment where I was glad to be a part in, and gave me all the creative freedom and trust for working on exciting research ideas. For inspiring my research interests early on, I also want to thank **Albrecht Schmidt**, whose lectures introduced me to the field of Pervasive Computing during my studies in Essen, as well as **Kent Lyons** and **David Nguyen** for sparking my interest in Wearable Computing during my internship at Nokia in Sunnyvale US when I did my Master's.

Before and during my transition from Essen to Ulm, **Christian Winkler** and **Julian Seifert** provided me guidance on scientific working and in general served as role models on how to do a PhD. You became great friends and being able to work with you on projects on tabletop and projector-based interaction really gave me a great start for my academic career for which iam very grateful. Starting in Ulm, I was sharing the office with **Jan Gugenheimer** and **Philipp Hock**. We had a great environment with a lot of fun and a lot of intensive discussions to exchange and challenge each other's research ideas. I will miss all the crazy conversations with the two of you. Being part of the research group has been a wonderful experience also due to the many people that made it so special. This becomes especially evident when besides the work, you also spend a lot of spare time together. For all the fun evenings, I want to thank **Marcel Walch**, **Julian Frommel**, **Felix Schüssel**, **Gabriel Haas**, **Katja Rogers**, **Frank Honold** and all the other great colleagues from the institute of media informatics that have become great friends throughout the years. In your company, the research group was like one big family!

I am furthermore grateful for having the opportunity to supervise and work together on research projects with very talented students like **Steffen Herrdum**, **Philipp Hock**, **Gabriel Haas**, **Evgeny Stemasov** and **Tobias Arnold**. Many of you ended up to be colleagues at the institute and I am excited to see that all of you continue to be successful in your career path.

Lastly, I want to thank my parents and friends for all their support and especially my beloved **Sonja** who was indefinitely patient, tolerant and considerate when I was writing this thesis on the many weekends and vacations, even though it would have been more appropriate to spend the time with you. I am eternally grateful for the emotional stability you provided, and for your devotion and love lightening up each of my days.

To all of the wonderful people who supported me throughout these years: Thank you all for your support!

Contents

Chapter 1

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals. The articles are reprinted with kind permission from the Association for Computing Machinery, Inc.

I) David Dobbelstein, Philipp Hock, and Enrico Rukzio.
Belt: An Unobtrusive Touch Input Device for Head-worn Displays.
In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems 2015* (CHI '15), Seoul, Korea, 4 pages, 2015.
`https://doi.org/10.1145/2702123.2702450`

II) David Dobbelstein, Christian Winkler, Gabriel Haas, and Enrico Rukzio.
PocketThumb: a Wearable Dual-Sided Touch Interface for Cursor-based Control of Smart-Eyewear.
In *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* (IMWUT), Vol 1. No 2., 17 pages, 2017.
`https://doi.org/10.1145/3090055`

III) David Dobbelstein, Gabriel Haas, and Enrico Rukzio.
The Effects of Mobility, Encumbrance, and (Non-) Dominant Hand on Interaction with Smartwatches.
In *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (ISWC '17). Maui, Hawaii, 4 pages, 2017.
`https://doi.org/10.1145/3123021.3123033`

IV) Jan Gugenheimer, David Dobbelstein, Christian Winkler, Gabriel Haas, Enrico Rukzio.
FaceTouch: Enabling Touch Interaction in Display Fixed UIs for Mobile Virtual Reality.
In *Proceedings of the 2016 ACM Symposium on User Interface Software and Technology* (UIST '16). Tokyo, Japan, 10 pages, 2016.
`https://doi.org/10.1145/2984511.2984576`

V) David Dobbelstein, Tobias Arnold, and Enrico Rukzio.
SnapBand: a Flexible Multi-Location Touch Input Band.
In *Proceedings of the 2018 ACM International Symposium on Wearable Computers* (ISWC '18). Singapore, 2 pages, 2018.
`https://doi.org/10.1145/3267242.3267248`

VI) David Dobbelstein, Philipp Henzler, and Enrico Rukzio.
Unconstrained Pedestrian Navigation based on Vibro-tactile Feedback around the Wristband of a Smartwatch.

In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (CHI '16), San Jose, California, U.S., 6 pages, 2016.
`https://doi.org/10.1145/2851581.2892292`

VII) David Dobbelstein, Evgeny Stemasov, Daniel Besserer, Irina Stenske, and Enrico Rukzio.
Movelet: a Self-Actuated Movable Bracelet for Positional Feedback on the User's Forearm.
In *Proceedings of the 2018 ACM International Symposium on Wearable Computers* (ISWC '18). Singapore, 7 pages, 2018.
`https://doi.org/10.1145/3267242.3267249`

VIII) David Dobbelstein, Steffen Herrdum, and Enrico Rukzio.
inScent: a Wearable Olfactory Display as an Amplification for Mobile Notifications.
In *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (ISWC '17). Maui, Hawaii, 8 pages, 2017. Best paper award.
`https://doi.org/10.1145/3123021.3123035`

Chapter 2

Author’s Contribution

Publication I: "Belt: An Unobtrusive Touch Input Device for Head-worn Displays"

The idea for studying the effect of unobtrusiveness of near-body touch input was formed by the author. The author designed the conceptual ideas of information access leveraging the users’ spatial mapping around their hip, and of unobtrusive interaction above the user’s pockets. The ideas were discussed and refined with the author’s supervisor, Enrico Rukzio. The work is partly based on the master thesis of Philipp Hock that was supervised by the author. The hard-and software was implemented by Philipp Hock. The user study was planned by the author and conducted by Philipp Hock. The author had the major role in writing the manuscript.

Publication II: "PocketThumb: a Wearable Dual-Sided Touch Interface for Cursor-based Control of Smart-Eyewear"

The idea for studying the effect of input expressiveness of near-body touch input by utilizing the user’s trouser pocket for stabilization was formed by the author after an initial discussion with Christian Winkler. The ideas were discussed and refined with the author’s supervisor, Enrico Rukzio. The author was responsible for designing the interaction concepts, and the implementation of hard-and software. The user study was planned and analyzed by the author. Gabriel Haas implemented the study software and carried out the user experiments. The author had the major role in writing the manuscript.

Publication III: "The Effects of Mobility, Encumbrance, and (Non-) Dominant Hand on Interaction with Smartwatches."

The idea for studying the effects of mobility conditions on interaction with smartwatches was formed by the author. The author was responsible for planning and analyzing the user study. Gabriel Haas implemented the study software and carried out the user experiments. The author had the major role in writing the manuscript.

Publication IV: "FaceTouch: Enabling Touch Interaction in Display Fixed UIs for Mobile Virtual Reality"

The idea for studying near-body touch interaction for virtual reality was formed by Jan Gugenheimer. The author assisted in designing the user studies and in writing the manuscript.

Publication V: "SnapBand: a Flexible Multi-Location Touch Input Band"

The idea for studying multi-location touch input was formed by the author. The ideas were discussed and refined with the author's supervisor, Enrico Rukzio. The work is partly based on the master thesis of Tobias Arnold that was supervised by the author. The hard-and software was implemented by Tobias Arnold. The user study was jointly planned by Tobias Arnold and the author. Tobias Arnold carried out the user experiments. The author had the major role in writing the manuscript.

Publication VI: "Unconstrained Pedestrian Navigation based on Vibro-tactile Feedback around the Wristband of a Smartwatch"

The idea for studying vibro-tactile feedback around the wrist for pedestrian navigation was formed by the author. The ideas were discussed and refined with the author's supervisor, Enrico Rukzio. The work is partly based on the bachelor thesis of Philipp Henzler that was supervised by the author. The hard-and software was implemented by Philipp Henzler. The user study was jointly planned by Philipp Henzler and the author. Philipp Henzler carried out the user experiments. The author had the major role in writing the manuscript.

Publication VII: "Movelet: a Self-Actuated Movable Bracelet for Positional Feedback on the User's Forearm"

The idea for building a self-actuated bracelet was formed by Evgeny Stemasov, Daniel Besserer and Irina Stenske in the context of a project seminar supervised by the author. The conceptual idea of positioning the continuous haptic feedback in contrast to temporal haptic feedback was formed by the author. The ideas were discussed and refined with the author's supervisor, Enrico Rukzio. The hard-and software was implemented by Evgeny Stemasov, Daniel Besserer and Irina Stenske. Anna Sailer and Alexander Vogel helped with design and construction of the prototype. The user study was planned and analyzed by the author. Evgeny Stemasov, Daniel Besserer and Irina Stenske carried out the user experiments. The author had the major role in writing the manuscript.

Publication VIII: "inScent: a Wearable Olfactory Display as an Amplification for Mobile Notifications"

The idea for building a scent-emitting wearable was formed by Steffen Herrdum. The conceptual idea of studying the effects of personal scents emitted in public was formed by the author. The ideas were discussed and refined with the author's supervisor, Enrico Rukzio. The work is partly based on the master thesis of Steffen Herrdum that was supervised by the author. The hard-and software was implemented by Steffen Herrdum. The user study was jointly planned and analyzed by Steffen Herrdum and the author. Steffen Herrdum carried out the user experiments. The author had the major role in writing the manuscript.

Chapter 3

Introduction

With the advance of ubiquitous computing [210], smart devices and mobile interfaces are getting evermore pervasive and available to users, so that nowadays information access is possible almost anywhere and anytime. With the frequency of mobile interactions increasing [193], the access time to mobile interfaces and the always availability of information access is becoming more and more important. For this purpose, the access to information can be positioned ever nearer to the user's body and made accessible via wearable interfaces. While smart phones enabled users to access and interact with information with reach from the user's pocket, wearable devices such as smart eyewear and smart watches are further advancing the trend of nearer access to information for users. These wearable devices are positioned to directly display information within or near the user's field of view to enable a faster access time and an always availability when the device is worn [191]. Thereby, wearable interfaces are envisioned to serve as an augmentation to the user's memory [190], and to be quickly accessible with short bursts of so-called micro-interactions [10], i.e. interactions that only last for a few seconds to minimize interruption and to allow the user to quickly return to a task at hand [109].

With current technology for wearable interfaces, however, many challenges remain to enable for such quickly accessible interaction. While smart watches inherited established interaction concepts from smartphones like direct touch input on a physical display, the small display size still poses challenges for displaying and interacting with visual information. Moreover, with smart eyewear, the challenges of interacting with a virtual screen image that is neither tangible nor touchable become apparent, so that for smart eyewear, no interaction technique could be established as state of the art yet. Designing for interaction with wearable interfaces poses many challenges due to the special characteristics of technology that is worn on the body and that ought to be accessible in highly mobile scenarios: The interface should not interfere with other activities in everyday life, so that the technology needs to be miniaturized and yet easy to access; since wearable interfaces are worn on the body and exposed to others, the social comfort of the wearer and the perception of the interaction is important for users to be comfortable to interact in public. Furthermore, the on-body positioning of wearable interfaces also affects the capabilities of the tracking and detection of user input as well as the capabilities for user feedback.

In this regard, this thesis contributes to the field of Human-Computer Interaction (HCI) by addressing remaining challenges and by investigating important properties of near-body interaction with wearable interfaces. Each included publication contributes to individual challenges of wearable interfaces by either novel means for user input or user feedback.

3.1 Research Methodology

This thesis contributes to the field of Human-Computer Interaction (HCI) by mainly two types of research contributions as defined by Wobbrock [217]:

Building Artifacts. "HCI is driven by the creation and realization of interactive artifacts" [217]. For this thesis, novel input and output devices were implemented as prototypes and accompanied by newly developed interaction techniques following a design-driven approach. By this, new knowledge was embedded into newly developed systems via horizontal and vertical prototyping. These built systems were composed of hardware and software designed to explore user interaction in regard to specific challenges of wearable interfaces and by this could generate new understanding.

Empirical Findings. "Empirical research contributions are the backbone of science" [217]. Qualitative and quantitative research methods were conducted via user studies, experiments and interviews based on the built artifacts. This was to evaluate specific research questions in relation to the investigated properties of the wearable interface, and the developed input and output techniques. By this, new knowledge was generated based on findings and observations of users interacting with the technology and of the data gathered in the process.

The field of HCI is about understanding interaction and the user's behavior with technology, but also about the invention of new interfaces that incorporate the achieved understanding [215]. In this thesis, invention can be found in the creation of artifacts that present new interfaces and new interaction techniques, whereas empirical methods were used to generate further understanding of the users' interaction with the respective interface. The design-driven approach used in this thesis is based on user-centered design [137], where the user's needs, behaviors and goals are given extensive attention. User-centered design follows an iterative process of requirement specification, solution design and evaluation, where potential users are involved in multiple stages of the design process. The design process used in this thesis started with problems and opportunities that were identified by talking to users, experts and interaction designers of wearable interfaces. This was followed by an analysis of the possible design space and the development of interaction concepts to address the respective problem or opportunity. At first, low-fidelity prototypes were created to be able to quickly validate and redefine the underlying ideas and concepts. The redefined concepts were then implemented as hard- and software as functional high-fidelity prototypes. Using functional prototypes for evaluation is important especially for new interaction devices and techniques in the context of ubiquitous and wearable computing, since the user's experience is closely linked to the functionality of the tangible interface [175]. The evaluation of the concepts then included users interacting with the interface by following specific interaction tasks that were designed to guide the user towards specific research questions. Within user studies, quantitative data was gathered by letting users perform measurable and comparable tasks related to the interaction concept, e.g. for measuring efficiency, selection time is a typical variable that allows the comparison of the efficiency of different interaction concepts, while for qualitative data, participants would use and interact with the presented interface and provide feedback via questionnaires or interviews, and by thinking aloud during the user study. Depending on the research questions, most often both, quantitative and qualitative methods were used to generate understanding.

3.2 Structure of the Thesis

As stated, this thesis addresses challenges of interaction with current wearable interfaces, but also investigates opportunities for novel interaction techniques and devices. The main body of this work is focused on challenges that remain for interaction with smart-eyewear, as a wearable interface where no interaction technique could be established as state-of-the-art yet. Important properties for these challenges were analyzed and novel near-body input devices were designed, implemented and presented to address the respective properties and challenges. Furthermore, opportunities for alternative means of user feedback going beyond the visual feedback of smart eyewear were identified that led to novel designs for wearable output devices. In this regard, identified challenges led to opportunities for new innovation, while identified opportunities opened new future challenges for interaction design.

Input	Publication	Output	Publication
Social Acceptance & Unobtrusiveness	I, II	Haptic Feedback	VI, VII
Input Expressiveness	II, III, IV	Positional Feedback	VII
On-and Off-body Locations	I, II, V	Scent-based Feedback	VIII

FIGURE 3.1: Properties of input and output for wearable interfaces that were investigated in this thesis.

3.2.1 Challenges in Mobile Interaction with Smart Eyewear

Smart-eyewear enables a quick access time by displaying information directly within the user's field of view, so that users can quickly shift their attention between the physical world and virtual content. Interaction with the virtual content, however, is yet a problem. The near-eye displays incorporated into smart eyewear leverage micro-optics to alter the visual perception to a virtual image floating in mid-air in front of the user. This virtual display has no physical representation and therefore cannot be touched or physically manipulated like a conventional display could be. It is also solely perceived by the user of the eyewear, thus making the interaction a very personal experience. Mobile interaction with such a virtual and personal display poses multiple challenges for interaction design that will be explored and addressed in this thesis.

Social Acceptance and Unobtrusiveness

Since wearable devices are worn on the user's body, they have strong social implications in that they are technology that is continuously exposed and visible to others. This is especially true for smart-eyewear that is worn on the user's head and thus easily perceivable by others at eye-level. With ongoing technological miniaturization, it is expected that smaller and less obtrusive form factors will be possible in the future. Alongside the device's appearance, however, the interaction with the device itself can draw unwanted attention upon the user in public. Due to the hidden presence of the virtual display, the intent of visible hand gestures like pointing in mid-air remains unclear to an observer. Spacious gestures are therefore prone to draw attention. Other possibilities like voice input allow for handsfree interaction, but are also obtrusive in shared public environments where they can disturb other people. Interaction techniques should therefore be designed to allow for unobtrusive input that draws as little attention as possible, so that users feel comfortable and are willing to interact in public.

Input Expressiveness

Designing always available wearable interfaces that yet allow for rich user interaction is a big challenge. Since these interfaces should not interfere with other activities in everyday life, they need to be miniaturized and yet easy to access in mobile situations. As a result, most interaction techniques for wearable interfaces are limited to only a small set of basic gestures. This fits the vision of microinteractions [10], i.e. of very short interaction lasting only a few seconds, but it remains unclear how basic gestures can be used to create rich interaction that is beyond very simple and restrained use cases to utilize the full potential of smart-eyewear. A lack of hand stabilization during mobile interaction dictate many interaction techniques to be fairly restricted, so that only simple tasks and applications are currently feasible. By designing input interfaces to provide for hand stabilization, however, the expressiveness can be increased.

On- and Off-body Locations for User Input

Finally, the on-body positioning of a wearable interface strongly affects its reachability, social acceptance and interaction affordance, so that current wearable interfaces are designed and limited to be worn at specifically defined on-body locations. Physical activities, however, can partly constrain body parts that are involved for interaction with the interface, so that the interaction is more difficult to perform or even completely impeded. To prevent this, wearable interfaces can be designed to utilize a form factor that can be worn or attached to multiple on- and off-body locations. By this, users can choose and adjust the positioning for varying mobile contexts and activities.

3.2.2 Opportunities for Alternative Means of User Feedback

Current wearable interfaces present their output mostly as visual and auditory feedback to utilize a high bandwidth of information. Depending on the mobile and social situation, however, users may already be focused on highly visual or auditory tasks in the environment. In these situations, alternative modalities for user feedback can provide useful characteristics.

Haptic Feedback

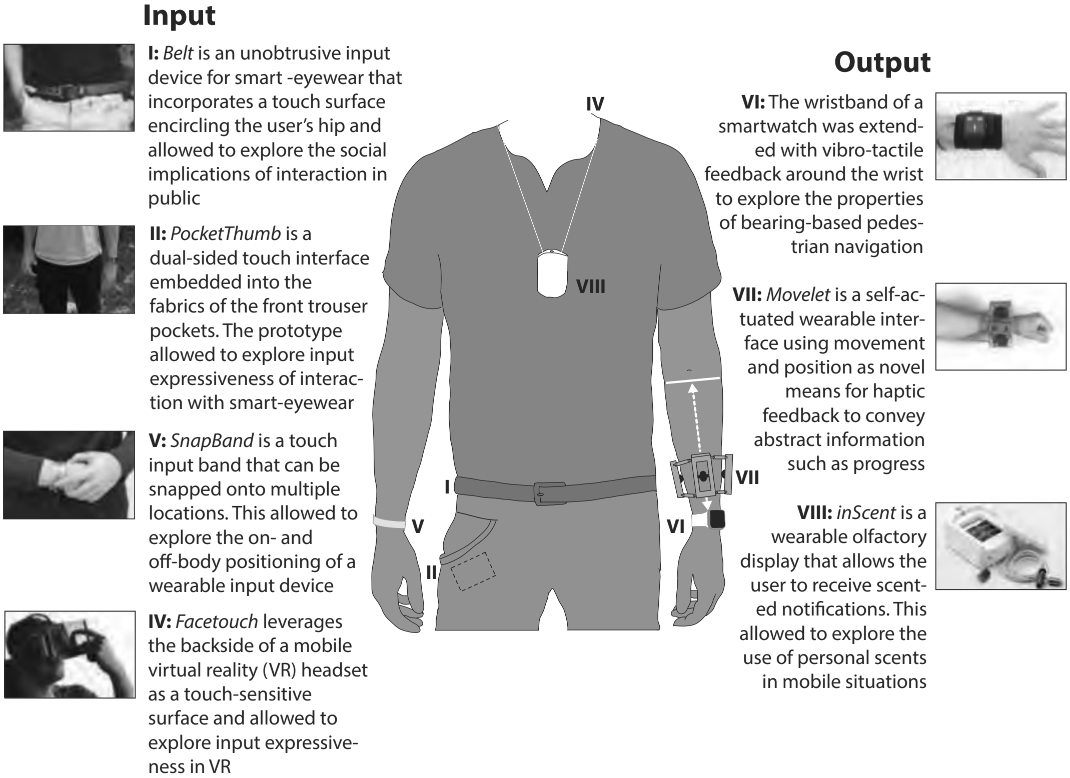
Haptic feedback is already used on mobile devices as vibro-tactile feedback to subtly notify users. As wearable interfaces are worn even nearer to the user's body, haptic sensations can be applied directly to the user's skin. This allows to position multiple tactors within an interface to convey more expressive information. For mobile scenarios, such as pedestrian navigation, this can be utilized to prevent the need of visual diversion from the environment.

Positional Feedback

Most eyes-free modalities, such as vibro-tactile feedback, present information only momentarily, so that it can be missed by the user. In contrast, the spatial position of an interface can continuously serve as a means of haptic feedback. This can be achieved by utilizing self-actuation, to allow the interface to alter its own positioning via movement along a body part such as the user's forearm. While the movement can be perceived momentarily, the position serves as a sustained haptic stimulus that can continuously convey abstract information such as progress.

Scent-based Feedback

The sense of smell is an important information channel that is strongly linked to emotions and memories. When perceiving the environment, smell is often an essential part of the experience and the stimulus of a distinctive smell can evoke memories that are more emotionally loaded than memories elicited through other senses. For a wearable interface, scents can be artificially generated and delivered to the user to enhance their personal experience, to convey abstract information or to amplify notifications in mobile scenarios.



I: *Belt* is an unobtrusive input device for smart -eyewear that incorporates a touch surface encircling the user's hip and allowed to explore the social implications of interaction in public

II: *PocketThumb* is a dual-sided touch interface embedded into the fabrics of the front trouser pockets. The prototype allowed to explore input expressiveness of interaction with smart-eyewear

V: *SnapBand* is a touch input band that can be snapped onto multiple locations. This allowed to explore the on- and off-body positioning of a wearable input device

IV: *Facetouch* leverages the backside of a mobile virtual reality (VR) headset as a touch-sensitive surface and allowed to explore input expressiveness in VR

VI: The wristband of a smartwatch was extended with vibro-tactile feedback around the wrist to explore the properties of bearing-based pedestrian navigation

VII: *Movelet* is a self-actuated wearable interface using movement and position as novel means for haptic feedback to convey abstract information such as progress

VIII: *inScent* is a wearable olfactory display that allows the user to receive scented notifications. This allowed to explore the use of personal scents in mobile situations

FIGURE 3.2: Wearable interfaces for input and output that were implemented as prototypes within the scope of this thesis. Each prototype served to investigate different properties of near-body interaction.

Chapter 4

Wearable Interfaces

A user interface is the means by which the user and a system interact with each other [47]. By designing interfaces to be worn directly on the user's body, a new synergy between human and technology can be facilitated [121]: Traditionally, personal computing devices are based on the assumption that interaction with the device represents the primary task of the user. In contrast, with wearable interfaces, it is assumed that users are conducting other activities at the same time [121] and that most often these other activities constitute the primary task of the user. In this regard, wearable interfaces enable to support activities that can be found in the user's everyday life, e.g. by providing relevant information, by reminding of upcoming activities or by assisting the user in daily situations. To complement rather than interfere with the user's activities, wearable interfaces need to be designed to maximize performance and to minimize the required investment in attention [190] which can be achieved by multiple design considerations: The access time should be made as quick as possible [11], so that switching attention from a main task towards the interface can happen quickly. This can be supported by making the interface always available, e.g. by presenting information already within the user's field of view. Secondly, by enabling for a short usage time, so that interactions only need to last for a few seconds to achieve their purpose. This was termed by Ashbrook as so-called *micro*-interactions [10]. Lastly, users need to be able to quickly return to their task at hand [109], so that overall the interruption time and needed attention can be minimized.

As a result, since wearable interfaces are quickly accessible and always available, they can serve as an extension of the user's self [191], that is readily available in mobile situations. By presenting relevant information, they can augment the user's memory [190] and by this, support the user's capabilities. In the information age [32], where knowledge and information access is increasingly important, wearable interfaces can thus provide useful characteristics.

4.1 History of Wearable Computing

Wearable Computing has a long history that dates back over half a century. The first wearable computer was conceived by Edward O. Thorp in 1955 [198] and was later built with Claude E. Shannon, the founder of information theory [184], in 1960. Its use was to increase the odds when playing roulette in casinos by measuring position and velocity of the orbiting ball to predict where it would eventually land. For this, a small analog computer was built and microswitches as push buttons were hidden in the user's shoe for toe-based input to clock the ball's revolutions. A tiny loudspeaker in one ear canal with painted hidden wires would then generate a tone sequence for audio output to signal the octant on which to bet.

4.1.1 Head-worn Displays

The main focus in the field of wearable computing has been on providing visual information. The first head-worn display that would allow users to see virtual information within their field of view was built in 1966 by Ivan Sutherland [195] who placed two half-silvered mirrors and small CRT displays in front of the user's eyes so that they would see both, virtual screen image and the environment at the same time. Due to limitations in computing power, this seminal work did not allow for mobile use cases yet, but pioneered towards visual augmentation. The first *wearable* head-worn display was then built by Steve Mann in 1980 as a battery-operated tetherless computing device that required a backpack for carrying a computer. It would allow to overlay text and graphics into the environment and was controlled by a handheld input device [120]. While being designed for wearable use in mobile and social use cases, the obtrusiveness of the bulky apparatus yet impeded social interactions and created a social barrier [120], which let to an ongoing effort in miniaturization and in less obtrusive form factors. Mann was the first to wear and use a head-mounted display in everyday life and further on developed several iterations of his wearable setup. In 1991, he founded the Wearable Computing Project at M.I.T.'s Media Lab [149], to scientifically push wearable computing as a new field of technology. Thad Starner, one of the co-founders, was the first to *constantly* wear a custom-designed head-worn display as part of his daily life starting from 1993. He developed the remembrance agent [189], an information retrieval system as a text-based interface that would allow him to type and retrieve notes during conversations to augment his memory [190]. This was operated by the Twiddler [115], a handheld chording-based text input device, that allowed him to blindly enter text using one hand. He pushed forward the notion that the time between intent and action in computing should be reduced and in 2010 became a technical lead of Google's Project Glass [191], a commercial effort to bring smart eye-wear into widespread adoption. Due to advances in miniaturization in hardware and sensor technology, low-power mobile processing and wireless communication [171], a commercialization seemed feasible. Google started selling prototypes of Google Glass, as a light-weighted stand-alone eyewear, in 2013 to developers. The device attracted public attention for its design, but also triggered critical reactions for privacy concerns as well as social acceptability [99]. As of now, a variety of head-worn displays are commercially available, however, concerns regarding the public use of the technology prevail.

FIGURE 4.1: Thad Starner, one of the pioneers of wearable computing in 1997 with a micro-display providing visual information within his field of view [190]. © by Sam Ogden. Used with permission.

4.1.2 Watches

Another location for wearable interfaces to provide a quick access to visual information is the user's wrist. Wristwatches have been popular for over a century [124], allowing the wearer to quickly glance at the current time. The history of wrist-worn computing has been driven by commercial attempts to build on the watch as an already established form factor: In 1977, Hewlett-Packard introduced the HP-01 [123], a calculator watch, featuring 28 tiny buttons and a digital display to enable for calculations on the go. Later on, in 1982, Seiko introduced the T001 as a watch model that would allow for video output linked to a portable television receiver and in 1984 the RC1000 wrist terminal, capable of uploading text files as memos from a connected computer [85]. In 2004, a first attempt was made by Microsoft to push smart-watches as a new technology to offer useful information like news, weather, sports and text messages at a glance of the user. The data was provided wirelessly over a radio network, which however required a paid subscription and could not gather wide adoption [85]. Smart-watches started to gain popularity in 2012 with the Pebble watch [153], a crowd-founded product, that was able to automatically display phone-notifications on its watch display. Since then, smart-watches are successful as a companion device for smart-phones, which due to technological advances became *the* pervasive technology [13] for mobile access to any kind of mobile communication. In this configuration, smart-watches are mainly used for providing glanceable information [145], as well as for providing fitness tracking by measuring the user's heart rate and physical activity and keeping this data readily available. In 2018, worldwide smart-watch sales exceeded 100m units yearly [194], making this form factor the commercially most successful wearable interface yet. In spite of that, the small device size of the watch form factor inherently limits the display size and by this the capabilities for providing visual information.

4.2 Smart-Eyewear

Nowadays, information access is possible almost anywhere and anytime with mobile devices that are *smart* by being continuously connected to the internet and by providing features for people to keep in touch and to manage everyday tasks [13]. In this regard, the smart-*phone* has become *the* ubiquitous input device for being quickly accessible with reach from the user's pocket or handbag [13, 192]. The trend of readily available access to information can further be advanced by presenting information directly within the user's field of view, with the use of smart-*eyewear*. This technology is often also referred to as smart-*glasses*, due to a currently prevailing form factor of glasses to visually augment information into the user's sight. Since the interaction concepts are not exclusive to smart-glasses and might also include other form factors such as contact lenses in the future [25], the technology is referred to the more comprising term of smart-*eyewear* in this thesis.

Beyond access time, smart-eyewear has inherently different properties than a handheld or stationary devices. The near-eye displays incorporated into eyewear leverage micro-optics to alter the visual perception for the user (see Fig. 4.2). For the human eye, focusing on close proximity is very straining. Using optics, however, the focal depth of the display can be increased, altering the user's perception of the display to a virtual image plane at some meter distance (depending on the optics).

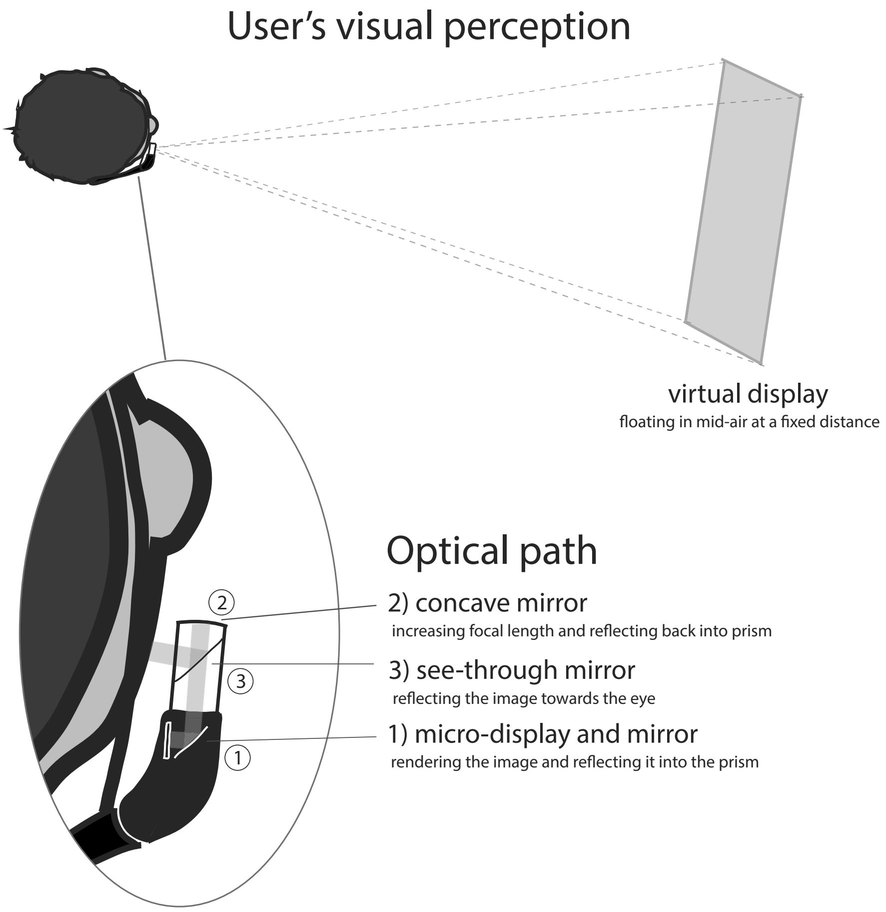


FIGURE 4.2: By utilizing micro-optics, the visual perception of a micro-display embedded into the eyewear is altered to a virtual display floating in mid-air at a fixed distance.

The virtual display has no physical representation and therefore cannot be touched or physically manipulated like a common display could be. It is also solely perceived by the user of the eyewear, thus making it a very personal display. This is unlike common handhelds that are tangible, can be handed around and potentially seen by multiple people at once. These conventional displays however are also tightly coupled to their form factor. The display space determines the minimum size requirement of the device, causing tradeoffs between mobility and screen size. Having a virtual display, smart-eyewear can overcome these screen limitations and enable a potentially large display space in combination with a small form factor.

As with the advent of smartphones [13], the use of smart-eyewear as a new technology will greatly differ from what we are used so far. Since information can be provided anytime and anywhere in a hands-free manner within the user's sight, novel interaction concepts will be utilized that are closely tied to the affordance of this new technology.

4.2.1 Information Space

Given that information is not limited to a physical representation, it can potentially be augmented anywhere in the user's field of view. Information can be presented spatially aligned (referred to as augmented reality) or fixed to the user's display [19]:

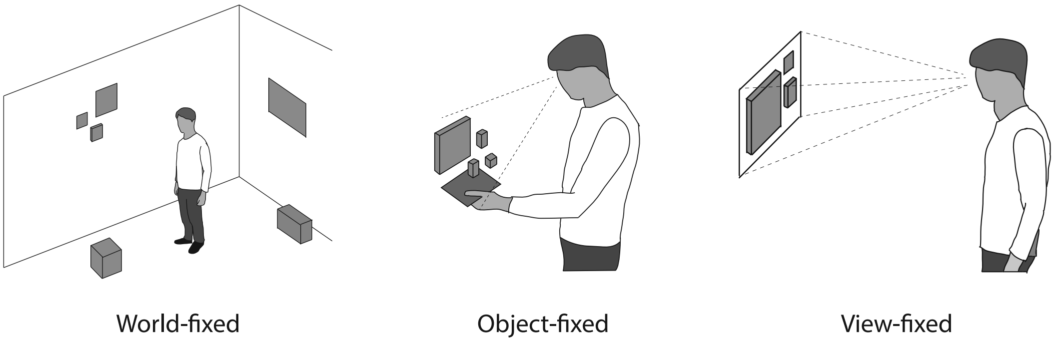


FIGURE 4.3: Concepts for displaying virtual information [19]: Fixing information into the world, next to a known object, or within the user's field of view.

World-fixed. Context related information can be augmented and virtually placed in the real-world to be seemingly mixed with real entities. Such information can span personal data such as photos, a calendar or a virtual clock on the wall, but also expand to user interfaces that are spread over a room, having virtual tools lying on the desk or floating around. Since the virtual content is fixed to the world, users can navigate and interact with content by positioning themselves or by remotely interacting with information. This requires tracking capabilities that allow a world-fixed system to build or understand a context model of the surrounding world including its own position within. While this is currently possible in defined and controlled environments, it yet remains a technical challenge relying on just the internal sensory of the eyewear.

Object-fixed. This is closely related to world-fixed information, however, the challenge of tracking the environment is reduced to tracking single objects. The eyewear can rely on camera tracking, e.g. by using fiducial markers or detecting visual features, to identify the position of known real-world objects. This can then be used to augment information onto or around these objects. An example is the Studierstube Augmented Reality Project [174] where panel and pen are used as a two-handed interface to augment and interact with 3D information above the panel. As can be seen in this example, having a physical object for augmentation enables the user a proxy for interaction. An object can be anything trackable by the internal camera sensory and is not limited to tangible items. A further example could be a friend or colleague that is detected by facial features. Useful information to augment nearby in this case could comprise a list of recently talked topics to follow-up a conversation.

View-fixed. From a technical perspective, this is the simplest presentation model. When information is fixed to the view it will follow head movements and be always within the user's field of vision, such as a virtual display floating in mid-air at a fixed distance. An example is the Google Glass that allows its user to glance at a virtual display that is located in the peripheral view. This enables a quick access time to information that is not spatially aligned to the real world. Nevertheless, reliant on context detection [176], the displayed information can be related to the user's current context.

4.2.2 Input Space

Independent from the presentation model of virtual information, *interaction* with the perceived content is yet a challenge because of its non-tangible nature. Due to this, interaction concepts for smart-eyewear often entail *indirect* interaction techniques.

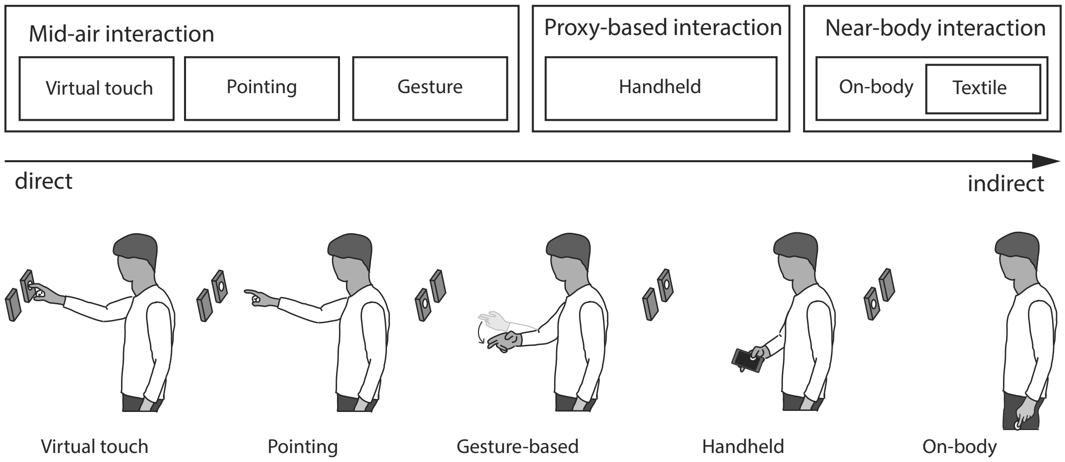


FIGURE 4.4: Concepts for interacting with displayed virtual information ranging from direct to indirect interaction.

Mid-air interaction. Interaction that involves finger or hand activity positioned in mid-air is referred to as mid-air interaction. Physiologically speaking, the human hand is an appendage for grasping, interacting with, and manipulating physical objects in the environment [131]. In this regard, a person will reach their hand towards an object for physical interaction. Applied to virtual information, the rationale of mid-air interaction is that users can similarly reach their hands towards virtual objects for respective interactions.

Virtual touch. The most *direct* interaction technique for users to interact with virtual content is via touching. This however remains a challenge due to virtual objects lacking physical tactile properties. Tactile touch feedback can be partly simulated [185], but this requires instrumentation of the user's hands, such as by gloves [226], an exoskeleton system [62] or electric muscle stimuli [110]. Furthermore, technical challenges that remain for direct touch interaction are precise tracking of the user's hand and fingers [26], as well as handling occlusion [97]. Virtual touch requires touch sensing capabilities, which for conventional touch-enabled systems can be provided by the surface to be touched, e.g. by capacitive sensing [61]. For virtual objects, finger touches must be sensed externally; tracking the user's fingers by camera however remains difficult from the visual perspective of the eyewear and otherwise requires instrumentation of the environment and is thus currently limited to laboratory environments. In regard to occlusion, the high degree of freedom of finger joints for motion of the user's hand is making precise finger tracking particularly difficult. Also, while virtual content will often be positioned *behind* the user's hand, optically it is always in *front* (c.f. the optical path in Fig. 4.2). To allow the hand (or other physical entities) to realistically occlude virtual objects during touch interaction, their occlusion needs to be computationally subtracted from the displayed image to seamlessly integrate physical and virtual entities for interaction [97].

Pointing. In contrast to touch interaction that requires the user to get into reach, pointing enables a more *distant* interaction [87]. Virtual content does not have to strictly follow physical laws, so that by pointing interaction, the manipulation of virtual objects can be enabled without approaching the object. Also, due to its distant nature, pointing does not rely on tactile perception for interaction with virtual objects. Pointing interaction however has to take object occlusion of virtual targets into account [52] and having the user to continuously lift their arm can quickly cause fatigue effects [73].

Gesture-based. Mid-air gestures can enable a more *indirect* distant mid-air interaction where a set of hand gestures are used to trigger defined actions [18] or by providing alternative metaphors for object manipulation [187]. Gesture-based interaction has similar properties in terms of distance and fatigue as pointing, but can add additional input expressiveness for interaction. Mid-air gestures often lack affordance and therefore need to be indicated by interface design [211], however ideally they are closely related to the user's natural gestural communication [2].

Proxy-based interaction. Due to the non-tangible nature of virtual content, physical proxies can be used to provide for tactile feedback and to enable means for user input. Such proxies often come in the form of mobile input devices that are held in hand by the user during interaction, but can also be situated directly on the eyewear (such as a touchpad on the temple of smartglasses).

Handhelds. When using handheld devices as a proxy for user input, already established form factors like the smartphone can be utilized. Similarly, due to the challenges of designing input capabilities, a range of commercial products (Epson Moverio, Vuzix and Sony SmartEyeGlass) provide a tethered handheld touchpad as a means for indirect touch input. Other examples are the Twiddler [115] as a handheld chording-based text input device, and the Soap [17] as a mid-air pointing device. Using a handheld however implies that an additional input device has to be carried along and retrieved from the pocket for interaction which increases the access time for user input.

Near-body interaction. Instead of situating the input near to the virtual content, the interaction can also be performed near the user's body. By this, the interaction is less direct, but in return can be quicker to access. Situating interaction near the body is also beneficial for recognition of the respective interaction, since the sensory can be included nearby into interfaces worn by the user. An example for this is Gunslinger [108], where mid-air interaction techniques are used in a relaxed arms-down position near the body instead of a more tiring position up in front.

On-body. The user's body can be used as an interface for touch input as an established concept for mobile interactions. Hereby, the user's skin [208] or clothes [148] can be extended with touch sensing interfaces to provide a surface for interaction. Such a surface can serve as a delimiter to distinguish intended interaction from natural occurring interaction such as gesticulating hand movements.

E-textiles. When using e-textile interfaces, touch sensing capabilities can be interwoven into the users clothing [148]. By this, the input interface can be designed in an unobtrusive manner [156] at various body locations [77] . In contrast to conventional touch displays, however, the touch surface is not as rigid for textiles interfaces, which significantly reduces the input speed and expressiveness [70].

While foremost the hands used for interaction and manipulation of physical interfaces, further means of human communication can be utilized for interaction with virtual content, such as using voice commands, moving the head for pointing interaction [84] or implicitly or explicitly utilizing the user's gaze point [27]. Furthermore, multiple interaction concepts can be combined for multi-modal user input [102].

4.3 Near-body Interaction

This thesis focuses on *near-body* interaction, where the input and output of wearable interfaces is closely situated to the user's body.

For user input, interfaces near the user's body have the advantage to be easy and quickly to reach. Particularly when the wearable interface is positioned near the resting position of the user's hands, only very little hand movement is required for access (c.f. Pub I & II). Also, this allows users to maintain a relaxed arm posture during interaction. This is beneficial in terms of physical effort [73], as well as for unobtrusiveness, since no spacious gestures are required, and instead, subtle hand or finger movements can be utilized (c.f. Pub I). Ideally, micro-interactions [10] could be performed directly within the user's palm or any surface by finger input independent of the hand's positioning. This however would require an instrumentation of the user's hands and fingers with tracking sensory [35][36], and it remains unclear how intended input is to be distinguished from unrelated finger movements. By using specifically defined body locations for touch interaction, these on-body surfaces can serve as a delimiter for interaction intents. For this, e-textile interfaces [77][148] provide a promising technology for near-body touch input in that the sensing capabilities can be interwoven and hidden directly in the user's clothing. Furthermore, interaction affordances such as to rest the hands in trouser pockets can be utilized for hand stabilization in mobile situations such as when walking to enable for a high input expressiveness (c.f. Pub II). Due to the quick access time and always availability, near-body interaction is especially suited for the vision of micro-interactions [10], i.e. for interactions that are quickly accessible and that only last for a few seconds.

For user output, wearable interfaces mostly utilize visual feedback as a primary information channel. For near-body interaction, visual displays can be worn on the body as with smart-watches, however presenting visual information directly within the field of view as with smart-eyewear provides for an even faster access time. In this thesis, alternative means of user feedback that can provide useful characteristics are investigated. By using haptic feedback for example, the output is presented directly to the user's body and can be perceived without any visual attention (c.f. Pub VI, VII). By furthermore utilizing the *positioning* of a self-actuated wearable, haptic feedback can also be provided continuously (c.f. Pub VII). Lastly, by utilizing scent-based feedback generated near the user's body, abstract information can be conveyed via olfaction, as an emotionally loaded information channel (c.f. Pub VIII).

As a conclusion, near-body interaction enables a quick access time for subtle interaction with little demand for the user and enables for personal eyes-free feedback capabilities.

Chapter 5

Challenges for Mobile Interaction

While wearable interfaces allow for a quick access time and an always availability, the user interaction with such an interface remains a challenge. Especially in mobile situations, where the user is potentially in motion, the capabilities for concurrent interactions are strongly reduced. For mobile touch devices, such as phones, is has already been shown that walking has a negative effect on the users' interaction performance [173]. Whereas such devices allow for the stabilization of grasping a physical interface [131], the *virtual* screen image of smart-eyewear does not provide for any physical stabilization when interacting in mid-air. When instead designing for *indirect* interaction, the capabilities for input can be positioned near the user's body on a physical interface. For this, however, the available input surface on the wearable interface often constitutes a limitation. Smart eyewear such as Google Glass for example enables for touch input on the device's temple, but the small form factor of the temple's arm dictates the touch surface to be small as well in size. Wearable interfaces and their input surfaces tend to be small and miniaturized due to social and functional considerations in wearability [224], but by this are also heavily limited in their input expressiveness for user interaction (c.f. Pub. II & III).

Besides input limitations due to miniaturization, users might also be conducting other activities at the same time that are situated in public situations. In this regard, user interaction with the wearable interface can interfere with other people and draw unwanted attention upon the user. For example, voice interaction can enable for handsfree user input, but is potentially obtrusive to other people in the surrounding, so that users are reluctant to its use in public [49]. For users of wearable interfaces, it is therefore important to feel comfortable not only in physical, but also in social aspects [50]. For this reason, the users' willingness to interact in everyday situations, depends on their perceived social comfort and social acceptance of the interaction [80]. In this regard, the body positioning of the wearable interface as well as the realization of user gestures are important for whether or not the interaction is perceived as unobtrusive respectively socially acceptable in public (c.f. Pub. I).

The challenges for mobile interaction that are addressed in this thesis are therefore (1) to enable for unobtrusive interaction with a wearable interface to allow users to feel comfortable when interacting in public, (2) to enable for interaction with a high input expressiveness that can be performed when the user is on the move, and (3) to investigate the on- and off-body positioning of a wearable interface regarding reachability and social comfort.

5.1 Social Acceptance and Unobtrusiveness

While the concept of user acceptance, including utility, usability and costs [183] has been well defined, the concept of *social* acceptance is rather intangible [127], but yet one of the biggest challenges for wearable interfaces [99].

Social acceptance is an essential part of a system's acceptability [136] and since wearable interfaces are a part of the user's appearance, the appearance of the interface and related user interaction must be perceived as acceptable in this context as well [158]. In this regard, Rico and Brewster stated that *"Social acceptability is determined when the motivations to use technology compete with the restrictions of social settings"* [157].

5.1.1 Social Interaction as a Stage

In social situations, individuals are intentionally or unintentionally expressing and presenting themselves to make an impression on others, even when they neither consciously nor unconsciously want to create such an impression [58]. This process is accompanied by gathering feedback through the reactions of others in regard to the individual's performed actions [58]. What is deemed appropriate or acceptable as an impression can vary wildly depending on the social context, so that individuals behave differently in different contexts.

In this regard, an interaction with a wearable interface has social implications as it becomes part of the individual's expression and presentation towards others. Whether intended or not, an interaction with the interface makes an impression, which effect might be carefully evaluated by the user. The social acceptability of a particular interaction is therefore depending on many social aspects within a given context such as location and audience [158], appearance and social status [58] as well as individual cultural characteristics [29, 150].

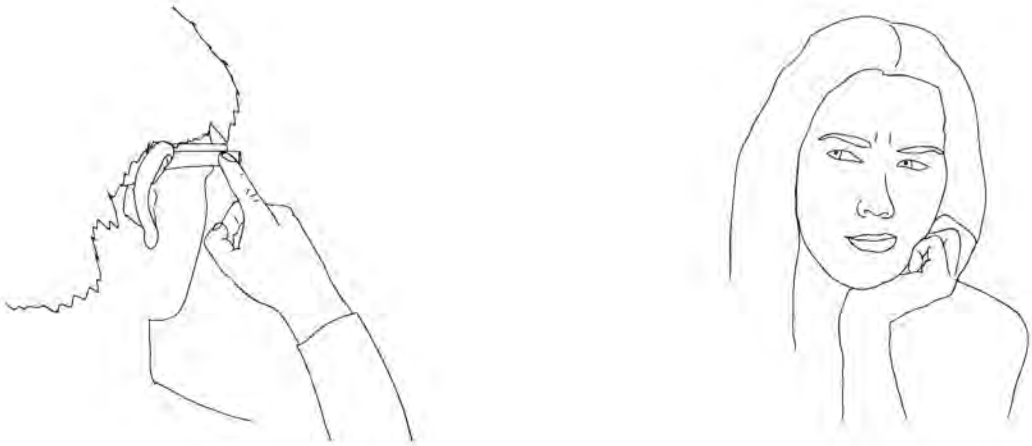


FIGURE 5.1: The social acceptance of an interaction can be viewed from two perspectives: by the internal perception of the *user*, and by the external perception of a *spectator*. Touch interaction on the glasses' arm for example is perceivable at eye level and might draw unwanted attention from a bystander.

To determine social acceptance, Brewster et al. [24] suggested to take two perspectives into account: the user's *own* perception of performing an action and the perception of *others* that could observe the user's action (see Fig. 5.1). This was termed by Montero et al. [127] as the *user's* and *spectator's* social acceptance:

User's social acceptance. The user's internal perception of their *own* actions and how comfortable they feel about performing these actions.

Spectator's social acceptance. The external perception of the user's actions by bystanders and whether they understand these actions and deem them appropriate.

For social acceptance with mobile interfaces, Rico et al. [158] investigated the *locations* and *audiences*, where surveyed participants stated they would be willing to use a newly introduced interaction gesture. They found that users are more likely to perform a gesture, the more socially familiar the context, i.e. gestures were perceived more likely as socially acceptable in front of friends and family than in front of strangers and likewise more acceptable in private locations than in public one's. These findings were reconfirmed with multiple wearable interfaces (e.g. [12, 80], Pub. V). In Rico et al.'s survey [158], interaction gestures were seen as most acceptable when the required movement was subtle, small and unobtrusive and when the gestures appeared and felt similar to everyday actions or existing technology. It was seen as least acceptable when the interaction looked weird, attention seeking, uncommon, uncomfortable or interfering with social communication.

It can be observed [127] that there appears to be an agreement in prior work to design for social acceptability by unobtrusive [156], subtle [42], and small gestures [163], i.e. to render the interaction techniques as barely perceivable to bystanders.

5.1.2 Manipulations and Effects

A factor influencing the *spectators'* social acceptance that can be already considered in the design stage is the relation between the visibility of the users' interactions and the visibility of the relating effects [127]:

Reeves et al. [155] defined the spectator's experience in regard to the extend in that these parts can be perceived ranging from *hidden* to *amplified* on an axis each for the visibility of the *manipulations* and for the visibility of the *effects* (see Fig. 5.2), whereas the *manipulation* is everything perceivable that is related to the interaction with the interface such as hand-, body- or eye-movement, or vocalized speech, and the *effect* is everything that is perceivable as an apparent *result* to these manipulations, such as visual feedback on a display or voice output.

They uncovered four broad design strategies as the quadrants along these two axes:

Secretive. Secretive interactions keep their manipulations, as well as resulting effects hidden to the spectator. This can as well be considered as a *private* or personal interaction. An example is a student glancing at their smart phone below their desks, trying to hide this interaction from the class teacher.

Expressive. Expressive interactions are the opposite of secretive interaction in that the manipulations as well as effects are clearly visible and thus very publicly perceivable. Expressive interactions ensure the comprehension of cause and effect to an observer. An example would be the student getting called out in class and having to solve an assignment in front of the class on a school board.

Magical. Magical interactions seek to hide the manipulations, while revealing only the effects. The observation is a magical experience in that spectators are amazed for seemingly miraculous effects that are not understood immediately and that make the *magician* seem powerful; an effect reached by misdirection and deception about the required manipulations [5].

Suspenseful. Finally, suspenseful interactions are showing the manipulations but hiding the effects. By this, curiosity and astonishment can be caused, since the spectator cannot comprehend the meaning behind the actions. An example is a user having a phone call on their Bluetooth headset. While the user's voice is audible, an observer might be confused whether the person is talking to themselves. There is no clear indication to whom the person is talking to, as the headset might not be immediately visible as an explanation to resolve the situation.

Montero et al. [127] conducted a user study on novel smart phone gestures based on these four design strategies and found that *secretive* and *expressive* gestures were more likely to be seen as socially acceptable than *suspenseful* gestures. As an explanation, the user's actions should allow spectators to get an impression of the meaning of their actions, which is a problem for suspenseful gestures where only the manipulation is seen. This makes it hard for spectators to construct a meaning, and hence making them feel uncomfortable.

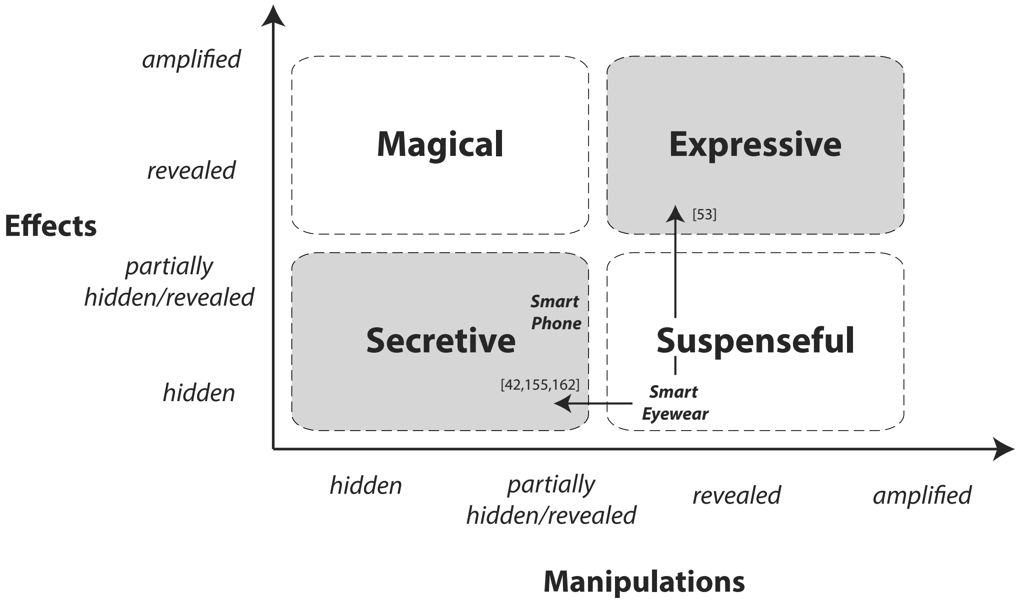


FIGURE 5.2: Reeves et al. [155] defined the spectator's experience in regard to the extend a spectator can observe the user's *manipulations* as well as *effects*. They uncovered four design strategies: secretive, magical, expressive and suspenseful. Montero et al. [127] found that small discreet *(secretive)* and big *expressive* gestures are more likely to be acceptable than *suspenseful* gestures. For this reason, interaction gestures can be designed to be subtle and unobtrusive (e.g. [42, 156, 163]), or to add resulting visual effects [53].

Interestingly, with smart *phone* interaction, it is often that bystanders cannot directly see the effect, but that the kind of manipulation is visually hinting at a *plausible* effect. Just by observing a smart phone user, a spectator can deduct from the user's actions whether they are reading, texting or taking a picture based on their hand posture and body language.

With smart *eyewear*, however, the virtual display is solely visible to the user, so that the effects are entirely hidden from a spectator. This comes with the result that for them the user's manipulations are lacking a comprehensive meaning. Also, there is no developed understanding of the user's body language to hint at their intentions, resulting in a low acceptance of the user's actions.

Interaction with smart eyewear might as well be designed to enable for effects, e.g. with Candid Interaction [53], it was explored to add visual effects to otherwise *suspenseful* interfaces. The question however remains, whether spectators approve for contrived *expressive* interfaces in public. A voice assistant for example can constitute as such an interface by making the user, as well as the system's feedback, audible to bystanders. While this kind of interaction allows them to form meaning, it can although be seen as annoying since it obtrusively draws for their attention. As the opposite approach, interaction can be designed as *secretive* by making the necessary interaction gestures and wearable interfaces subtle and unobtrusive (e.g. [42, 156, 163]), so that spectators are less likely be put into an uncomfortable position.

5.1.3 Current Attitudes towards Smart Eyewear

Although head-worn displays had a long history as wearable computers (see Chap. 4.1.1), the concept of smart eyewear, in the form of smart *glasses*, has gained increased public attention only recently with the announcement and wide media coverage of Google Glass [191] in 2013. While Google Glass first gained a positive recognition as an innovative product, it quickly received very critical reactions regarding its perceived lack of social acceptance and potential for privacy concerns [99].

Technical innovations initially often trigger fear, anxiety and objections [33], e.g. the Sony Walkman, introduced in 1979, was in the beginning divisively discussed for isolating its user with the use of headphones in public spaces [79], but then pioneered towards a wide popularity of mobile music listening. The medial discussion of smart eyewear however is distinctive in that the majority of potential users did not get to come into contact with actual devices to experience exposure before forming an opinion [152], so that it is unclear whether comparisons with the attitude and acceptance towards other novel technologies in recent history can be drawn [100].

Koelle et al. investigated the factors that influence the current attitudes of potential users [99, 100] and found the biggest reported issue to be the potential capability of permanent video and audio recordings. The pure potential existence of such recordings is being seen as a threat to privacy [46], that is making many people feel uncomfortable [21] and leading to a negative attitude towards the form factor. While Google Glass did not allow for long video recordings due to limitations in battery capacity, the mere thought of the existence of a camera continuously pointing face-to-face made many people feel wary. With ubiquitous technology such as smart phones, permanent recordings are feasible as well, however people assume that in these cases a clearer communication would be involved.

In this regard, it can be concluded that smart-eyewear devices should either clearly communicate whether data is recorded or forgo the face-to-face camera entirely. While such a camera might be convenient for quick captures from the user's point of view, it is otherwise not required for many functionalities, such as the quick access to displayed information.

Further factors for the currently prevailing concerns [99, 100] are the lack of comprehension of the interaction as a bystander (as discussed in the last subchapter), a lack of usability (as will be discussed in Chap. 5.2) and a too obtrusive form factor.

Regarding the form factor, current smart glasses are still mostly considered as head-worn technology rather than fashionable objects [152]. While smart glasses intend to build upon the design language of conventional eyeglasses as an established form factor, for most commercial attempts, the miniaturization of the required components has not reached that point yet. This however might change in the future with ongoing efforts in hardware miniaturization. As recent commercial examples, in 2016, a joint venture of ZEISS and Telekom announced the development of a pair of smart glasses[1] that attempts to hide the near-eye optics within the lenses, while more recently in 2018, North announced Focals[2], smart glasses that are supposed to more closely resemble conventional eyeglasses (see Fig. 5.3).

FIGURE 5.3: Google Glass (top), as announced in 2013, including optional glass frames, and Focals (bottom, © by North [138]), as announced in 2018, as an attempt to more closely resemble conventional eyeglasses.

Similar to other technology, that was initially met with concerns, the prevailing negative attitude towards smart glasses might diminish over time with continuous effort in miniaturization of the form factor, an addressing of the challenges regarding user interaction, and an actual exposure of the form factor in public.

5.1.4 Social Acceptance as a Function over Time

While social acceptance, or the lack thereof, is often approached as an *absolute* characteristic of a system, it must also be considered that a current attitude towards social acceptance is only a snapshot in time, the perception of which can drastically change over the course of a few years.

An example for this is the wristwatch, with the wrist as an established and well preferred body-location for watches. Nowadays, wearing a watch on the wrist appears to be very natural, but this was not always the case [124]. Back in the early 1900's, wristwatches were seen as a solely *feminine* accouterment, inferior to pocket watches. It took World War I for soldiers to value the capability of glancing at the time while keeping both hands free. Only after these soldiers returned home from the trenches sporting wristwatches, the wristwatch as a form factor became socially acceptable and furthermore widely popular among men as well [124].

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[1] ZEISS and Telekom Strengthen Commitment to Smart Glasses in Joint Venture. `https://www.zeiss.com/corporate/int/newsroom/press-releases.html?id=future-technology-zeiss-telekom_2018` Retrieved on 2018-10-27.

[2] North. Introducing Focals. `https://www.bynorth.com` Retrieved on 2018-10-27.

As can be observed, the mere usefulness of an innovation does not autonomously lead to acceptance. For the first Sony Walkman [79], that debuted in 1979, it took clever ad campaigns showing young role models to convince potential users to wear the device in public [150], which ultimately turned out to become the cultural phenomenon of mobile music listening [48]. With Google Glass, a similar approach was attempted, by featuring the device with runway models at a fashion show [203], however to a lesser effect.

With other technologies, such as Bluetooth headsets, users initially had to act very unfamiliar as during phone calls they would appear as talking to themselves. This factor however did not prevent the usage of headsets in public. The benefits of hands-free phone calls outweighed the social costs of acting outside of normal behavior, so that by seeing others or personally using such devices with a benefit, over time, their usage became socially acceptable through continued exposure [158].

For the diffusion of innovation, Rogers theorized [160] that people can be divided into categories based on the assumption that certain individuals are more open towards adaptation than others. This is known as the Technology Adoption Curve (see Fig. 5.4), which indicates that a first small proportion of *innovators* and then *early adopters* are very open towards trying new technology. By their behavior this small group will then consciously or unconsciously influence the more conservative - but yet open to new ideas - group of the *early majority*, which then later on influences the *late majority*.

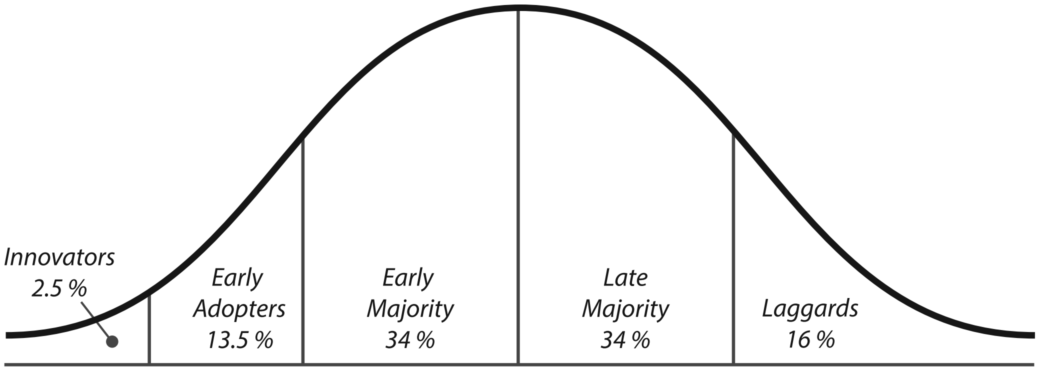


FIGURE 5.4: The Technology Adoption Curve by Rogers [160] as a sociological model to categorize potential users in their openness towards adaptations.

For the adoption and social acceptance of smart eyewear as a new innovation, this sociological model implies that *innovators* and *early adopters* need to be convinced first by providing a value to these groups, where the benefit of using the device in public outweighs potential social costs. This thesis contributes to this, by investigating concepts of unobtrusive interaction techniques to reduce the social costs of using smart-eyewear in public.

5.1.5 Designing for Unobtrusive Interaction

With an ongoing miniaturization of smart eyewear, it can be expected that an unobtrusive form factor can eventually be achieved. Besides the appearance of the form factor, however, the appearance of the *interaction* is important as well for potential users to feel comfortable of interacting with such devices in public. For this reason, interaction concepts for smart-eyewear should be designed to allow for unobtrusive interaction that draws as little attention as possible.

In contrast, many current interaction techniques for commercial smart eyewear are rather obtrusive: Touch-panels on the glasses' arms, for example, require users to lift their hand up into the eye-level of bystanders where the interaction gestures stand out and can immediately be seen, whereas voice input is especially obtrusive in shared focused environments, such as lectures or meetings, where the audible sound can disturb other people.

Wearable expert users, such as Thad Starner, who have already integrated smart eyewear into their daily lives for many years, are mainly operating their devices via the Twiddler [115], a chording based text input device, that is strapped into one hand. The Twiddler can be used in an unobtrusive manner, e.g. by leaning against a wall and typing one-handedly behind one's back, but it is unclear whether such an input device could see wide adoption by regular users due to a long learning curve [112] and due to the commitment of keeping only one hand entirely free since the other hand is partly constrained by the worn input device [113]).

Ideally an unobtrusive input capability would be quickly accessible when it is needed, and gone when it is not. This can be envisioned by subtle micro-gestures within the user's hand that can be performed independently from where the hand is positioned. The question however remains how such little movements can reliably be tracked. In prior work, multiple technical solutions have been presented, such as Nenya [9], a magnetically tracked finger ring that allows for subtle one-handed twisting and sliding movements of the ring for 1-dimensional input. Other solutions are Nailo [91], a nail-mounted touch surface that can be accessed by another finger of the same hand, Digits [96], a wrist-mounted camera to track coarse finger gestures, and finger-mounted magnets [35, 36, 81] that can enable for subtle interaction using the fingertips. Unfortunately, these input capabilities have the downside of requiring an instrumentation of the user's fingers (such as with magnets and hall sensors) or are limited in their input expressiveness (e.g. a ring can only be twisted in one dimension and a wrist-mounted camera can unfortunately not be aligned to spot subtle finger movements within the hand). Another challenge for subtle micro-gestures within the hand is how to distinguish *intended* interactions from *naturally occurring* interactions, e.g. random hand movements, as an interface.

An appropriate delimiter can be introduced by positioning the subtle touch input onto the user's body, e.g. iSkin [208] is a silicon-based touch sensor that has a tattoo-like visual design and can be worn on the user's skin, whereas SkinTrack [225] can track on-skin finger touches near a wristband by emitting an electrical signal with a worn finger ring. Holz et al. [78] even go further by provocatively proposing to implant the interface underneath the skin. One downside of skin-based touch input however is that mostly *two* hands, resp. arms, are required, with the second one serving as the surface to be touched.

When utilizing the user's *clothing* as a near-body touch surface, users can potentially reach for the interface *one*-handedly. An example for an e-textile interface is Google ATAP's Project Jacquard [148], where conductive yarn is embedded into existing weaving processes to enable for touch-sensitive areas within clothing. In the literature, Rekimoto already proposed to utilize interactive clothing for unobtrusive touch input [156], whereas Toney et al. [199] suggested that clothing can be used to conceal a variety of wearable interfaces. Possible input locations for capacitive touch input were evaluated by Holleis et al. [77], where the upper thigh area would most often be mentioned for where to potentially accept wearable touch input. Profita et al. [150] evaluated the *spectator's* perception, and found the wrist and forearm location (on a long-sleeved pullover) the most acceptable for a stitched textile.

Principles for Unobtrusive Near-body Interaction

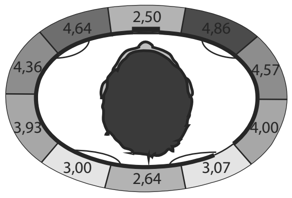
In this thesis, two interactive systems were built to investigate the concept of unobtrusive interaction with near-body interfaces (Pub. I & II). These concepts were designed based on two principles: 1) by situating the interaction at locations that are out of immediate sight, e.g. out of the eye level of bystanders, and 2) by requiring only very little hand movement to access the interface to, moreover, reduce the chance of drawing visual attention by the user's motion [1]. These principles do not inherently lead to interaction that is entirely *secretive* or *imperceptible*, but rather to interaction that is *unobtrusive*, so that users feel comfortable to interact in public. Based on these principles, the input location was situated for both interfaces (Pub. I & II) near the resting position of the user's hand.

A Touch-sensitive Belt as a Quickly Accessible Location

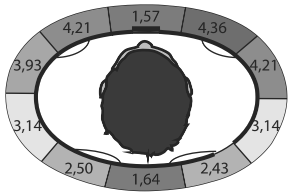
As a first concept for unobtrusive near-body interaction, a touch-sensitive belt was implemented as a wearable interface (see Fig. 5.6) by extending the surface of a common belt with touch sensing functionality. In contrast to other possible touch locations, such as the glasses' arms, the user does not have to lift up their arm and can instead reach for the belt with their thumb while resting the hand within the trousers' pockets, so that only very little movement is required to access the interface. For touch interaction, subtle swiping gestures can be used to navigate through virtual menus as familiar from existing technology. Furthermore, the large surface area on a belt can be leveraged for a spatial horizontal mapping of information, so that applications or shortcuts can quickly be opened by tapping assigned locations on the belt, e.g. a digital wallet application could be placed in close proximity to the user's physical wallet. Due to kinesthetic memory and the sense of proprioception [63], users can reach to different locations without a glance. Finally, a touch-sensitive belt does not have to expose itself as a wearable interface and can be designed to look like a common belt to be unnoticeable to bystanders. Short interaction on the belt, such as brief tapping, can then look like the user keeping their resting hand busy, which is a common sight and not immediately obtrusive to bystanders.

To evaluate whether users feel comfortable to perform touch gestures on a belt in public, a user study was conducted in a public setting. Participants were asked to conduct tapping and swiping gestures on a common belt while standing in a heavily frequented passage in a cafeteria and would rate the perceived social acceptance on a 5-point Likert scale (ranging from *very uncomfortable* to *not uncomfortable at all*) for ten different areas on the belt, as well as for two different lengths of interaction (tapping as a micro-interaction and subtle swiping gestures up to 10 seconds).

The areas above the trouser pockets were preferred for touch input in general. For brief interactions, such as tapping, participants felt comfortable interacting around the belt, since shortly fumbling along the hip was perceived as a common sight in everyday life. When it came to longer interactions for up to 10 seconds, however, participants felt less socially comfortable at locations around the belt than above the front trouser pockets. Especially on the back side of the belt, a longer interaction implied an uncomfortable and uncommon arm position that could no longer be confused with random hand movements, whereas at the front areas above the pockets, the belt could comfortably be reached while resting the hands within the pocket allowing for a more subtle interaction.



micro-interaction (2-4 seconds)



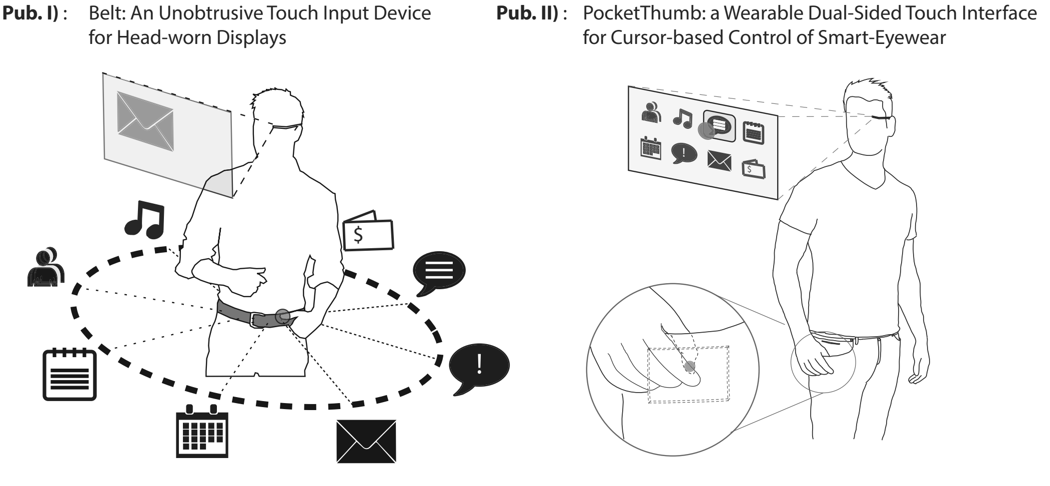
longer interaction (5-10 seconds)

FIGURE 5.5: The user's perceived social acceptance of their interaction in public. **Pub. I)**.

As a conclusion, it was shown that the *duration* of an interaction is a contributing factor for the user's perceived social acceptance, in that *shorter* interactions were seen as more *unobtrusive* and less likely to be perceived by bystanders.

Utilizing the Trousers Front Pockets for Touch Input

As the pocket area showed to be a promising location for reachability with only little hand movement, it was furthermore explored with a second concept, where a touch sensor was embedded into the front trouser pocket, so that the user could reach into the pocket with their thumb to control a virtual cursor (see Fig. 5.6). By this, the thumb's movement can be kept concealed from spectators in public. When feeling comfortable, the user can additionally perform multi-finger gestures on the outside of the pocket to furthermore increase the input expressiveness of the wearable interface.


Pub. I) : Belt: An Unobtrusive Touch Input Device for Head-worn Displays

Pub. II) : PocketThumb: a Wearable Dual-Sided Touch Interface for Cursor-based Control of Smart-Eyewear

FIGURE 5.6: In this thesis, two concepts were implemented as hard- and software to investigate unobtrusive near-body interaction.

5.2 Input Expressiveness

Besides social acceptance, *usability* is another big challenge for the user's interaction with wearable interfaces like smart eyewear [100]. Since these interfaces should not interfere with other activities in everyday life, they need to be miniaturized and yet easy to access and to operate in mobile situations to be useful to their users.

As of now, however, no interaction technique could be established as state-of-the-art for smart eyewear. For wearable interfaces in general, input techniques are often limited in their expressiveness and consist of only very basic interaction gestures. Simplicity certainly fits the vision of mobile micro-interactions [10], i.e. of very short interaction lasting only a few seconds, but it remains unclear how basic gestures can enable for *rich* user input that is beyond very simple and restrained use cases. Input expressiveness is hence important to enable for a rich user interaction for wearable interfaces.

5.2.1 Mobility & Miniaturization vs Input Expressiveness

With the advances in ubiquitous computing [210], smart devices and interfaces are getting more and more interwoven into our daily *mobile* lives. The *mobility* of smart devices and the wide availability of wireless connectivity enable us to carry them along and to access information almost anywhere and anytime. For this reason, such smart devices are positioned ever nearer into reach of their users, so that with *wearable* interfaces, they are designed to be always available and quickly accessible. To not interfere with the users' everyday life, however, such interfaces also need to be evermore miniaturized, and as a result, the smaller the physical form factor, the more likely it affords for *mobility* (see Fig. 5.7).

For personal, mobile, and wearable devices, the interaction of their users can be categorized based on the device's affordance for mobility:

Stationary Interaction. This is afforded by traditional devices that are stationarily bound to a specific location due to their large form factor, such as desktop computers that are sitting beneath their user's desk, often for their whole life cycle. Some users also use their laptop computers solely in a stationary fashion.

Nomadic Interaction. Certain devices are stationarily used, but are yet portable, so that users can move from one location to another before interaction, hence the term *nomadic* interaction [98]. Laptop computers are mostly used nomadically, so that users may work at their desks, in a meeting room, or during a train ride, but are rarely interacting *while* they are mobile themselves. Tablet computers are likewise mostly used in a nomadic fashion, with the distinction that the form factor affords for many more possible locations for interaction, since the devices can be held in hand and don't need to be put on a surface. Yet the usage of a tablet computer is likewise rarely *while* the user is mobile.

Mobile Interaction. Some devices afford to be used even in *mobile* conditions, such as when the user is walking and at the same time potentially doing other activities, such as shopping in a store, carrying grocery bags, or walking a dog. The smart phone is the prevalent interface for mobile interaction [13], whereas *wearable* interfaces have the potential to further advance the trend of mobility by being even faster accessible.

While the trend for ever more smart and accessible devices has *increased* their mobility, the input expressiveness of the user's interaction has *decreased* due to smaller form factors that afford for less and less input capabilities (see Fig. 5.7).

Personal Computing Personal computing devices such as desktop and laptop computers are running traditional WIMP (windows, icons, menus, pointers) interfaces [74] that offer a high input expressiveness by an indirect cursor-based pointing interaction with a mouse or a touchpad. Due to a variable cursor-display ratio, only little hand movement is required to quickly and yet precisely move a cursor along one or multiple displays. Additionally, with available physical keyboards, users can quickly input text and various shortcuts.

Mobile Computing. Mobile computing devices such as smart phones and tablets are mainly operated by a touch display that enables for direct touch input, which is easy to learn and hereby feeling natural for potential users [206]. While direct touch input, can be more efficient than indirect cursor interaction [178], it comes with the downside of the 'fat finger' as a pointer [204] that does not offer the same precision as a virtual cursor and causes occlusion effects during interaction. Mobile touch interfaces are coping with this problem by larger target sizes for interactive touch elements [6, 7], however, due to a limited display size, this means that less input functionality is immediately accessible than with traditional personal computing devices. Additionally, for text input, software keyboards are utilized instead of physical keyboards, that would take away too much valuable screen estate, however, due to a lack of tactile perception, the typing efficiency is lower [181].

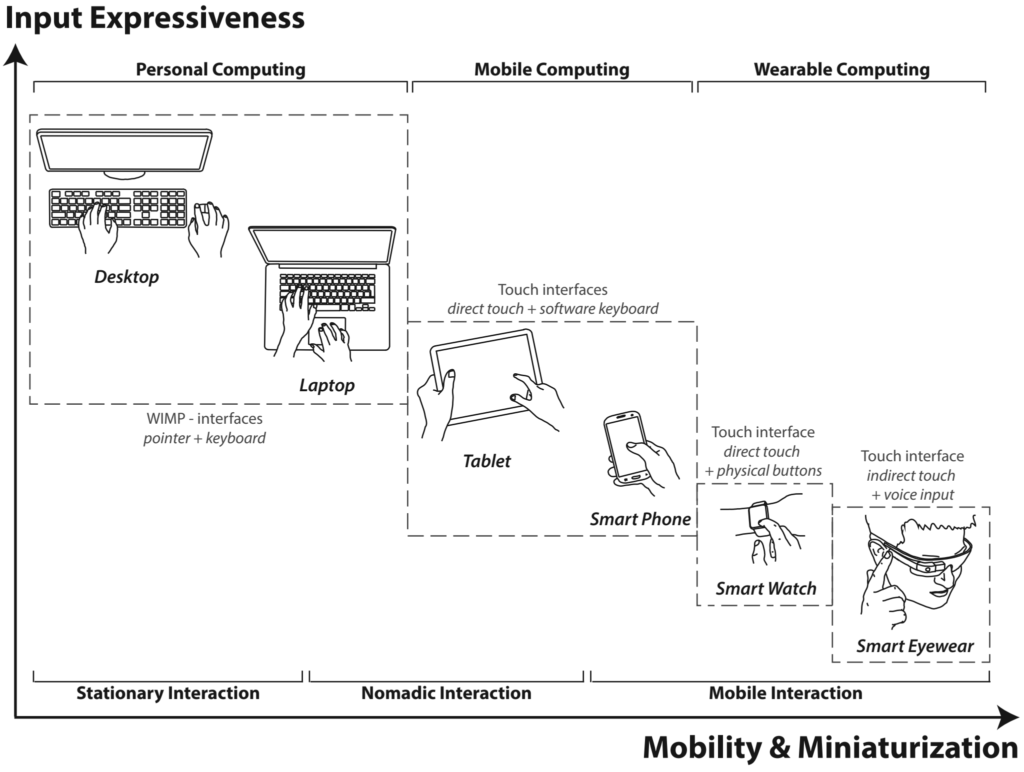


FIGURE 5.7: While smart devices have become more and more *mobile*, their smaller form factors afford for less and less input expressiveness.

Wearable Computing. At the early beginning of wearable computing, it appeared reasonable to transfer well established interaction paradigms of personal computing to wearable devices [197]. A physical keyboard, strapped to the user's forearm, however, is hard to imagine with today's standards in wear and usability. Instead, wearable interfaces could only gain popularity building on top of already established form factors such as the wrist watch, which affords only very little surface area for user input. Much like mobile computing devices, direct touch interaction is prevalently being used, however, due to the small form factor, the fat finger problem and occlusion effects are further reducing the user's input expressiveness, so that only few interactive elements can be displayed at the same time and barely any text input is supported [101]. Due to the small touch displays, some watches provide additional physical input capabilities such as the digital crown for the Apple Watch [7] or the rotating bezel of the Samsung Gear [169] which can both provide for navigation without finger occlusion. Another means to provide for more input expressiveness on a small screen size is ForceTouch as integrated in the Apple Watch [7] which enables to open a context menu on the touch display by finger pressure. Nevertheless, due to their limitations in input capabilities, smart watches are still rather used as a glanceable information display than for *interactive* user interaction [145].

With smart eyewear, in contrast, no interaction technique could be established as state-of-the-art yet. Google Glass provides for indirect touch input on the glasses' arm, however, only a small set of basic gestures is enabled, which is swiping to the left or right to scroll through a one-dimensional timeline and then a single tap to select the displayed entry. To compensate for the lack of input capabilities, additional voice input is provided for users to more quickly open applications. However, similarly to smart watches, the device would rather provide glanceable visual information than providing for means to actively engage with the content. While this might be sufficient for the smart watch form factor, it begs the question whether this provides enough value for potential users to perceive it as *useful* to be wearing smart eyewear [100]. A higher input expressiveness could therefore provide additional value by enabling for *richer* interaction. As smart eyewear can conceptually provide for a large display size with a small form factor, the limitations of the input expressiveness are therefore not found in a lack of screen estate but rather in the non-tangible properties of the virtual screen image and the lack of suitable interaction techniques that could offer a high input expressiveness even for mobile interaction.

5.2.2 Metrics for User Input

The expressiveness of user input is composed of many important properties, so that a design space for input techniques can be systematized from multiple perspectives.

Card et al. [30] analyzed the design space of input techniques by parametrically describing their physical properties as a taxonomy: They defined input techniques based on the *manipulated property* (of either *position*, *movement*, or *force*), the *point of reference* (either *relative* or *absolute*), their physical *input dimensions* (x, y, z), and the *value range* that can be entered.

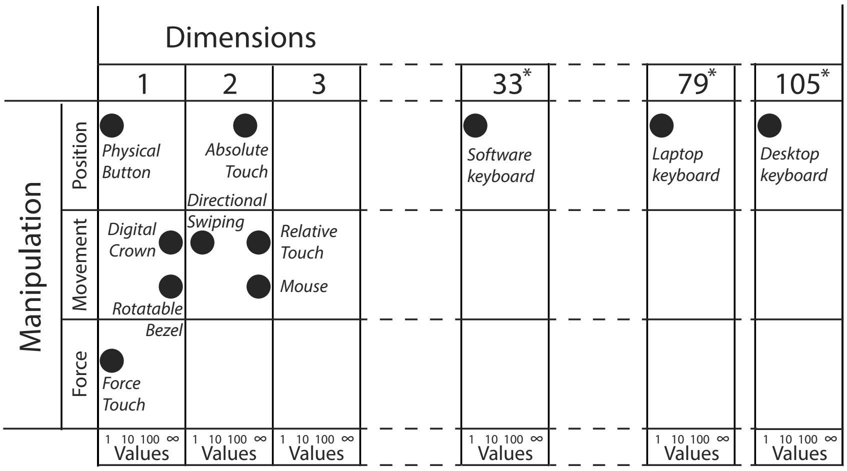


FIGURE 5.8: The design space of various input techniques based on their physical properties [30] as classified by the author. *The number of dimensions for the keyboards are based on the IOS 12.1 software keyboard, the Macbook Pro 13.3 laptop keyboard, and the German T1 desktop keyboard design.

While these properties do not allow to inherently *measure* the expressiveness of input techniques, their quantity of possible *input dimensions* and of their *value range* can give an indication of the physical operability of potential user input. In this regard, input techniques that have a high quantity in these properties, i.e. *dimensions* and/or *value range*, are likely contributing to a high expressiveness (see Fig. 5.8). As an example, a keyboard has a large amount of input dimensions, i.e. buttons, while a mouse can provide an infinite range of values over two dimensions, so that both contribute to a high input expressiveness. As examples for low input expressiveness, directional swiping gestures provide for only two values (each direction) in two dimensions (horizontal and vertical). From a physical perspective, an arbitrary number of swiping angles could be performed, and therefore many more dimensions, however it was shown in previous work that users have difficulties with more complex angular movements [43]. Furthermore, with Google Glass, only horizontal swiping gestures are supported due to physical constraints of the touch pad, so that merely *one* dimension is enabled for navigation, further reducing the capabilities for user input.

Another perspective, to assess input techniques, is to systematically evaluate their *performance*. Fitts' Law [116] for example is frequently used as a design tool to measure the speed of various interaction techniques in one-dimensional or two dimensional [117] target selection tasks. As a result, the *target selection time*, as a function of target *size* and *distance*, can be derived for each technique, where it was shown that direct touch input can outperform the traditional computer mouse [178]. Keyboards on the other hand can be evaluated by standardized typing tasks, where the *typing speed* and *error rate* is measured. By this, it was shown that software keyboards enable for less *words per minute* than physical keyboards [180] and that smaller keyboard sizes lead to lower performances [181].

Each of these metrics, however, only depict a specific part of a multitude of important properties. Other important factors for example comprise the *access time* to initiate an interaction [11], the *accuracy*, the chance of *errors*, the *ease of use*, *learnability*, *physical* and *cognitive demand* [67], the ability to *interrupt* [109] or *switch* to another task, the hand-eye *coordination*, the perceived *usability* and *user experience*, and more. The important factors for individual input techniques can vary widely depending on the interaction context, so that for example just by introducing *mobility* as a variable with a walking condition, the influencing factors can become evermore complex. Systemically analyzing a *comprehensive* design space for input techniques is therefore difficult to achieve due to too many affecting variables. For this reason, in the HCI (human-computer interaction) literature, novel interaction techniques are investigated by evaluating properties that *distinguish* the technique from existing work. By this, a high input expressiveness can be demonstrated by showing the applicability of novel *use cases* for interaction that weren't possible before.

5.2.3 Increasing the Expressiveness of Wearable Interfaces

For smart watches, multiple approaches have been presented to increase the limited input expressiveness of the small form factor. For handling the occlusion of the finger for example, the occluded area could be displayed as an overlay *beside* the finger to increase the precision of selections of smaller target sizes [204]. Another possibility is to avoid the occlusion entirely by utilizing the *backside* of a device for touch input and to then visualize the touch input on the regular display [212, 16]. As the backside of a watch, the back of the encompassing watch band could be considered. Also, the *ambient* area next or around the watch body is utilized as an input space for multiple concepts. With WristIt [140], simple gestures like scrolling can be performed eyes-free on the band below the watch face. Laput et al. [103] implemented a system to project interactive icons onto the skin right beside the watch to enhance not only the input, but also the output space. Mid-air interaction above the watch body has additionally been proposed. Harrison et al. [65] showed that a small magnet mounted to a finger can enable for a sensing of very precise finger movements above the watch, whereas Google ATAP's Project Soli [106] showed that micro-gestures can be used in close proximity to a small wave radar sensor that could be embedded into a watch form factor. Finally, users could also use a variety of physical manipulations directly with the watch body, such as panning, tilting and twisting [219], by reconfiguring a tangible watch design [182], or by using multiple watch displays [114] to expand the input vocabulary of the form factor.

For smart eyewear, the focus in the literature has been less on *extending* interaction capabilities, but more on finding suitable interaction concepts in general. Most work has been focusing on very basic interaction gestures like tapping and swiping-based touch gestures on various body locations [104], such as on the skin [208], or on e-textile interfaces, on the finger [223], forearm [177], and the upper thighs [70]. A higher input expressiveness can be reached by positioning the input into *mid-air* and to enable for more complex hand and finger gestures either sensed by a camera in front of the eyewear [216], or with sensory on a glove [80] to enable for a more relaxed hand position. For near-body interaction, a nail-mounted magnet and hall sensor can enable for precise touch gestures on the finger tips [35], while an infrared-emitting ring [95] can enable for 2d cursor-based finger interaction but requires a steady surface to rest the hand. In contrast, this thesis aims to enable for a high input expressiveness for near-body interaction that is also feasible in *mobile* conditions and that does not require an *instrumentation* of the user's hand (see Pub. II).

Course vs Precise Movement

FIGURE 5.9: Investigation of user input on a smart watch with various mobile conditions. Users would try to stabilize their hands to increase the accuracy. **Pub. III)**.

To investigate how various mobile conditions affect the interaction with smart watches, a quantitative user study was conducted in the scope of this thesis (see Pub. III). Measured were the effects of *mobility* (walking), *encumbrance* (by carrying items like shopping bags) and wearing the watch on the *(non-) dominant hand* on interaction techniques present with current smart watches, which was *tapping*, *swiping* and *flicking* the wrist.

Interestingly, *swiping* interaction was barely affected by any mobile condition, which might explain its wide exploitation as an interaction technique also for other wearable interfaces such as smart eyewear. In contrast, for selecting targets with *finger tapping*, the error rate would significantly increase when walking. This can be explained by the factor that swiping is a *course* movement, while tapping requires *precision*. Interestingly, the *non*-dominant hand is as good in rough motion as the dominant hand [88], so that users could swipe efficiently with both hands. Users in general found coping mechanism to handle the mobile conditions, so that for tapping and swiping, they would rest their interacting hand on the watch hand to increase the stabilization during interaction. In previous studies on mobile encumbrance with smart phones, Ng et al. [135] found that using both hands for interaction increases the accuracy. In this regard, the cost of requiring both hands for touch interaction with smartwatches can be beneficial for hand stabilization. Furthermore, this shows the importance of hand stabilization as a factor for interaction in general to enable for *precise* input that is required to enable for a high variety of input values for a high input expressiveness.

Hand Stabilization as an Important Factor

Designing for hand stabilization for *one*-handed near-body interaction with smart eyewear is difficult to achieve, since body motion during *mobility* renders most body parts to be in motion as well. For the interactive belt (see Pub. I), the stabilization could be improved by providing a firm surface area and by utilizing the body's hip area as the body's center of mass [41] that is the most steady while walking.

As a second approach, the pocket area of trousers was furthermore investigated as a near-body input location as it allows users to rest and stabilize their hand at the pocket while walking. For the interaction with a textile touchpad, Heller et al. concluded that the rigidity of a touch surface strongly influences the capability for rich touch gestures, especially when the user is walking [70]. This can be a problem for elastic clothing materials, that are prone to produce foldings along a gesturing finger and that do not provide for a firm surface. However, Saponas et al. [170] showed that capacitive touch sensing is also feasible *through* fabrics. Building on top of these findings, for PocketThumb (see Pub. II), a *firm* touch surface at the pocket was implemented by embedding a capacitive touch layer into a thin *rigid* support casing that was sewn into the layers *in-between* the pocket's fabrics. This rigid touch interface was slightly curved to match the curvature of the thigh and would allow for touch sensing not only from the *outside* but also from the *inside* of the pocket for a combined dual-sided touch interaction. To provide for a high input expressiveness, the dual-sided touch interface would enable the control of a virtual *cursor* to quickly select visual targets on the virtual display. The cursor is controlled with the *absolute* position of the thumb, sliding along the inner side of the sensor, whereas a selection is triggered by tapping the index finger against the thumb's position from the outside. By this, the hand can be stabilized by anchoring the thumb's joint into the pocket fold (see Fig. 5.10).

FIGURE 5.10: Users can quickly access the PocketThumb interface by sliding the thumb into the pocket. The thumb can then stabilize the hand by anchoring its joint to the pocket and enable for a high input expressiveness for *cursor*-based dual-sided touch interaction. **Pub. II)**.

A quantitative target selection study was conducted to evaluate the efficiency of this cursor-based *dual*-sided touch technique in different mobile conditions (*standing*, *walking*, and *sitting*). It was compared to two baseline techniques: single-sided *absolute* as well as *relative* touch interaction using the index finger, as familiar from current touch devices, e.g. from smart phones and from the touchpad of laptop computers.

Target selection based on the newly introduced dual-sided touch technique showed to be significantly faster than with the more familiar baseline techniques. This effect was largest when participants were *walking* (24%, resp. 31% faster) and lowest when participants were *sitting* (14%, resp. 11% faster). In the *walking* condition, participants benefited most from being able to stabilize the hand at the pocket fold, whereas in the *sitting* conditions, participants could additionally rest their hand at the horizontal thigh.

An analysis of the touch behavior furthermore showed two distinctive strategies of hand movement: Participants either moved the thumb horizontally via wrist joint rotation (left and right) and vertically via arm movement (up and down) or instead moved the thumb independently via its saddle joint in all dimensions. It was shown that users could pinch the thumb using the index finger with the thumb as a proprioceptive point of reference, but also that fingers could be moved more independently utilizing the high degree-of-freedom of the thumb's saddle joint [218]. Since the thumb can not only be used as *cursor*, but also as a spatial point of reference for the remaining hand, the capabilities for using the thumb for pointing and the remaining fingers for jointly performed gestures were explored with four interaction techniques: With *spatial tapping* users could willingly tap left or right of the pointing cursor, which, as an analogy to left and right clicking on a mouse, could increase the expressiveness of a touch selection. With *grab-and-drag*, users could pinch a virtual icon and drag it to a new location. *Pinch-and-circle* would allow users to rotate a virtual knob with a finger, pointed at by the thumb, to continuously navigate through a one-dimensional list, whereas with *point-and-swipe*, users could perform multi finger swiping gestures while *simultaneousl* pointing with the thumb at a target.

As a conclusion it was shown that by providing for hand stabilization during one-handed near-body interaction, a high input expressiveness can be achieved.

Expressiveness für Nomadic Interaction

Increasing the input expressiveness for wearable interfaces is also beneficial for *nomadic* interaction, where users need to find a suitable location to interact with a wearable device first. With FaceTouch (see Pub. IV) it was shown that users can take up a *thinker's pose* (see Fig. 5.11) to interact with a nomadic virtual reality display by resting their elbow with their hand or on a steady surface to perform a *rich* touch interaction in front of their face. By this, users could precisely select individual targets with a low error rate within the large virtual reality display.

FIGURE 5.11: Stabilizing the elbow enables for a high input expressiveness for *nomadic* virtual reality. Based on **Pub. IV)**.

5.3 On- & Off-Body Locations

The on-body positioning of a wearable interface strongly affects its reachability and the involved body parts for potential user input. Under *mobility*, physical activities can furthermore constrain involved body parts, so that interaction gestures are more difficult to perform or are even completely impeded. Wagner et al. [205] introduced a body-centric design space for multi-surface interaction showing that for on-body touch input, a varied amount of body parts is constrained during interaction. Only when the touch input is located *within* the hand, the user's body remains entirely mobile. When the touch input is situated somewhere else on the body, at least two body parts are involved: the arm of the *interacting* hand and the body part to be touched. If the touch location is located on a limb, such as the forearm of the non-dominant hand, this body part is inherently *constrained* in movement during interaction. For this reason, the implemented touch input for mobile on-body interaction was located near the user's torso, as a *one*-handed touch interaction (c.f. Pub I & II).

Beside inherent body constraints during interaction, the users' *proxemics* are important to ensure the user's mobility as well [55, 224]. *Proxemics* are defined as the layers around a human body that define which space is intimately perceived as the size of the person's self [64]. By designing wearable interfaces to stay within the intimate space of the user's body, they can be considered a natural part of the person's size awareness of their own body and prevent the user from getting physically hindered during motion. Taking proxemics into account for the design of a wearable interface is important as the size awareness varies depending on the on-body location. While this perceived layer is as low as ~0.2 cm around the user's fingers it can be as high as ~10 cm around the user's hip [224]. Due to this, it requires a lot of miniaturization to design technology that can be worn within the user's hands, such as a wearable ring, to not hinder the user in their everyday life. However, when eventually achievable, the user's brain will perceive the device as a part of the own self.

5.3.1 Reachability and Social Weight

Reachability is an important property for potential body locations of wearable interfaces, as an easy to reach body location will allow for a quick access time [11] and a low physical demand [73], constituting as preferable properties to enable for short micro-interactions [10] in everyday life.

The on-body reachability for touch interaction can be assessed by regarding the user's demand in involved body movement (see Fig. 5.12). The easiest to reach location for a touching finger can be found in immediate proximity within the user's hand, e.g. on the remaining finger tips (a), followed by the immediate proximity on the user's torso, i.e. the upper thigh (b). By arm rotation over the elbow joint, users can reach a circular area along their torso (c) that can be extended by rotation over the shoulder joint (d). The flank (e), however, can only be reached by extensive shoulder extension, whereas the interacting arm itself (f) can anatomically not be reached. When involved, the shoulder joint dominates the physical demand for moving the arm [73]. Finally, for touch interaction on the second arm (g) users can split the required demand in movement by nearing this arm into easier reach.

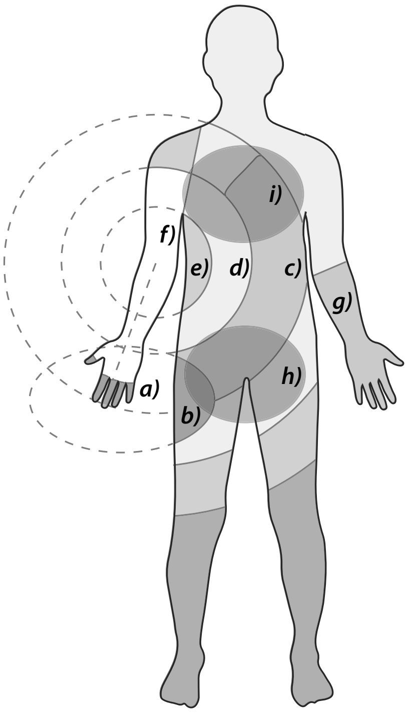


FIGURE 5.12: Reachability of on-body locations for touch input and regions of increased social weight.

Some locations for on-body touch interaction, however, also carry a social weight regarding the visual properties of the interaction. This is especially the case for locations that are sexually suggestive by proximity to the user's private parts (h) [50]. While Dunne et al. [50] excluded the *pocket area* entirely for potential user input after coding mentioned user concerns, Holleis et al. [77] found that users would mention this area the most for where to accept potential touch input. This shows that user input along the user's pockets can be considered a fine line, whose social weight depends heavily on the realization. For the interactive belt (see Pub. I) for example, users were very uncomfortable interacting at the belt directly above the trouser button, but felt comfortable along the pocket areas at the sides (see Fig. 5.5). Furthermore, for this reason, for PocketThumb (see Pub. II), the touch sensor was embedded into the outer area along the side pockets (see 5.10), so that the location would be easy to reach but outside the socially weighted area. Another region that carries an increased social weight, is the chest area (i) that is especially sensitive for female users [50] and therefore seldom used for wearable interfaces.

5.3.2 Giving Users a Choice

As has been shown, various factors can be relevant for the suitability of an on-body location, such as the *reachability*, *social acceptance*, *ease of use* and *input expressiveness*. These factors can be perceived and prioritized differently by users depending on their social context, their current activities and potential constraints by their mobility. With current wearable interfaces, however, the form factors are designed and limited to be worn at only specifically defined locations on the user's body, so that the input location is *fixed* for a respective wearable interface. This can limit the interaction capabilities based on the user's situational context and its physical or social constraints. Lyons et al. [113] argued that for a wearable interface the on-body positioning it not only important for the *active* use case, but also for the *passive* cases where the interface might remain on the body. They introduced the concept of multiple *dispositions*, as the physical relationship between the varying body poses of the user and the wearable interface. In this regard, the on-body placement could be adjusted for *active* as well as *passive* uses cases. As an example, conventional sun glasses can be *passively* worn on the neck and then be actively repositioned into their usage location at their user's head.

Extending on this, the design and realization of a multi-functional wearable interface was investigated that could be placed, worn and *actively used* at *various* locations *on*, but also *off* the body (see Pub. V). This would allow users to adjust the interface's location to different affordances of varying situations and use cases. The design of such a multi-location wearable interface could take various forms, such as a clipping-mechanism (c.f. the iPod Shuffle[3]), which would allow the interface to be attached to various locations on the user's *clothing*. Clipping directly onto the user's skin (such as onto the wrist) however remains unsuitable due to skin clamping. A multi-location form factor that can be comfortably worn on both, *clothing* as well as *skin*, was found in the SnapBand, a flexible bistable spring band that can be quickly snapped to different locations on the body, but also onto various objects within the environment, to serve as a multi-location touch input device (see Fig. 5.13).

In a user study with the interactive system, participants appreciated the versatility and flexibility of the form factor, but also commented that the band size would constitute a compromise and could be too large or too small for some locations. Participants would rate a set of 10 locations, 6 *on*-body and 4 *off*-body, whether they can picture themselves using the touch input band on the respective location in public, resp. in private. For the *on*-body locations, the resulting ratings strongly resembled the previously assessed on-body *reachabilities* (see Fig. 5.12). Interestingly, while *on*-body locations were rated *lower* for interaction *in public* (in comparison to *in private*), off-body locations, e.g. attached to the strap of a worn backpack or mounted to the edge of a desk, were rated *higher*, hinting at present concerns regarding the

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[3] iPod Shuffle. https://support.apple.com/kb/SP592

FIGURE 5.13: The SnapBand as a touch input band (a) that can be snapped, worn and attached to multiple locations, e.g. at the wrist to serve as an input device for smart eyewear (b), held in the hand as a tool for presentations (c), or attached to the handlebar of a gym machine for an easier reachability during a workout (d). Based on **Pub. V)**.

social acceptability of on-body interfaces in public (c.f. Chap. 5.1). In this regard, a multi-location input device like the SnapBand can enable users to choose and adjust the input location based on the *individual* preferences of a respective usage situation, including expected efficiency, reachability, comfort and social acceptance.

5.4 Conclusion of Research Questions

As a conclusion, current challenges for the interaction with smart eyewear were identified and investigated, as the *non-tangible* nature of the virtual screen image poses challenges for mobile interaction. In this thesis, three research questions in regard to these challenges were addressed:

RQ 1: How can interaction with smart eyewear be designed to be unobtrusive, so that users feel comfortable to interact in public?

It was found that near-body touch interaction can be designed that requires only very little hand movement by positioning the interface in close proximity to the resting position of the user's hand. An interactive belt (Pub. I) was implemented as a wearable interface to enable for a quick access situated out of immediate sight of potential bystanders. In a user study, it was found that for interaction in public, users felt comfortable interacting at the belt region above the trousers' front pockets, since this region was in immediate proximity to the hand and could be reached while resting the hand within the pocket. It was furthermore found that the perceived unobtrusiveness is not only related to the interaction's *positioning*, but also to its *duration*: The *shorter* the interaction, the more *unobtrusive* it was perceived, due to its resemblance to random hand movement. The utilization of the pocket location for touch input was furthermore explored with a second implemented system (Pub. II) that would allow to conceal the thumb's movement *within* the pocket.

RQ 2: How can interaction with smart eyewear be designed to enable for a high input expressiveness while the user is mobile?

It was shown that for *precise* hand movement, users can benefit from a stabilization of their interacting hand (Pub. III & IV). Furthermore, it was shown that by providing for hand stabilization, a wearable interface can be designed to enable for a high input expressiveness even in mobile situations (Pub. II): With PocketThumb, users could stabilize their hand by anchoring the thumb's joint into the pocket fold of their trouser's pocket, and by this, *precisely* select visual targets with a virtual cursor even while walking. This was shown to be significantly faster than with on-body touch interaction using traditional approaches. Additionally, the input expressiveness of this novel wearable interface was furthermore increased by enabling for *jointly* performed gestures with the remaining fingers of the same hand.

RQ 3: How can a wearable interface be designed to be worn at multiple locations?

It was shown that wearable interfaces could be designed to be worn or attached to multiple locations *on* and *off* the body (Pub. V). The SnapBand was presented as such a multi-location input device that can be quickly snapped onto various *active* locations, and also be *stored* in a curled configuration. It was found that the users' preference for usage locations varies depending on the context, so that a multi-location interface can provide users a choice depending on their *individual* preferences.

Chapter 6

Opportunities for Alternative User Feedback

Current interfaces present their output mostly as visual and auditory feedback, as sight and hearing dominate the human perception system and can perceive the highest information bandwidth [154, 59]. In this regard, *wearable* interfaces like smart eyewear and watches present their output mainly *visually*, by displaying the information within or nearby the user's field of view. Visual and auditory feedback however not always constitute as ideal output modalities. For mobile notifications, for example, audio feedback can be distracting to the user [20] as well as to bystanders, so that the audio capabilities of mobile devices are often disabled by their users [75]. Visual notifications are less disruptive, but are also less likely to be perceived immediately [66], so that alternative output modalities can provide useful characteristics.

By presenting information as vibro-tactile feedback for example, the user can remain their visual and audible attention in the environment. This can be useful when other concurrent tasks demand the user's attention. When exploring a new city for example, vibro-tactile feedback can be utilized for pedestrian navigation, so that the user can remain their visual attention on experiencing the city's surrounding (c.f. Pub. VI). Vibro-tactile feedback however is taking place in the temporal domain, so that it can be missed by an inattentive user, since the information is presented only temporarily. In contrast, the positioning of a wearable interface can serve as a continuous haptic feedback, so that by utilizing self-actuation, a wearable interface can alter its positioning on the user's body via movement. While the interface's movement can be perceived momentarily by the user, the taken position serves as a sustained haptic stimulus that can continuously convey the state of abstract information (c.f. Pub. VII). Finally, olfaction, i.e. the sense of smell, provides useful characteristics as an alternative information channel. The sense of smell is strongly linked to emotions and memories and an essential part of experiencing the environment. For a wearable interface, scents can be artificially generated and delivered to the user to enhance their personal experience, to convey abstract information, or to amplify personal notifications in mobile scenarios (c.f. Pub. VIII).

The opportunities for alternative user feedback that are addressed in this thesis are therefore (1) to enable for haptic feedback as an eyes-free near-body output modality for bearing-based pedestrian navigation, (2) to enable for positional feedback via self-actuation of a wearable interface as an furthermore *sustaining* haptic stimulus, and (3) to enable for scent-based feedback as an emotionally loaded information channel that can furthermore be used as an amplification for mobile notifications.

6.1 Haptic Feedback

The sense of touch is based on mechanoreceptors localized in the various layers of the human skin that can sense applied tactile stimuli such as brushing, stretching, vibration and pressure [165]. Since the sense of touch is mainly used as an active exploration of the environment, the word *haptic* is based on the idea of an active exploration of the shape and properties of surfaces and objects. In this regard, haptic perception was defined by Gibson as the sensibility of the individual to the world adjacent to their body, by making use of their body [57].

For computerized systems, haptic feedback is important in that it presents information of tactile properties during active user interaction with an interface, such as the shape, position and state of a physical button when pressing it with a finger. The haptic perception of a user can although not only be used for an active exploration, but also to passively receive feedback. For this use, haptic feedback is utilized in many mobile devices as a subtle means to notify the user, e.g. for incoming mobile notifications. In these devices, the vibro-tactile sensations generated by mechanical actuators can propagate through layers of fabrics to be sensed by the skin even when the emitting device, such as a phone, is worn in a pocket. When furthermore presenting haptic feedback nearer to the user's skin, as feasible with wearable interfaces, more expressive information can be provided. While vibro-tactile feedback for mobile devices is mostly presented to let the entire rigid device vibrate, multiple actuators can be embedded and spatially aligned into wearable objects or garments to render more *localized* vibro-tactile sensations [38].

Brewster et al. [22] described multiple properties in tactile actuation, namely: *frequency*, *amplitude*, *waveform*, *duration*, *rhythm*, and *body location* that can be utilized to encode varying information into the perceived tactile sensations. The mapping to a respective meaning, however, is most often *abstract* and must therefore be learned by the user. Choi et al. [38] argued that a high reliability for abstract information can be reached when the stimuli are optimized for the context of use. In this regard, vibro-tactile feedback as a modality is efficient when visual and audio information are unavailable, the user's sensory capacity is overloaded, redundant sensory cues are desired, or complementary signals are useful [38]. They found such use cases mainly for *communication*, e.g. to present a multitude of geometric shapes [105] for the visually impaired, for *mobile devices* to distinguish multiple notifications [118, 22, 196], for *vehicles* to haptically warn against hazardous driving situations [76], and for *navigation*, where the *location* of tactile stimuli can provide a natural cue for the user's orientation [54].

6.1.1 Vibro-tactile Feedback for Pedestrian Navigation

Pedestrians that navigate along city parts using traditional visual feedback on mobile devices can quickly loose the awareness about their surroundings, which can even cause accidents like bumping into other persons or objects [119]. Audio instructions can be provided instead, such as with wearable headphones, however by this, the capability to react to audio cues in the surrounding, e.g. by approaching vehicles, is partly impaired.

For this reason, much work has been done on providing *vibro-tactile* cues for pedestrian navigation by utilizing either *localized*, *pattern*-based, *rhythm* or *timing*-based haptic feedback approaches. By spatially aligning multiple actuators around the user's torso for example, ego-centric directional cues can be provided that are easy to understand and enable for hands- and eyes-free navigation [51, 72, 142]. Such *localized* feedback has also been shown to be efficient when integrated into a vibro-tactile belt [201, 54]. Another possibility to provide for navigational cues is by using different vibrational patterns with a *single* vibro-tactile actuator, e.g. for PocketNavigator [144], *duration* and *sequence* of two tactile pulses convey the direction of the next turn. Another similar possibility is to use different vibrational *rhythms* to convey left, right and stop signals [107], which has recently been adopted in commercial smart watches like the Apple Watch [8]. A radar-based metaphor for a single actuator was introduced with NaviRadar [167], where an imagined radar sweep rotates clockwise and vibro-tactile feedback is provided for each full radar sweep as well as when the sweep hits the direction of the next turn. By this, the direction is encoded into the *timing* between the two signals, whereas the turn distance can be provided by the tactile amplitude. This showed to be more effective for navigation than the pattern-based approach of PocketNavigator [144], however an ongoing tactile feedback for the radar sweep is required rather than the more subtle feedback of a single vibrational pattern before the next turn.

6.1.2 Bearing-based Pedestrian Navigation

Much like turn-by-turn based navigation for automotive vehicles, navigation for pedestrians has mostly been treated in the literature as an *optimized route* following the shortest or fastest path to a given target. This dictation of the route, however, can take away much of the exploratory nature of an individual and has an effect on their ability to form cognitive maps of their surrounding [28]. Robinson et al. [159] argued for *bearing*-based navigation that would instead allow users to make their own navigational choices by scanning the environment with a handheld device to receive vibro-tactile feedback when pointing towards the direction of the destination. By this, pedestrians could find their own way and explore new city parts, while still being able to verify their orientation. This bearing-based approach built up on Social Gravity [213], the idea of a *virtual tether* for people to find each other. As another approach, Pielot et al. [143] showed that vibro-tactile patterns, when emitted periodically, can be used for *bearing*-based navigation as well, so that no active pointing interaction for the orientation is required.

Bearing-based pedestrian navigation approaches so far have been limited to mobile phones, where users need to actively hold the device in their hand to either point into a direction [159] or to perceive a directional pattern [143]. To allow for a more passive and *unconstrained* interaction, a hands-free approach was thus investigated, where directional feedback is provided by a wearable interface that can be passively worn in everyday life (see Pub. VI). For this purpose, the wristband of a smartwatch was extended with four vibro-tactile actuators that would allow for *localized* directional cues around the user's wrist. In contrast to other body locations such as the user's torso, as utilized for navigation before (e.g. [72]), the wristband constitutes a more subtle form factor to be worn in everyday life. To further increase the perceived direction of the *localized* actuation, the respective angular offset was additionally encoded into the *duration* and *amplitude* of the vibro-tactile signal, which, as a feedback, would periodically reoccur (see Pub. VI).

In a user study with the implemented system, participants would navigate to a predefined target unknown to them and walk their own path as they like to. As a result, they would take on different routes (see Fig. 6.1). While most participants were walking along the shortest and quickest paths towards the target, a few, albeit, would stroll off a little bit before eventually turning towards the direction of the target. In all these cases, the participants reached the headed target without any further help or complications. Participants reported a low cognitive demand and were talking with the accompanying presenter during navigation, which further suggests that the navigational task was not very demanding and rather liberating for the user's attention. As a conclusion it was shown that vibro-tactile feedback around the wrist can effectively enable for bearing-based pedestrian navigation, where users can choose their own path to their own liking.

FIGURE 6.1: Investigation of bearing-based pedestrian navigation using vibro-tactile feedback on the wristband of a smartwatch. Pedestrians were allowed to choose their own route to an unknown target. While most took the shortest path, some went off for a small detour, but eventually turned towards the target. **Pub. VI)**.
Map data © 2015 GeoBasis-DE/BKG (© 2009), Google.

6.2 Positional Feedback

Most eyes-free feedback modalities, such as vibro-tactile feedback, present information only *momentarily*, so that they can be missed by an inattentive user. The rendered feedback, in theory, can be *repeatedly* provided, but for many use cases this is rather distracting and contradictory to the desired objective of a subtle means of user feedback.

In contrast, to provide for a *sustained* means of eyes-free feedback, in this thesis, the novel concept of *positional feedback* is presented, where the spatial on-body positioning of a self-actuated wearable interface can serve as a *continuous* means of haptic feedback (c.f. Pub. VII). By utilizing self-actuation, the interface can alter its own positioning via movement along a body part such as the user's forearm (see Fig. 6.2). While the actuated movement can be perceived momentarily, the *position* serves as a sustained haptic stimulus that can continuously convey the state of abstract low-bandwidth information, e.g. to gradually display progress, for pedestrian navigation to represent the distance to the next turn, for mobile notifications to provide a sense about the amount of unread message, or for time scheduling to convey an ongoing feeling about the time left until the next meeting. The sense about the respective state is available to the user in the background of their haptic perception, as, much like the feeling of a worn wristwatch, they can feel the weight and light pressure on the respective location on their skin.

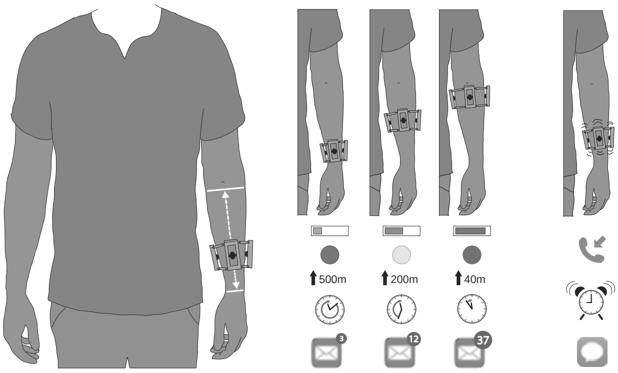

FIGURE 6.2: (Left) Positional feedback by a self-actuated wearable interface on the user's forearm. The device can move itself into a position along the forearm to gradually display abstract information, such as progress, urgency, distance for navigation, time left until an approaching meeting or the amount of unread notifications. (Right) The movement serves as *momentary* means of feedback, while the attained position provides for *sustained* haptic feedback. **Pub. VII)**.

6.2.1 Mechanoreception in the Human Skin

While vibro-tactile sensations only reach the rapidly adapting mechanoreceptors within the human skin, i.e. the Meissner's and Pacinian corpuscles [86] (see Fig. 6.3), the *continuous* haptic stimulus of a worn interface, via contact force and indented skin, reaches the slowly adapting receptors, i.e. the Merkel's disks and Ruffini endings. The afferents in the Merkel's disks are particularly suited to the representation of surface response and skin deformation with a high spatial resolution, while the afferents in the Ruffini endings are very responsive to stretching of the skin [86]. The latter has already been utilized for haptic skin-stretch displays that utilize the contact force of a small movable tactor dragging along the skin for directional haptic cues with a high accuracy [14, 82]. Since the affected mechanoreceptors are slowly acting, the tactile sensation does not need to rapidly vary for a response [15]. However, even though the resolution of skin stretch is higher than with a vibro-tactile sensation [15], the feedback response is only *momentary*.

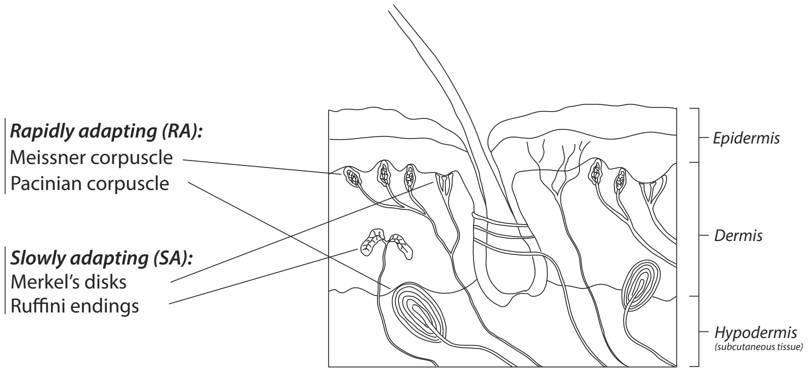

FIGURE 6.3: Mechanoreceptors in the human skin. Vibro-tactile sensations only reach the rapidly adapting affectors in the Meissner and Pacinian corpuscles, whereas *positional feedback* also utilizes the slowly adapting affectors for their responsiveness to touching surfaces.

6.2.2 Sustained Feedback

While for *momentarily* presented haptic feedback, many alternative output concepts have been presented in the literature, such as skin-stretching [14], -brushing [83], -poking [166], or -itching [146], the opportunities for *sustained* haptic stimuli have only sparsely been explored. One possibility has been found in *pressure*-based feedback, where artificially applied pressure on a body limb can work as a constant haptic feedback. This has been implemented via inflatable air chambers around the forearm [68], moving plates [37], or uniform pneumatic compression around the user's wrist [147]. For pneumatic compression, a strap around a body limb such as the wrist can inflate and thus tighten to provide for a sustaining pressure-based feedback in the background. The compression can ramp up from subtle to forceful by slowly inflating (or deflating) the device as an abstract means of progress or to slowly bring something to the user's attention [147]. As a downside, however, the applied stimulus has to become *stronger*, which can be perceived as increasingly less pleasant. Another possibility is to apply *thermal* feedback onto the skin using Peltier elements [214, 188], so that the user can locally feel a change in temperature as heat or cold as a feedback. Unfortunately, however, the thermal perception is more sensitive to the stimuli of a *changing* temperature, rather than the *absolute* temperature [214], which makes it less suitable for a sustained means of feedback.

In contrast to pressure- or thermal-based feedback, *positional* feedback does not require an increasing stimulus, but rather a distinguishable *localization* of the wearable interface on the body and the capability of the interface to actuate towards the respective location by itself (see Pub. VII). While position-based feedback as a sustained means of haptic feedback has not previously been investigated, the utilization of position and self-actuation of wearable interfaces has been proposed in the literature before. Roudaut et al. [164] for example presented a mobile device that could actuate and change its form for varying affordances, whereas Radziewsky et al. [151] introduced a scarf that could alter its shape to represent emotions and attitude to bystanders. Furthermore, Dementyev et al. built miniaturized on-body robots as wearable interfaces that could freely move along the user's clothing via magnetic wheels [45], or along the skin via two suction legs [44]. These served to potentially provide various functionalities for input, output and body sensing. Building on this, Kao et al. envisioned that body accessories, that for a long time have remained static and non-interactive, could in the future act as interactive *kinetic* wearables [90]. In this regard, the *positional* properties of a self-actuated wearable can be utilized as a novel means for sustained haptic feedback (c.f. Pub. VII).

6.2.3 Haptic Acuity

For positional feedback, the user's ability and accuracy in *localizing* the wearable interface on their body is most crucial. As a potentially eyes-free feedback modality, this localization is based on the haptic stimuli induced by the respective contacting surface of the worn interface and based thereon, the user's estimation of the respective positioning. Since the varying human's skin regions are differently innervated, the haptic acuity of various skin regions has been quantified in the literature. For this, multiple methods have been introduced. The *two-point discrimination threshold* for example measures the smallest distance where two concurrent tactile stimuli can be separated as such rather than being perceived as a single stimulus, while the *point* *localization threshold* measures the distance where users cannot distinguish anymore whether two successive stimuli were presented at the same location. Weinstein reported on both measurements for varying skin regions [209] and showed that the skin regions at the outer limbs such as the fingers provide for the lowest thresholds and thus the highest acuity. Such measurements are mostly taken with a caliper and are conveniently used for neurological examination, e.g. after nerve injury, but in this context are also widely criticized for their variability [111]. While such methods have shown to be useful to compare the haptic acuity of the receptors at different skin regions, they however do not inform about the capability of estimating the *position* of a haptic stimulus. So far, studies regarding the *localization* of haptic stimuli have been limited to setups with multiple vibro-tactile actuators placed on respective body parts (e.g. [39]), each with a distinct position.

Positional Feedback on the Forearm

To investigate the ability of users to *localize* positional feedback, a self-actuated wearable for the forearm was implemented, capable of moving up- and downwards into any position and otherwise keeping its respective positioning on the user's forearm (see Fig. 6.4).

FIGURE 6.4: Positional feedback on the user's forearm using a self-actuated wearable. **Pub. VII)**.

A user study was conducted, where participants would estimate the device's position, as well as the length of movement, each time after an automated self-actuated positioning. For this, the view onto the (left) forearm was concealed by a visual cover, while the respective participant could operate a mouse and computer screen with the remaining hand. For the estimation of the device's position, they were presented a pre-taken image of their empty forearm on which they would place an indication marker for the position. The device's position was tracked by a marker setup, and as a baseline, the *haptic* perception was compared to a *visual* condition, where participants were allowed to visually observe and estimate the device's positioning and movement.

As a result, users were able to blindly estimate the device's position on the forearm with an average deviation of 1.20 cm to the actual position and estimate the length of a movement with an average deviation of 1.44 cm to the actual movement. This measured accuracy in the users' estimations was higher than expected and only slightly lower as when visually confirming the estimation, where users were only 43% resp. 18% more accurate. The difference in accuracy was smaller than expected considering that vision is the primary human sense for assessing a position and movement in the environment. As a conclusion, position-based feedback relying on only the spatial haptic perception was shown to be feasible as a means of haptic feedback.

For further analysis, the forearm was divided into ten regions of equal size (see Fig. 6.5). Participants were more accurate in their estimations when the device was positioned at the outer regions, i.e. close to wrist and upper forearm. In contrast to the center of the forearm, wrist and elbow could serve as positional landmarks for the user, which could benefit their perception as points of reference when the device was close to either cue. The outer most forearm regions, i.e. lower wrist and elbow, were excluded from the study, since they would provide further distinct haptic cues

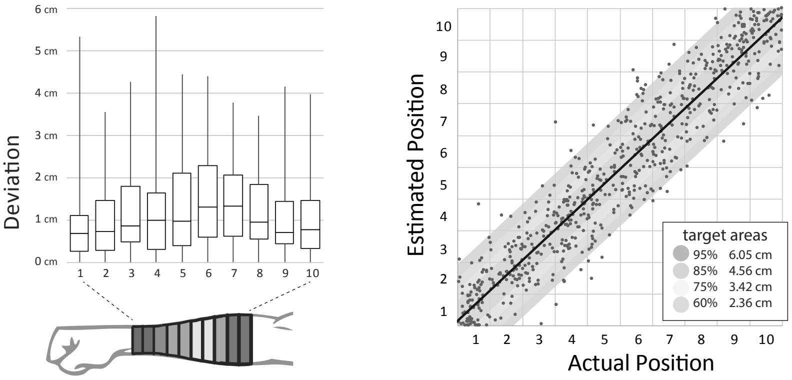

FIGURE 6.5: (Left) For the positional estimation, participants were most accurate at the outer forearm segments where wrist, resp. elbow, could serve as anatomical points of reference. (Right) 60% of the estimations fell within an area of 2.26 cm along the actual position, whereas an area of 6.05 cm along the device would cover 95% of all estimations. **Pub. VII)**.

on the hand or upper arm, that are absent on the remaining positions. Overall, 60% of estimations for the position fell within an area of 2.36 cm along the actual center of the device, while an area of 6.05 cm along the center covered 95% of all estimations. For an average forearm length of ~25 cm [60], this implies that only four distinct target positions could be placed along the forearm without an overlap to be reliably distinguishable by a potential user.

As a conclusion, positional feedback on the forearm is less suitable in conveying multiple *distinct* information, and more suitable in conveying the *state* of a single information where perceiving the exact quantity is less important than getting a close estimation about its extent. Such use cases for feedback can be found in gradually increasing (or decreasing) properties, such as a temporal or spatial distance, or in the approximate quantity of unread notifications. Positional feedback enables to continuously make the state of such information accessible to the user.

6.3 Scent-based Feedback

Unlike other human senses, like sight, hearing, and touch, that are widely addressed for computerized user feedback, the sense of smell is underrepresented in human-computer interaction [92]. Yet, olfaction, i.e. the sense of smell, is an essential information channel for individuals in daily life to form an experience of their environment. Olfactory stimuli are strongly linked to emotions and memories, and memories evoked by smells are more emotionally loaded and well preserved than when elicited through other perceptory senses [71]. For this, contextually *distinctive* odors are especially good retrieval cues [71].

Socioculturally, scents have been utilized throughout human history to support various distinctive experiences [40], e.g. the burning of incense for religious practices, the use of individual perfume to give oneself a personal scent, or the usage of essential oils in aromatherapy for personal well-being. Individual pleasant odors can enhance a person's mood [3], whereas a *reduced* odor perception comes with the risk for an imbalance of emotion processing [134] that can be linked to mental discomfort and disorders [172].

Nowadays, most cosmetic products contain fragrances, and for many markets, the smell of a product is considered an important part of the user's experience [31] that can drive respective buying decisions [186]. Likewise, smell can entail inherent *warning* cues about hazards, such as the smell of a burning fire, or the foulness of rotten goods [93]. Individual *perception* of smell can vary widely among different persons in how they perceive specific odors, as well as in their general olfactory acuity [94]. This can make it difficult to artificially design for designated olfactory experiences, which is particularly the case for linked *emotions* that are based upon the individual's previous experiences. Due to this, albeit, the perception of a particular odor can also be of very *personal* nature.

6.3.1 Olfaction

Olfaction is based on chemoreception, i.e. the binding of chemicals of aroma compounds onto the olfactory receptors in the human's nasal cavity [122]. In there, the odorant's molecules are solubilized by olfactory mucus. Detected chemical signals are transformed into electrical one's and sent across the ethmoid bone to the olfactory bulb, a neural structure of the forebrain responsible for spreading the olfactory information to various other parts of the brain for either conscious or emotional aspects of the respective perception [122]: *Associative learning* between the stimulating odor and the individual's behavioral response is taken place within the amygdala [89]. Hereby, varying odors can reinforce behavioral responses and are associated with pleasant (or unpleasant) emotions [141]. In the hippocampus, information is consolidated from short-term to long-term memory. In regard to smell, the hippocampus contributes to the formation of *episodic memory* where a past personal experience is associated with a corresponding odor. Exposure of the respective smell may then work as a retrieval cue to recall the episodic memory [161]. Beside *emotions* and *memories*, olfactory processing is also an important component in nutrition. In the orbitofrontal cortex, odor is associated with taste and activates the reward system of eating [162].

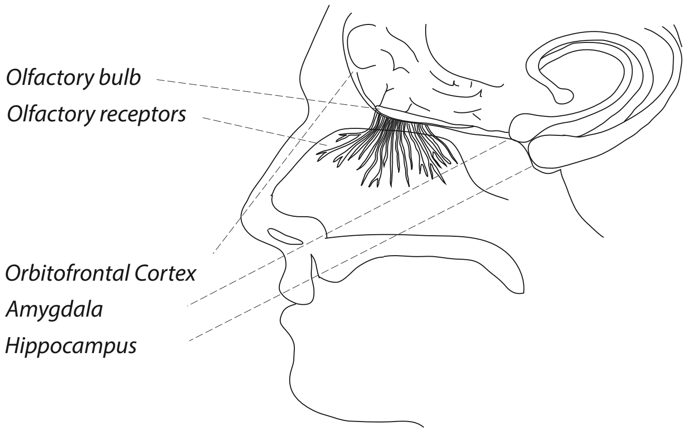

FIGURE 6.6: Chemicals of aroma compounds are bound onto olfactory receptors in the nasal cavity. Electrical signals are then sent to the olfactory bulb and spread to various other parts of the brain for conscious or emotional aspects of the olfactory perception.

6.3.2 Computer-generated Scents

For computer-generated scent output, Kaye explored the *symbolic* properties of smell and suggested that the peripheral qualities of scent make it suitable as an ambient and calm display for user feedback [92, 93]. He concluded that for a symbolic meaning, users are better able to find meaning in different *distinguishable* scents than in different intensity levels. Obrist et al. [139] collected smell experiences of participants via user stories and found that smell was strongly associated with memorable events of the participant's lives, with recalling specific times, places, and people through the stimulus of a present smell, with emotional and stimulating unique experiences, and with the desire for more of largely positive experiences. In light of this, the properties of olfaction are unique in providing an emotional and *personal* link to experiences.

Addressing this link *artificially* with scent-based feedback, however, remains a challenge, as the dimensions of smell are not as well understood as the dimensions of other modalities such as vision that can be structurally coded by color [92]. While human vision is based on only four kind of color receptors, about a thousand different olfactory receptors are involved for smell-based perception [202]. For this, no systematic classification scheme has yet been established [92], so that as of now, scents are mostly classified by association to their source, e.g. the aroma of brewed coffee. As a result, it is difficult to create *arbitrary* scents on demand and existing scent-generating systems only provide for a limited chosen scent selection. Herz et al. argued that individuals do not have a hedonic preference when experiencing novel smells, except for irritating smells inherently associated with toxicity [71, 139]. In this regard, for novel smells, the individual's responses are based on associative learning of the respective positive (or negative) experience. This makes it possible for interaction designers to either build upon *existing* associations or to create *new* associations for scent-based applications.

Scent-based Applications

Computer-generated scents have been utilized for a variety of applications to enhance the users' experiences. An early attempt to create a *multi-sensory* multimedia system was already made in the 70's with the Sensorama simulator [69], a machine that enhanced the cinematic viewing experience of a single user with additional modalities such as wind, motion, and smell. Later on in experiments, Nakamoto et al. [129] found that video scenes enhanced with smell output especially attract the user's attention, whereas Ghinea et al. [56] showed that smell output significantly adds to the users' multimedia experience by heightening the sense of reality. This has also been utilized for *interactive* scent-based applications, such as for smelling screen [125], where smell is distributed on a display screen by fans on the corners, so that a virtual odor source on the screen can spatially be located by a user leaning forward. Nakamoto et al. [130] built an interactive olfactory display for a virtual cooking game and with the MetaCookie+ system [133] it was shown that a perceived taste can be manipulated by overlaying visual and olfactory information.

Brewster et al. [23] utilized the *memory recalling* properties of olfaction for smell-based tagging and searching of a digital photo collection via relating odors. Participants, however, found it mentally demanding to manually tag photos via provided smell options and would have preferred to choose their own smells.

Scents can also be utilized as an alternative *notification* mechanism. Bodnar et al. [20] conducted a user study to compare the effect of visual, auditory and olfactory notifications on the user's engagement of a cognitive primary task. They found that olfaction is less effective in delivering the notification, but that olfactory notifications also provide the least disruptive effect on the user's task at hand. With SensaBubble [179], a multi-modal notification system was presented where bubbles where filled with scented fog related to the displayed notification. By this, users would first see the notification as a floating bubble with visual information projected onto it. Upon bursting of the bubble, a longer-lasting scented trace is left of the event, so that the notification is changing its sensory modality.

Kaye provided multiple examples how scents can be used to convey environmental and semantically related information [93]: For 'Dollars & Scents' he utilized ambient smell at a building's lobby to abstractly symbolize whether the stock market had gone up or down at the present day. For this, the symbolic meaning has first to be learned by a passersby to establish the respective association. With 'inStink', he explored how scents could be remotely reproduced, e.g. to already smell the partner's dinner cooking before heading home from work. He concluded, however, that it is very difficult to realistically recreate the exact smell so that potential users would be more likely to accept an abstract representation. With 'ScentReminder', he explored how semantically related scents can be utilized as a means of personal notification (e.g. by using the scent of baby powder to pick up the kids), and with 'Honey I'm Home', he provided a system that allows remote couples to automatically notify each other via a personal scent for their arrival at home. Additionally, the system would allow to manually trigger a scent-based connection. By this, the couple's presence awareness and feeling of connectedness could be supported via *personal* scents that build upon existing *positive* associations.

Scent Delivery

To release computerized scent for a respective user, scented air has first to be created from the stocked form of odor to then be delivered towards the user's nose. For this, scents can either be released via natural vaporization, via heating, or by atomization [221]. Natural vaporization describes the process of a natural release of high-volatile chemical particles into the ambient air as with conventional odor sources (e.g. the natural release of scent by flowers). However, as natural vaporization is an *ongoing* process for odor sources, its use for *temporary* scent delivery remains a challenge that needs to be controlled by preventing air exposure, e.g. by adding a mechanical sealing. The releasing process can also be supported by providing an additional accelerating airflow. Via heating of the odor material, the release of odor components can be furthermore increased. With some materials, however, this can lead to a denaturation of the composition due to the high temperature. Another method is to use atomization by a sprayer, diffuser or with ultrasonic waves, where a fine mist of scent is emitted. This however comes with the downside that the fine mist of atomized scent can adhere to surfaces and much like a sprayed perfume continues to naturally vaporize over time, hindering the design of *temporary* scent delivery as a means for user feedback.

Olfactory displays in the literature as well as in commercial products have mostly been *stationary*, which makes it a challenge to design for a *localized* rather than ambient scent delivery [207]. For this reason, Yanagida et al. [222] built a remote air cannon that was able to launch small toroidal vortexes of scented air towards a user's nose. Users, however, would feel the airflow of the vortex ring hitting their faces, so that as an improvement with SpotScents [128], they would utilize *two* air cannons to let two scented vortexes collide *in front* of users' faces.

As a more simple approach, the olfactory sources can be actively moved towards the user's nose, e.g. my mounting the olfactory displaying system onto the user's hand [126], wrist [34], or phone [200], or by using mobile graspable cubes containing different odor sources [23]. The user, however, has to *actively* initiate the delivery process by moving the odor sources towards their nose, preventing a *passive* means of user feedback.

Wearable Olfactory Display

With wearable interfaces, a *mobile* scent delivery for *passive* user feedback can be realized. For this, tube-based systems have been utilized to deliver scented air directly towards the users' noses [220, 132]. Such systems, however, have to be worn in front of the user's faces and are arguably too invasive for mobile everyday life contexts. A small wearable olfactory display that can be worn in public as a necklace was presented by Amores et al. [4]. The device was built to affect the user's mood and cognitive performance by releasing a *single* scent periodically throughout the user's day.

To investigate the use of *multiple* varying scents, in this thesis, a miniaturized wearable olfactory display was built that can be worn in mobile everyday situations and allows the user to passively receive personal scented notifications as a means of user feedback (see Pub. VIII). This has been utilized to investigate the use of scents as an amplification for mobile notifications in public.

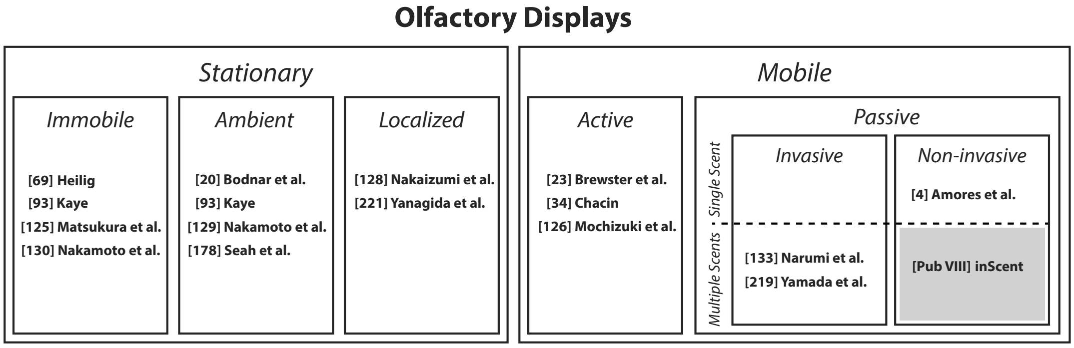

FIGURE 6.7: Olfactory displays in the literature (as well as in commercial products) have mostly been stationary. To investigate scent-based feedback for *mobile* situations, inScent was built as the first olfactory display to passively and non-invasively deliver multiple scents towards the user (see **Pub. VIII**).

Scents for Mobile Amplification of Notifications

FIGURE 6.8: (Left) *inScent* is a miniaturized wearable olfactory display that contains up to 8 cartridges with varying scents for mobile notifications. (Right) The device is worn on a necklace. For scent emission, scented air is blown towards the user's nose. (For this photo, the airflow was made visible by adding glycerol for smoke). **Pub. VIII)**.

Mobile notifications so far are mostly based on a *combination* of sound, vibrotactile, and visual feedback to address the users' multiple perceptory senses.

To investigate how *scent*-based feedback can contribute to mobile notifications as an olfactory information channel, a miniaturized wearable olfactory display was built that could display multiple varying scents in mobile situations to its wearer (see Fig. 6.8). The device would be worn as a pendant around the neck and contains up to 8 different scent aromas that can be inserted via small scent cartridges. For the release of scent-based feedback, scented liquid is vaporized, i.e. heated, within the respective cartridge to create scented air that is blown towards the user's nose to be perceived by the user.

A qualitative user study was conducted in which participants wore the *inScent* wearable in public. Participants would each walk along various frequented passages at the university and buy an item at the local cafeteria as public settings that include bystanders and social interaction. In the meantime, they received a scripted set of notifications on a provided phone that each was accompanied by a scent release on the wearable. Subsequently, semi-structured interviews were conducted with the participants about their experiences of scent-based feedback in the mobile situation. The interviews were audio recorded and transcribed into text files. Grounded theory with open coding [168] was then used to establish a common understanding of the users' perception.

Participants perceived the mobile scent-based feedback as *pleasant*, *non-disrupting* and as a *novel* experience. The olfactory sensation was seen as rather an impression that slowly emerges than an interrupt, and in contrast to other modalities for notifications, such as sound or vibration, perceiving scent-based feedback was in general seen as more pleasant and positively connoted.

For scent releases in public, however, participants were also worried about the smell perception of bystanders and whether they could be bothered by the sensation (as by a person wearing too much perfume). Due to this, a *subtle* and *unobtrusive* intensity for scent releases was seen as important to not invade the personal space of others. Furthermore, participants wanted to to able to be *in control* of when a scent can be emitted, as in certain situation a scent release can be inconvenient, such as when it would superimpose a pleasant smell, e.g. of a tasty meal. Ideally the wearable would be aware of its context and also allow the user to easily silence its scent-based capabilities.

The perception of scent-based feedback was seen as *less* reliable than other modalities, as it can be missed or misinterpreted depending on the mobile context. Due to this, important information shouldn't be solely conveyed by olfaction. Since scents, however, have a strong personal link to emotions, scent-based feedback was seen as *adding* emotional aspects to the moment of being notified. As a mentioned example

FIGURE 6.9: Scent-based feedback can add a *pleasant anticipation* to a notification. When receiving a message of her partner on the phone (a), she smells his scent (b) and in pleasant anticipation reaches for her phone (c) to read his message (d). **Pub. VIII)**.

of a participant, a scent-based notification can add a *pleasant anticipation*, where the user is thrilled when sensating the smell before reading the actual message (see Fig. 6.9). Participants also appreciated the *personal associations* of scents to the user and the possibility for individualization, which for the *inScent* prototype was enabled by exchangeable scent cartridges. Ideally, a wide variety of different scent options would be offered, so that users can choose their individual scent selection.

As a conclusion, scent-based feedback can add a *personal* and *emotional* association to notifications. It is inherently different from other feedback modalities, by being less reliable, but also less disruptive and more pleasant. Individual scents can entail a very personal meaning for the user and add a pleasant anticipation to the moment of being notified. By this, scent-based feedback can serve as an emotional amplification for mobile notifications.

6.4 Conclusion of Research Questions

In this thesis, alternative means of user feedback were investigated for mobile and social situations where users' may already be focused on visual or auditory tasks within their environment. In these situations, alternative output modalities can provide useful characteristics over prevailing visual and auditory means of user feedback. In this thesis, three research questions in regard to new opportunities were addressed:

RQ 1: How can haptic feedback be designed to allow for unconstrained pedestrian navigation?

It was shown that vibro-tactile feedback around the wrist can effectively enable for bearing-based pedestrian navigation, where users can choose their own path to their own liking. For this, the wristband of a smartwatch was extended with four vibrotactile actuators allowing for localized directional cues around the wrist (Pub. VI). This constitutes a subtle form factor that can be worn in everyday life and allows to passively and in a hands-free manner convey direction to the user.

RQ 2: How can haptic feedback be designed to allow for sustained rather than only momentary feedback, so that users can still perceive the information even when momentarily distracted?

The novel concept of *positional* feedback was presented, where the spatial on-body positioning of a self-actuated wearable interface can serve as a *continuous* means of haptic feedback (Pub. VII). To investigate this concept, the *Movelet*, a self-actuated wearable for the user's forearm was implemented, capable of moving up- and downwards, and subsequently keeping its adopted positioning on the forearm. By this, the actuated movement can be perceived *momentarily*, while the new positioning serves as a *sustained* haptic stimulus that remains perceivable by the user. It was found that with just their haptic perception, users are almost as accurate in estimating the wearable's positioning as when visually confirming by looking at the device. Positional feedback on the forearm as a novel means of user feedback affords for use cases where the state of a single *gradually increasing* or *decreasing information* is to be conveyed, such as a temporal or spatial distance, or the quantity of unread notifications.

RQ 3: How can scent-based feedback be utilized for mobile notifications?

With *inScent*, a miniaturized wearable olfactory display was implemented that can be worn as a pendant around the neck to *passively* amplify mobile notifications by individual scent-based feedback (Pub. VIII). For this, the device contains up to eight different scent aromas insertable via small scent cartridges. For mobile scent releases, scented aroma is briefly vaporized within a respective cartridge to create scented air that is then emitted towards the user. In a qualitative user study investigating the user's perception of scent-based feedback in public, it was found that scents can add an individual *personal* and *emotional* association to mobile notifications that can lead to a pleasant anticipation to the moment of being notified. By this, scent-based feedback can serve as an *emotional amplification* for mobile notifications. Scent-based feedback was appreciated as a *pleasant* means of user feedback, but similar to other means of near-body interaction its utilization in public needs to be *subtle* and *unobtrusive*.

Chapter 7

Conclusion

This thesis addressed challenges of interaction with current wearable interfaces, and also investigated opportunities for novel interaction techniques and devices. Important properties for these challenges and opportunities were analyzed and, in each case, novel near-body input or output devices were designed, implemented and evaluated to address the respective properties and to generate further understanding of the users' interaction.

For user input, this thesis focused on challenges of mobile interaction with smart-eyewear, as a wearable form factor that can readily display information directly within the user's field of view. Current challenges for interaction were identified and investigated, as the non-tangible nature of the virtual screen image makes it difficult to design for mobile user input, so that no interaction technique has been established as state-of-the-art yet. This thesis argued for near-body touch interaction, where the user's body can serve as an interaction delimiter that is quickly accessible. It was found that by positioning the touch input in close proximity to the resting position of the user's hand, only very little hand movement is required, so that users can feel comfortable to unobtrusively interact in public without drawing attention from bystanders (Pub. I). Building on this, it was shown that users also benefit from a stabilization of their interacting hand (Pub. III & IV), which enables for more precise hand movements and thus a higher input expressiveness in mobile situations (Pub. II). Furthermore, as an opportunity for a wearable input device, it was shown that a touch interface can be designed to be worn or attached to varying locations on and off the body (Pub. V), so that users can choose and vary the input location depending on the mobile context.

For output, new opportunities for alternative means of user feedback that go beyond the visual feedback of smart eyewear were identified and led to novel designs for wearable output devices. Depending on the mobile and social situation, users may already be focused on a highly visual or auditory task in the environment, so that in these situations, alternative modalities for user feedback can provide useful characteristics. It was shown that vibro-tactile feedback around the wrist can effectively enable for bearing-based pedestrian navigation, where users can remain their attention within the city's environment, while choosing their own path to their own liking (Pub. VI). The capabilities of haptic feedback were furthermore extended to the new concept of positional feedback, where the spatial on-body positioning of a self-actuated wearable interface can serve as a continuous means of haptic feedback (Pub. VII). Lastly, the concept of mobile scent-based feedback was explored (Pub.

VIII). It was found that scents can serve as an emotional amplification for mobile notifications by adding a personal and emotional association to the moment of being notified.

Overall, this thesis makes the argument that information access in mobile situations will become evermore important. In light of this context, near-body interaction enables for a quick access time with little demand for subtle and rich user input as important properties for mobile interaction. Furthermore, it enables for personal eyes-free feedback capabilities that provide useful characteristics in mobile situations.

7.1 Limitations

For each identified challenge and opportunity, in this thesis, novel near-body input or output devices were implemented and evaluated to address respective research questions and to investigate important properties. The design of each prototype, however, would focus on addressing *individual* challenges, so that not a *single* solution for near-body interaction was presented that would address and solve all presented challenges. In this regard, the presented new interfaces for input and output serve as an exploration of respective aspects of the users' interaction that are important towards the design of a final solution of near-body interaction. For wearable interfaces, miniaturization in size and weight plays a crucial role to not interfere in everyday life contexts. The custom-made hardware prototypes presented in this thesis, however, were mainly optimized to allow for specific user evaluations to find and understand individual characteristics, but otherwise had limitations partly in sizing, weight or power supply. Final solutions, would thus have to be more miniaturized to be usable in mobile everyday life contexts.

7.2 Future Work

In this thesis, the investigated properties of input and output were individually addressed with newly presented wearable interfaces. The investigated challenges and opportunities, albeit, can each be addressed in a variety of different ways, so that there is still the potential to explore different aspects in future work.

7.2.1 Input for Smart-eyewear

As for a solution for mobile interaction with smart-eyewear, with PocketThumb (Pub. II) it was shown that a wearable interface for indirect touch input can be designed to allow for *unobtrusive* input with a high *input expressiveness* by the provided hand stabilization of the trousers' pocket. The touch sensory that was tightly integrated into the trousers' fabrics, however, could in the future also be designed as a miniaturized clipable interface to allow for multiple on- and off-body locations as presented with Snapband (Pub. V), where the front pocket could then be *one* out of multiple suitable dispositions. For such a wearable interface mainly engineering challenges for the necessary miniaturization of the form factor remain. Another quickly reachable input location can be found within the user's hand (c.f. Chap.

5.3.1), so that by designing a miniaturized ring for user input, a quick access could be realized, albeit with the remaining challenge of a low input expressiveness due to the small surface area.

7.2.2 User Benefits vs Social Costs

For mobile interaction with smart-eyewear, it was argued that the benefit of using the device in public needs to outweigh the potential social costs (c.f. Chap 5.1). This thesis contributed to this, by investigating concepts of unobtrusive interaction to reduce the social costs of using smart-eyewear in public. A further aspect of future work is to also increase the user's benefits in these situations. As a first aspect, in this thesis it was shown that the input expressiveness can be increased (c.f. Chap 5.2). To fully exploit the capabilities of smart-eyewear, however, the wearable interface needs to further understand the user's mobile context to be capable of presenting context-relevant information within the user's field of view. This challenge is addressable by means of *computer vision* and *machine learning*, which, with current technology, is limited by the available mobile computation and power supply of the wearable form factor.

7.2.3 Social Interaction with Wearable Devices

Mobile interaction with wearable interfaces like smart-eyewear has social implications due to a lack of understanding of the user's actions by the social environment (c.f. Chap 5.1.2). This thesis argued for unobtrusive interaction that does not draw the attention of bystanders in public. Secretive interaction with a wearable interface, however, can likely be perceived as inappropriate in situations that are shaped by social interaction. In these situations, interaction with a wearable interface could still provide a benefit to the social interaction, but it needs to be investigated how *social signaling* can be facilitated to incorporate interaction with the device into the situation. In this regard, it needs to be investigated how the wearable interface can convey a *shared* rather than only personal experience to support the social interaction of multiple users.

7.2.4 Hearables as Audio-based Wearable Interfaces

Another promising form factor for a wearable interface can be found in the concept of *hearables*, as smart-*earwear*, providing for audio-based information access in mobile situations. In terms of social acceptance and miniaturization, smart-*earwear* could potentially foster user adoption earlier than smart-*eyewear* due to the less obtrusive positioning of the interface. For this, however, the control of a solely audio-based interface needs to be investigated. While visual systems can provide for the quick feedback loop of multiple perceivable information, the audible information of smart-earwear would need to come in sequence to be perceivable in that moment. In this regard, it will be important to find the right moment and extent of context-relevant audible information for varying mobile situations.

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Declaration of Authorship

Ich versichere hiermit, dass ich die Arbeit selbständig angefertigt habe und keine anderen als die angegebenen Quellen und Hilfsmittel bennutzt sowie die wörtlich oder inhaltlich übernommenen Stellen als solche kenntlich gemacht und die zur Zeit gültige Satzung der Universität Ulm zur Sicherung guter wissenschaftlicher Praxis beachtet habe (§ 8 Abs. 1 Nr. 5 Rahmenpromotionsordnung).

Ich bin damit einverstanden, dass die Dissertation auch zum Zweck der Überprüfung der Einhaltung allgemein geltender wissenschaftlicher Standards benutzt wird, insbesondere auch unter Verwendung elektronischer Datenverarbeitungsprogramme (§ 8 Abs. 1 Nr. 8 Rahmenpromotionsordnung).

Ulm, Deutschland, Juli 2019

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Belt: An Unobtrusive Touch Input Device for Head-worn Displays

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ABSTRACT

Belt is a novel unobtrusive input device for wearable displays that incorporates a touch surface encircling the user's hip. The wide input space is leveraged for a horizontal spatial mapping of quickly accessible information and applications. We discuss social implications and interaction capabilities for unobtrusive touch input and present our hardware implementation and a set of applications that benefit from the quick access time. In a qualitative user study with 14 participants we found out that for short interactions (2-4 seconds), most of the surface area is considered as appropriate input space, while for longer interactions (up to 10 seconds), the front areas above the trouser pockets are preferred.

Author Keywords

Wearable input; Unobtrusive; Touch; Spatial mapping.

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation (e.g. HCI): User Interfaces. - Input devices and strategies.

INTRODUCTION

Head-worn displays (such as Google Glass) allow for a quick access time to information and by that can serve to augment the user's memory [15]. Interaction with such a display, however, is yet a problem. Especially when it comes to user input, the challenges of interacting with a virtual screen image become apparent. The virtual image is neither tangible nor touchable, making direct interaction a difficult task. Pointing gestures in mid-air have strong social implications and can call unwanted attention upon the user. In addition, such gestures can suffer from arm fatigue [7]. Voice input allows for hands-free interaction, but has inherent limitations. It is obtrusive and in a shared focused environment, like a meeting or a lecture, it is prone to disturb other people. Another option is to use a handheld input device, such as the Twiddler [11]. This allows for rich interaction, but implies another device has to be carried along by the user. To prevent this, interfaces can be interwoven into clothing and worn at the body. By this, technology and fashion is combined into an electronic-textile interface. Besides being usable, such an interface has to bound within the user's fashion choice and perceived social comfort.

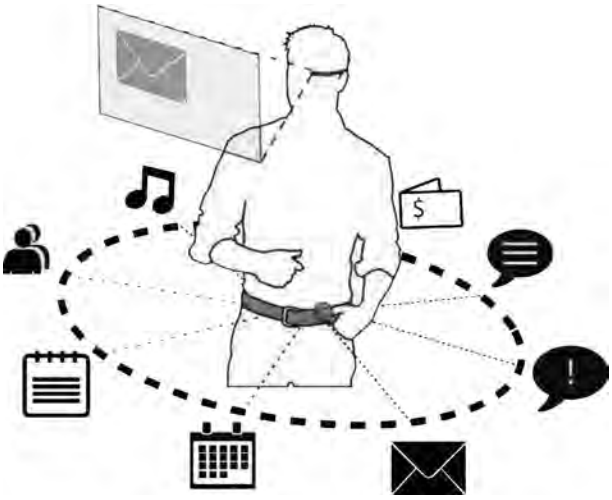

Figure 1. ***Belt*** **is a touch-enabled input device. Information and applications are quickly accessible on the large horizontal input space.**

In this work we present *Belt*, an e-textile input device that extends the surface of a common belt by touch sensing functionality. Belts have a long history as being worn for decorative reasons as a fashion accessory as well as practical reasons to support trousers. The inherent properties of a belt make it a useful tool for a body-worn interface. Being worn at the hip, a belt is close to the resting height of the human hands, enabling a quick access time to the surface area. The large horizontal surface area is reachable with both hands without interfering each other, allowing for bi-manual user input. The tight nature makes it suitable for touch input without having to clutch the interface. Depending on hand and pocket size, it can be reached comfortably with the thumbs while resting the hands within the trouser pockets, enabling unobtrusive input. A belt can be worn and combined with a diverse collection of garments, making it easier to blend the input interface within the user's style of clothing. By this, the e-textile interface has only to be interwoven into one accessory, rather than multiple garments, reducing potential expenses for the user.

The contributions of our paper are: (1) a novel unobtrusive on-body touch input device with immediate access, (2) information access leveraging users' spatial mapping around their hip and (3) a study investigating the user's perceived social acceptance of touch input on a belt in public.

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RELATED WORK

Surprisingly, the belt as a wearable input device has gained little attention within the literature. ActiveBelt [18] is a wearable interface that enables users to obtain directional information via vibrations around their hip. By this, the user's tactile sense is used to generate an unobtrusive information channel. Sumitomo et al. present a belt-like input interface worn around the abdomen to measure changes in its circumference as a concealed mean for user input [16].

Belt utilizes the large horizontal input space to enable a body-centric spatial mapping of information, in which the user can use the belt to place or open shortcuts to digital content (such as their contacts or a digital wallet). Spatial mappings for information, contents and virtual displays for wearable computers have been introduced in multiple works [3]. Chen et al. used a mobile device to navigate and manipulate digital content that is visually anchored around or onto the user's body [5]. In Virtual Shelves [10], the orientation of a mobile device in relation to its user is used to realize a user-centric shelve-metaphor, where information is stored around the user and is being retrieved by holding the mobile device in the associated direction. It was shown that users can use their spatial awareness and kinesthetic memory to select shortcuts in an eyes-free interface. In addition, the proprioceptive and tactile senses help in reaching parts of the user's own body with their hands blindly [6]. This allows for a quick access time for a belt-like interface.

Wagner et al introduced a body-centric design space for multi-surface interaction [19]. A belt as a touch-enabled input device has a fixed-to-the-body input space that involves two body parts, arm and torso, but only constrains the arm during interaction.

On-body interaction has mainly been researched for projection-based and eyes-free user input. In Pinstripe [9], pinching and rolling gestures on folds of smart garments are used for fine and coarse analog input control. Holleis et al. built capacitive touch buttons in diverse garments such as a helmet, phone bag, glove and an apron [8]. The hip and thigh area was mentioned by users most of where to potentially accept wearable touch controls. In PocketTouch [14], it was shown that capacitive touch input can work through diverse fabrics, so that users can operate a touch device located within their pocket. With Rekimoto's Gesturepad [13], a touch sensor module is attached to the inside of clothes to sense finger touches in conjunction with a transmitter worn at the wrist. Another eyes-free input device that doesn't rely on touch input is Nenya [1], a magnetically tracked finger ring that allows subtle twisting and sliding movements for 1-dimensional input. Social acceptance is increased by embodying the input device in a commonly worn item, in this case, a ring.

CONCEPT AND INTERACTION

In *Belt*, a common belt is envisaged that blends within the user's clothing but is additionally extended with input capabilities. We chose to base on touch interaction that is currently familiar within society, which is swiping and tapping interaction on mobile touch devices (e.g. smartphones, tablets and laptop touchpads). In contrast to such devices, the belt does not have to be taken out of pocket to be accessible and is quickly reachable with both hands. The input space is large by embedding touch functionality into the whole surface area encircling the user.

Spatial Mapping of Information

The large input space can be leveraged for a horizontal body-centric spatial mapping of information and applications.

Users retrieve a lot of information frequently on their personal mobile devices, such as messages, news feeds, time, voice calls and many more. The amount, a mobile device, such as a phone is taken out of one's pocket and being unlocked is reaching over 100 times on average on a daily basis [4]. Interaction can be enhanced by enabling a quicker access time to these informations. *Belt* allows placing virtual shortcuts and bookmarks to frequently requested information on the belt around the user. By this, the user can quickly reach for information with low effort to enable microinteractions that only last a few seconds [2]. As an example, a wallet application can be placed on the belt above the user's back pocket (a frequent place to store one's wallet). Reaching for and tapping this location will open the user's account balances in their wearable display. Likewise contacts and missed calls can be placed on the belt in proximity to the phones storing position in another pocket.

Even though the belt offers no visual cues for placed shortcuts, attention awareness and kinesthetic memory help the user in reaching the desired location. Users often develop habits, such as using their tactile senses to quickly check their trouser pockets whether they carry along their belongings (e.g. their wallet, phone and keys). In a similar way, the belt can quickly be checked for information by tapping desired locations or sliding along its surface. Additionally, it is possible to extend the awareness for application-related notifications by using spatial vibration cues such as in [18].

Unobtrusive Interaction

By embedding the input sensors in a conventional wearable item, an input device can be used in everyday situations in varying social contexts [13]. When not being in use, the device is potentially unnoticeable to bystanders and therefore doesn't have the social implications of an unusual looking electronic device. The unobtrusiveness of the device however is only one part of the interaction. To minimize social consequences, interaction should either visually communicate intent [12] (e.g. by interacting with conventional technology) or appear as if the user is not interacting with technology at all [17]. For this reason, *Belt* allows for user input that is designed to be as unobtrusive as possible. Users can subtly interact with the belt by performing small swipe and tap gestures on the sides, e.g. with the thumb while resting the hand in their pocket. Shortly fumbling on a belt or pocket to keep one's resting hand busy is socially acceptable and not obtrusive to bystanders. The input space is close to the resting level of the hands while standing, so that only small hand movements are required to reach for the belt, which by itself is no uncommon sight to bystanders. These movements, as well as the interaction, are not at eye level in a typical face-to-face conversation and can be performed without calling attention upon the user. This is important, because the perceived level of social acceptance affects in whether or not users are willing to perform the interaction in public [12].

Benefits and Limitations

Besides being quickly accessible, *Belt* allows to instantly interrupt the interaction. This immediately leaves both hands free, allowing users to shift their full attention to a different more important real world task at any time when required. This is an advantage compared to a handheld input device that needs to be put aside first.

Figure 2. Left: Subtle user input with the thumb. Right: Opening a digital wallet application. Shortcuts can be placed anywhere around the touch surface.

Due to the hip height of *Belt*, users can interact with the device while maintaining a relaxed body posture. The hand has to be raised only slightly from a dangling resting position to reach for the touch surface. Even when resting the hands within trouser pockets, users can comfortably reach for the belt with their thumbs, depending on shape and size of the pocket. As the body's center of gravity, the hip is relatively steady while walking. This supports touch gestures in mobile settings.

The spatial accessibility however has its limitations. Reaching for the back of *Belt* is less subtle and comfortable than reaching for the sides, because of the larger involved motion. Related work suggests that the forefront area and belt buckle are less appropriate for interaction because of their proximity to the users private parts [8]. Likewise, reaching for the back of the belt can be misleading. Interaction in these areas can communicate wrong social intents.

DEVICE IMPLEMENTATION

For the *Belt* prototype, a common leather belt was extended with small metal rivets (see Fig. 2). While this extension diminished the unobtrusiveness of the device, it allowed us to use the rivets' surface for touch sensing functionality. Each rivet is wired to one of 6 touch sensing units that are placed on the inner side of the leather belt (see Fig. 3) coated by woven fabric. Each unit is composed of an Arduino Pro Mini (ATmega328), a Bluetooth low energy module (BLEmini) and four MPR121 capacitive touch sensor controller boards. A small wearable battery is hidden behind the belt bucket, powering all of *Belt's* modules. By embedding all of these electronics into the device, *Belt* can be used in a mobile setting. Overall 288 rivets can be sensed independently as a touch point. Detected touch point locations are sent via Bluetooth to a connected phone, which distinguishes a simple touch gesture set composed of left, right, up and down swipes as well as a tapping gesture using blob detection. A Google Glass is connected via Bluetooth to the phone and serves as a wearable display.

We implemented five sample applications (music player, digital wallet, facebook, contacts and a reminder app) that benefit from the quick access time. These applications can be placed anywhere around the belt and opened by tapping the respective location. By swiping and tapping, the user can navigate within each application. These gestures are enabled anywhere on the belt, allowing to reach for the most comfortable input location.

USER STUDY

While we are planning on conducting larger user studies, in a first investigation we wanted to find out if the implemented features of *Belt*, the spatial mapping of information and the unobtrusive input are comfortable for potential users to use. We were especially interested in whether they feel that this kind of interaction is appropriate and to what extent they are willing to perform touch gestures on their belt in a public setting.

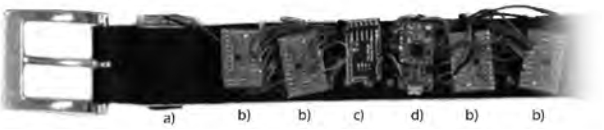


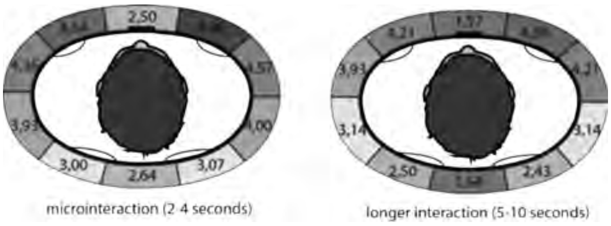
Figure 3. Inside *Belt* (without paling woven fabric): a) battery to power all modules and one of six touch sensing units each consisting of b) four touch sensor boards, c) Arduino and d) a Bluetooth low energy module.

We recruited 14 participants between 18 and 30 years (*m*=24; 7 female). All but one stated to retrieve information on their personal mobile devices very frequently. The study lasted about 45 minutes and was conducted in two consecutive settings: The initial part took place in a lab environment, where the participant used the worn *Belt* prototype and Google Glass to retrieve information using spatial aligned shortcuts and by navigating within the applications. Applications were aligned on the belt by the participant themself.

The second part of the study took place in the passage of a university cafeteria as a public setting that was heavily frequented throughout. For this second part we did not use the technical prototype but a common leather belt for interaction instead. This was chosen because we anticipate a touch-belt that does not expose itself as a technical input device. Using a common belt allowed us to study the appropriateness solely of the interaction gestures rather than the look of the device. For the same reason, Google Glass was not worn for this study part. We asked participants to repeat the very same tapping and swiping gestures on the common belt that they performed before and asked for their willingness to perform these gestures in public. This was done while participant and experimenter were standing and talking in front of an openly visible bar table directly within a heavily frequented passage.

Participants were motivited to think aloud during the study. In addition, participants provided feedback using structured-interviews with open-ended questions and 5-point Likert scales (from 1 – no agreement to 5 – strong agreement). Feedback was mostly positive. Participants saw the quick access time to applications as a benefit and strongly agreed that they would like to be able to interact with a device as unobtrusively as possible (*m*=4.71) and without calling attention upon themselves (*m*=4.64). There was also agreement that unobtrusive interaction is possible with a belt as a touch input device (*m*=4.28). While participants did not necessarily want to make bystanders aware of their interaction (*m*=2.28), there was a slight fear that other people might be confused upon noticing it (*m*=3.28). For the input at hip height, the touch interaction was seen as easy to use and quickly reachable with small hand movements. As a downside, the potential effects of complementary worn garments such as warm clothing were mentioned. Participants were wearing light clothing during the study due to warm weather, but with colder weather conditions, warm tops such as jackets or long pullovers could cover the belt, making it harder to access. Also other garments, such as skirts, are not typically combined with a belt. As an alternative, participants suggested the strap of a messenger bag or handbag as a location for touch input.

For the spatial mapping, participants were asked to place the five sample applications (music player, digital wallet, facebook, contacts and reminders) at any convenient location on the *Belt*



microinteraction (2-4 seconds) longer interaction (5-10 seconds)

Figure 4. Level of perceived social acceptance in which participants felt comfortable interacting in public on a 5-point Likert scale (from 1 – very uncomfortable to 5 – not uncomfortable at all)

prototype for retrieval. Three strategies for placing applications were frequent throughout all participants: (1) Placing the preferred applications quickly available on the front next to the pockets, (2) placing applications in close proximity to a relating physical object within a pocket (e.g. wallet, mp3-player, phone) and (3) grouping applications by mental links (e.g. social applications on one side and notifications on the other). Participants utilized the whole touch area with a slight preference to the side of the dominant hand.

The front area next to the trouser pockets was preferred for touch input in general, while the area next to the belt buckle as well as the very back were seen as least suitable. We asked for the user's perceived social acceptance in public on a 5-point Likert scale (from 1 – very uncomfortable to 5 – not uncomfortable at all), which highly depended on the length of interaction. For very short interactions, participants did not feel awkward or very uncomfortable interacting around the belt, since shortly fumbling at hip height was perceived as common sight. Yet, the front pocket areas were preferred (see Fig. 4). When it came to longer interaction for up to 10 seconds, the preference for the front pocket areas was more distinct. Other areas were perceived as less suitable, because of a less comfortable arm position and the fear of sending wrong social intents. This confirmed our design assumption to use the whole belt surface to quickly access information with just a single tap and to mainly use the front pocket areas for subtle swipe gestures within applications.

CONCLUSION AND FUTURE WORK

Belt is a touch input device for head-worn displays that does not expose itself as a technical device. It allows for quick access to information due to a spatial mapping on a large horizontal input space and for unobtrusive interaction supporting subtle swipe gestures while resting the hands in the pockets. In a user study it was shown that participants perceived this interaction as socially acceptable in public.

In the future we want to improve *Belt* with a higher touch resolution to enable swipe-based text entry. We also plan on implementing subtle rotation based touch gestures for quicker navigation and on conducting a user study regarding the perceived social acceptance of bystanders.

ACKNOWLEDGMENTS

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PocketThumb: a Wearable Dual-Sided Touch Interface for Cursor-based Control of Smart-Eyewear

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We present *PocketThumb*, a wearable touch interface for smart-eyewear that is embedded into the fabrics of the front trouser pocket. The interface is reachable from outside and inside of the pocket to allow for a combined dual-sided touch input. The user can control an absolute cursor with their thumb sliding along the fabric from the inside, while at the same time tapping or swiping with fingers from the outside to perform joint gestures. This allows for resting the hand in a comfortable and quickly accessible position, while performing interaction with a high expressiveness that is feasible in mobile scenarios. In a cursor-based target selection study, we found that our introduced dual-sided touch interaction is significantly faster in comparison to common single-sided *absolute* as well as *relative* touch interaction (~19%, resp. ~23% faster). The effect is largest in the mobile conditions *standing* and *walking* (up to ~31% faster).

CCS Concepts: • **Human-centered computing** → **Graphics input devices**; **Pointing devices**;

Additional Key Words and Phrases: Wearable input; dual-sided touch; smart-eyewear

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1 INTRODUCTION

Smart-eyewear allows for information access and retrieval that is potentially always available and quickly accessible when the device is worn. This is envisioned to serve as an augmentation to the user's memory [32] and to enable short bursts of interaction that minimize interruption from the task at hand [2]. With current technology such as Google Glass, however, interaction is yet a problem. Much like other wearable devices, input capabilities are negatively affected by the user's mobility, by sensing capabilities as well as by a limited input space at the device due to a desired miniaturization for wearability.

Smart-eyewear potentially allows for rendering a large virtual display into the user's field of view while maintaining a small form factor. The displayed virtual information, however, is neither tangible nor touchable, which makes direct touch interaction that would be familiar from mobile touch devices

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DOI: http://dx.doi.org/10.1145/3090055

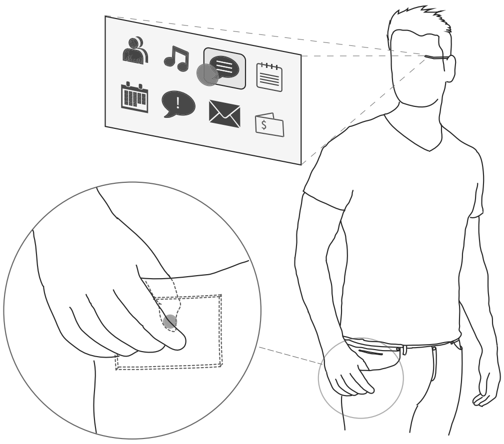

Fig. 1. *PocketThumb* is a dual-sided touch interface embedded into the fabric of the trouser's front pocket. The user controls an absolute cursor with the thumb by sliding along the touch surface from within the pocket (green dot) and can tap to select from outside.

difficult to achieve. Mid-air pointing gestures suffer from arm-fatigue [9] and may cause unwanted social implications, since the pointed virtual content is only visible to the user themselves. For this reason, current devices restrain to indirect interaction techniques, e.g. Google Glass uses two input methods, voice commands and touch input on the side of the eyewear. Both methods, however, are limited in many mobile scenarios. Voice input has the inherent limitation, that it can disturb other people in shared environments, such as lectures and meetings, while touch interaction at the eyewear near the user's temple is limited by the small surface space that only allows for horizontal one-dimensional swiping and thus has a very limited input expressiveness.

Moving touch input from the temple to a more accessible location could enable for richer wearable interaction. Some commercial eyewear products (Epson Moverio, Vuzix and Sony SmartEyeGlass) are shipped with a handheld touch controller as an input device. This however implies that an additional device has to be carried along and retrieved from the pocket for each short burst of interaction, which to some extent contradicts the vision of quick access and enabled microinteractions [2] in mobile contexts. To allow for quick access, the touch interface can instead be worn at the body as a textile interface. By this, the sensing capabilities are interwoven or embedded into clothing to combine fashion and technology [24].

Wearable interfaces allow to quickly interact while being mobile. However due to a lack of available input space and difficulties providing hand stablization in mobile conditions, most wearable touch interaction systems provide only very limited basic gestures, such as dimensional swiping, the detection of a general finger tap or individual fixed buttons. While this can be sufficient for very narrow use cases that do not rely on many different options, such as accepting or declining a phone call, or pausing music, it does not allow for complex interfaces with many options as familiar from other mobile devices that allow to directly point at icons using a finger or indirectly using a cursor.

In this paper, we show the applicability of cursor-based pointing and selection in wearable contexts. We propose to use a combined dual-sided touch interaction at the front pocket of the user's trousers. By sliding the thumb into the pocket, the hand is stabilized into position where a capacitive multi-touch sensor is embedded into the fabric (see Fig. 1). The thumb is always in contact with the interface through the fabric and serves as a pointer that is rendered into the virtual image of the wearable display. The cursor positioning is *absolute*, so that the whole display can be reached by sliding the thumb along the interface. Thus it doesn't need to be lifted from the interface during interaction, which enhances comfort and hand stabilization at the pocket. The other fingers can access the dual-sided touch sensor from outside the pocket to tap for selection and to furthermore perform swiping gestures while jointly pointing with the thumb. We show that this can be used to increase the input expressiveness of wearable touch interaction.

The contributions of our paper are: (1) the *PocketThumb* concept of dual-sided cursor-based pointing located at the pocket, (2) a target selection study highlighting the efficiency in mobile conditions and (3) the introduction of interaction techniques utilizing dual-sided touch for combined pointing and finger gestures.

2 RELATED WORK

2.1 On-Body Interaction Around the Pocket

The pocket and upper thigh area has already been of interest in the literature for wearable touch interaction. Thomas et al. [34] investigated the placement of a body-attached touchpad mouse for wearable displays in terms of body position and body posture and concluded the front of the thigh to be the most appropriate position when sitting, kneeling and standing. Holleis et al. [10] built capacitive touch buttons into various garments. People most often mentioned the thigh area for where to potentially accept wearable touch controls.

By contrast, Profita et al. [27] found the pocket to be less socially acceptable than other body locations due to its proximity to the user's private parts. Dobbelstein et al. [7] investigated the perceived social acceptance of touch interaction on a belt. Participants were most comfortable at the belt area above the front pockets, but least comfortable with the more anterior area located next to it near the belt buckle. This reconfirms that a certain distance to the trousers' fly is crucial to avoid socially sensitive sentiments. Thus, for *PocketThumb* we carefully chose to locate the touch sensor facing most sidewards at the pocket (see Fig. 2), which also made it closer to the resting position of the hand.

Pinstripe [15] is a textile interface that allows to pinch-and-roll a fold of garment between two fingers for continuous one-dimensional input. In a user study on rating potentially suitable areas, multiple participants suggested the trouser pocket as a new location to include, with placing the thumb inside the pocket and the fingers outside. This was unexpected, since this location was technically not a grabbed fold that can be sensed by the prototype implementation. The pocket was included for the evaluation and graded among one of the best locations to perform the pinch-and-roll gesture, especially when walking.

FabriTouch [8] is a flexible touch sensitive fabric integrated into the front thigh area of a pair of trousers. When placed onto clothing and the body however, the flexible touchpad had a significantly reduced input speed compared to a rigid support surface (i.e. a table), so that only basic gestures were feasible (i.e. horizontal and vertical swiping). For this reason for *PocketThumb*, we embedded the capacitive sensor into a thin rigid support casing (see Fig. 4).

Through-pocket techniques have been introduced to interact with a phone without having to take it out of the pocket for quicker access. Tap Input [29] and Whack Gestures [12] utilize the phone's accelerometer to detect taps (resp. whacks) from outside. Both however have only a very limited input vocabulary. Saponas et al. [30] showed that capacitive sensing through fabric is feasible. They re-calibrated a capacitive sensing grid to enable touch interaction through pockets and investigated signal strength for various fabric materials. It was shown that stroke-based gestures could be performed from outside with most fabrics. We built on top of this finding, by embedding a thin capacitive layer in-between trouser and pocket fabric to allow for sensing not only from the outside but also from the inside of the pocket for combined dual-sided interaction.

2.2 Wearable Interaction and Input Expressiveness

So far no wearable interaction technique could be established as *the* state-of-the-art for smart-eyewear, nor for wearable devices in general. It is a huge challenge to design an always available wearable interface that yet allows for rich interaction.

Many interfaces reach for being subtle, e.g. Nenya [1] is a magnetically tracked finger ring that can be turned and by that allows for one-dimensional input, and Nailo [14] is a nail-mounted miniaturized touch sensor that can sense directional swiping of another finger tip ontop of the nail. Fingerpad [5] enables subtle and private pinching gestures of thumb and indexfinger, but requires to mount a magnet and hall sensor ontop the finger nails.

Finger gestures and hand postures can be tracked by a wrist-worn camera [16] or electromyography (EMG) [31]. This, however, is limited to detect a set of distinguishable gestures to avoid false triggering by accident. Seamless interaction is one of the goals of wearable computing [35], however lack of seam can also cause problems of distinguishing planned interaction from natural occuring interaction such as random hand movements, e.g. rich interaction has been proposed for finger gestures [5][17] but a delimiter remains unclear.

An appropriate seam could be to place the input onto the body. iSkin [36] is a flexible silicon-based touch sensor that can be worn on the skin as a tattoo-like visual design, while SkinTrack [39] enables touch tracking directly on the skin by using a continuous high frequency AC signal and a sensing wristband. Holz et al. [11] go one step further by proposing to implant an interface underneath the skin. Google ATAP's Project Jacquard [26] aims to make textile interfaces available to commercial manufactures by optimizing a novel conductive yarn for existing textile weaving technologies. As a first collaboration, a commuter bike jacket by Levi's was announced[1] allowing for simple gestures like tapping and swiping on the sleeve to adjust music volume or to silence a call.

One common characteristic among most wearable touch interaction techniques is the limitation to basic gestures. This fits the vision of microinteractions [2], i.e. of very short interaction lasting only a few seconds, but it remains unclear how basic gestures can be used to create rich interaction that is beyond very simple and restrained use cases, like a music player, to utilize the full potential of smart-eyewear. Hand stabilization during mobile scenarios dictate the wearable interaction to be fairly restricted, so that only simple tasks and applications are feasible. A notable exception is the Twiddler [2], a handheld controller that is strapped into the user's palm to offer a joystick and a chording keyboard for rich pointing and typing interaction. The device is used by experts [18], but has a high learning curve for novices [19].

The main goal of this work is to enable wearable touch input with a high input expressiveness for rich interaction by presenting a cursor-based selection technique that is feasible in mobile scenarios (e.g. when walking). Furthermore, we investigate joint gestures that can be performed while pointing at a target utilizing the dual-sided touch sensor.

2.3 Dual-Sided Interaction

Using the front and backside of a device for combined touch interaction has first been introduced with HybridTouch [33], where a user, operating a PDA with a stylus, could simultaneously scroll with a finger on the rear. Wigdor et al. [37] introduced the concept of *pseudo-transparency*, where the occluded fingers

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[1] Project Jacquard. https://atap.google.com/jacquard/

[2] Twiddler 3. http://twiddler.tekgear.com

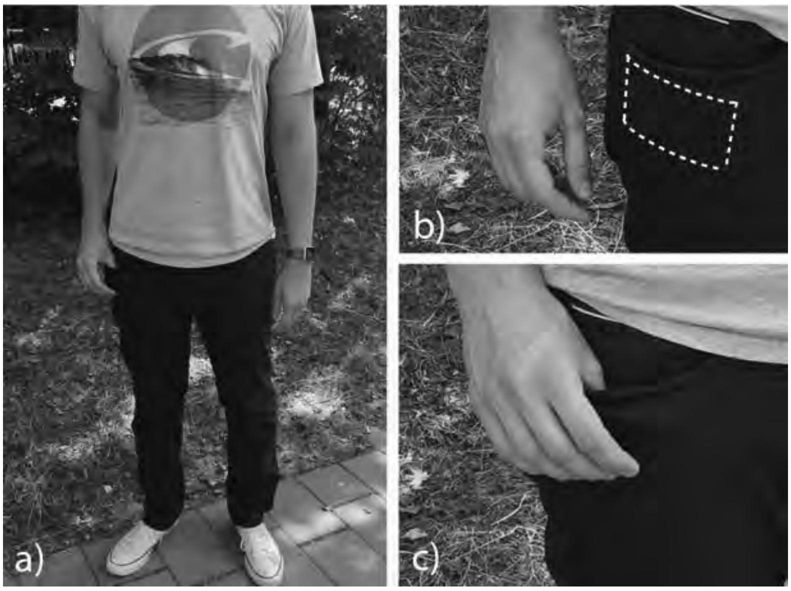

Fig. 2. The *PocketThumb* touch interface is embedded into the fabric of a trouser's pocket (a). The interface (highlighted in white) is in close distance to the resting position of the hand (b). By sliding the thumb into the pocket, the user can start to interact (c).

on the backside are getting visualized onto the display. By this, all fingers could be used for interaction while holding a device for combined multi-touch. Baudisch et al. [3] showed that using the backside for interaction enables touch interaction on very small devices, since positioning the finger on the back doesn't occlude the displayed content.

Wolf et al. [38] investigated thumb-based pointing towards fingers on the rear of a grasped handheld device. Users only see their thumb on the front, but can use it as a proprioceptive reference for the other fingers on the backside. They call this *pinch-through*, since users can target their fingers with their thumb. Similarly, Corsten et al. [6] use haptic landmarks on the back of a phone for proprioceptive pinching used for absolute indirect touch. By this, the user doesn't have to look on the phone and can instead focus on another larger display during screen mirroring.

For handheld devices, dual-sided interaction was introduced to avoid the fat finger problem [3] or to enhance the interaction expressiveness by allowing multiple fingers to jointly interact while holding the device [37]. In the wearable context of *PocketThumb*, the body-worn touch interface doesn't have to be actively held on during interaction, leaving a high degree of freedom for finger movements. Albeit, the positioning of the interface at the pocket allows the user to willingly grasp it to enhance the hand stabilization when being mobile.

3 POCKETTHUMB CONCEPT

We introduce *PocketThumb*, a wearable dual-sided touch interface for smart-eyewear that is embedded into the fabrics of the front trouser pocket. The user can access both sides of the interface by sliding the thumb into the pocket. Inside the pocket, the thumb is then leaning against the fabric which is embedding a capacitive touch sensor (see Fig. 3). The surface area of the thumb is tracked and its tip used as an indirect cursor for selection of targets in a wearable display. By sliding the thumb to the right, to the left, or deeper into the pocket, the whole touch surface can be reached for an absolute 2D-mapping. Unlike a traditional indirect touchpad (e.g. in a laptop), the pointing finger (i.e. the thumb), is not also used for tapping to select a target. Thus it doesn't need to be lifted and by leaning against the interface from inside the pocket can increase the hand stabilization. Instead, the fingers on the outside can tap to perform a selection. This resembles a *pinch-through* gesture (see Fig. 3), where the thumb is used as a proprioceptive point of reference for the other fingers allowing to pinch the thumb blindly [38].

3.1 Access time

Ashbrook [2] highlighted the importance of wearable systems to be quickly accessible to enable an efficient ratio of access and usage time. The *PocketThumb* interface is very quick to access due to its immediate proximity to the resting position of the human hand (see Fig. 2b). Only very little motion is required to blindly slide the thumb into the pocket. Users can as quickly interrupt or abandon the interaction when it is required to return to another task at hand [17].

3.2 Hand stabilization

The saddle joint of the thumb has a higher level of movement-dependent degrees of freedom than any the other finger of the human hand [38]. When interacting with physical objects it stabilizes the grip of the hand [23]. For *PocketThumb*, the thumb can stabilize the hand by anchoring its joint to the pocket. The thumb itself is furthermore stabilized by the fit and tension of the encompassing pocket fabrics. In mobile scenarios, this stabilization can help to increase the input efficiency.

3.3 Social Acceptance

By embedding input sensory into a conventional wearable item such as clothing, interaction can be unobtrusive, which is essentual to use the device in everyday situations [28]. It is a common sight to rest one's hand at the pocket or to unconsciously keep one's hand busy so that we believe that the small movement required to access the pocket for *PocketThumb* can be performed subtly and without calling attention upon the user. The interface itself is concealed in the fabric and potentially unnoticeable to bystanders and by that does not expose itself as a technical input device. Although, it is possible to highlight the interface by adding stitchings or fabric color to communicate its presence.

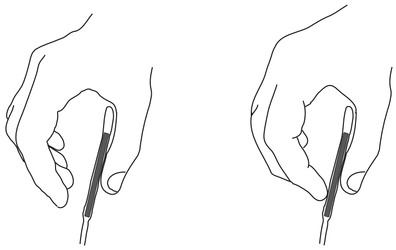

Fig. 3. The thumb is leaning against the rigid touch interface (gray) from within the pocket and serves as a cursor. By tapping with the index finger from the other side, the user can perform a selection.

Dobbelstein et al. [7] showed that for an on-body interface, the willingness of users to interact in public is depending on the interaction length. People feel comfortable interacting for a few seconds, as long as the interaction looks like a random movement, but feel less comfortable when the interaction time is longer. Social acceptance is also a function of time and cultural perception [21]. Wearable devices like headphones and even mechanical wrist watches a century ago only gained social acceptance upon continued exposure, when function and placement proved to be useful [27].

3.4 Interaction seam

Chalmers et al. [4] discussed the notion of *seamlessness* and *seamfulness* in wearable computing, where seamless integration and interaction is seen as a design requirement to focus on the task rather than the device, but can also take away some of its characteristics. For *PocketThumb*, we embrace *seamlessness* when it comes to immediate access to the interface, but take advantage of *seam* to avoid accidental triggering of input. The user might accidentally touch the interface and by that render a cursor, but does not trigger a selection until performing a *pinch-through* gesture from both sides.

We also allow for a *seamless* transition from subtle small gestures to richer interaction with a higher expressiveness when the circumstances allow for it, i.e. combined pointing and gesture interaction utilizing the dual-sidedness of the interface.

4 IMPLEMENTATION

For our *PocketThumb* prototype, we disassembled a Microsoft Touch Mouse and reused its capacitive touch layer as well as inbuilt processing chip and Bluetooth capability. Microsoft provides a sensor API [3] with a 15x13 touch sensing resolution with each pixel providing a measured capacitive intensity between 0 and 255 allowing to interpolate touch positions. We carefully detached the capacitive layer that is glued to the plastic casing beneath the mouse's surface and cut it into shape to match the 16:9 aspect ratio of a Google Glass, leaving a touch resolution of 15x8 pixels.

4.1 Rigid body and integration

The capacitive layer was embedded into a thin 3d-printed casing (82x59x4mm). The sensor response of capacitive sensing relies on a relative change in permittivity [22]. A rigid body encasing the sensor is required to attribute this change to a touch of a capacitive material (i.e. the finger), rather than flexible movement of the capacitive layer. This is unlike resistive touch sensing that allows for flexible touch sensors (e.g. [8][25]), but requires pressure of the finger during touch. The rigidity of the interface allows to feel its dimensions as tactile feedback and serves as a support surface during interaction.

The casing is slightly curved to match the curvature of the thigh and by its dimension taking up only a small portion of the pocket surface to minimize bulging (approx. the width of a common smartphone, but a smaller height and thickness). The interface was embedded between trouser and pocket fabric of a common pair of trousers (see Fig. 4). It was sewn to both fabrics along the rim to create surface tension and to avoid folds that could have created resistance when sliding along a finger.

The processing chip is loosely stored inside the pocket, as well as three small alkaline button cell batteries (LR44) to power the device.

4.2 Dual-Sided Touch on a Single Capacitive Layer

PocketThumb is the first dual-sided touch interface utilizing a single capacitive touch layer for sensing on both sides. The capacitiy intensity of finger touches is similar on both sides. Thus, the sensing grid

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[3] Microsoft Touch Mouse Sensor API
https://www.microsoft.com/en-us/download/details.aspx?id=52502

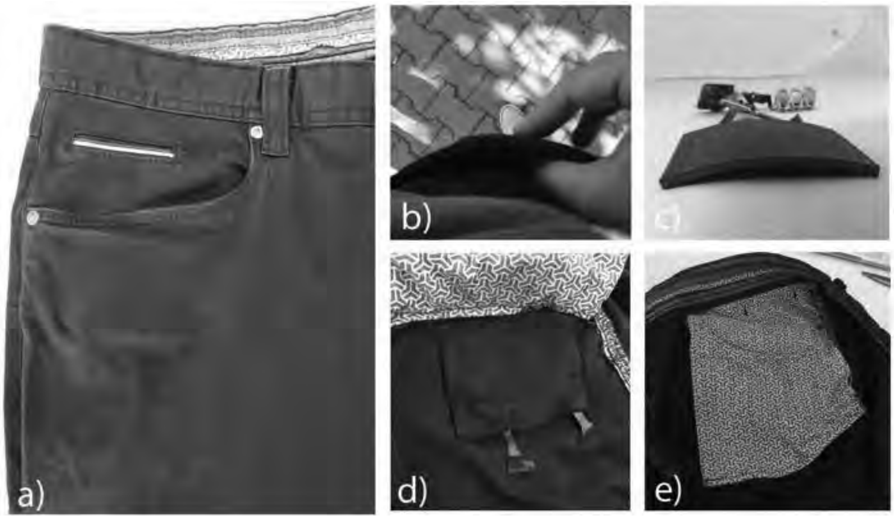

Fig. 4. Integration of the *PocketThumb* interface into a common pair of trousers (a). The interface is slightly curved to match the curvature of the thigh (b). The capacitive layer was embedded into a thin (4mm) rigid body (c) and sewn between trouser (d) and pocket fabric (e).

cannot distinguish and assign its measured signal to a respective side which generates ambiguity. However, its measured intensity is *additive*, so that a *pinch-through* gesture has a high intensity that cannot be reached by only touching from one side (see Fig. 5). By this, no separating and shielding layer is required, enabling the interface to be thinner.

When slid into the pocket, the thumb's surface is in contact with the touch interface, rendering a large blob into the sensor image. We use a weighted average of the bottom of the blob as the cursor position representing the tip of the thumb. As long as in pocket, the thumb remains leaning against the interface even during movement, so that it's *absolute* position is always rendered as an *absolute* cursor into the display. This way, the thumb does not need to be lifted from the interface (as required by *relative* touch interfaces) and can remain leaning against the fabric, which enhances hand stabilization.

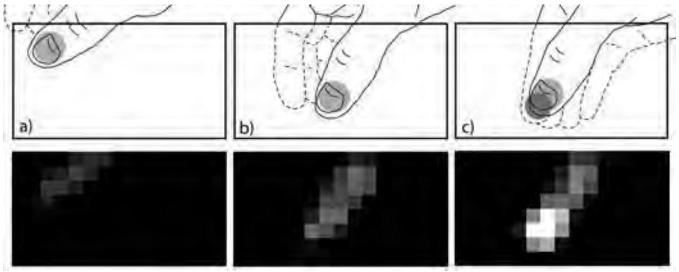

Fig. 5. The thumb is sliding along the interface and by that moving the cursor at its tip (a&b). As soon as the index finger touches the interface, the *pinch* generates a higher capacitive intensity and can thus be detected (c).

The thumb is distinguishable from finger touches by blob size due to the larger surface area in contact. Upon *pinching*, we use the cursor position before the event to prevent cursor shifting during selection. Begin and end of a *pinch* are detected by a rapid surge, resp. fall, in the overall blob intensity of the thumb, as well as the blob's peak (pixel with highest intensity) exceeding a threshold (see Fig. 5).

The processing chip automatically calibrates the sensor's capacitive intensity when turning on, but we also added a software calibration step to normalize the measured intensity along the pocket fabric.

5 TARGET SELECTION STUDY

We conducted a user study to investigate cursor-based target selection with our proposed dual-sided *PocketThumb* interaction. We furthermore were interested in the potential and efficiency of this interaction in mobile conditions. As a baseline, we compare our approach to single-sided *absolute* as well as *relative* touch interaction using the index finger, as familiar from current touch devices: *absolute* touch is known from direct touch interaction with mobile devices, while *relative* touch is frequently used for indirect cursor-based control in touchpads (e.g. in laptop computers). In the context of wearable touch interaction, we compare these techniques positioned at the pocket location for the thigh being the on-body location with the highest touch efficiency [34]. Due to hand stabilization, we expected dual-sided touch interaction to be significantly faster for selecting targets.

The study was conducted as a repeated measures factorial design with two independent variables. As independent variables we chose *interaction technique* (*absolute, relative,* and *dual-sided*) and *mobility* (*standing, walking,* and *sitting*).

5.1 Interaction technique

We implemented the introduced *dual-sided PocketThumb* interaction with the addition that participants could tap anywhere with their index finger to commit a selection. This allowed us to analyze whether participant would follow the mental model of pinching their thumb. For *absolute* as well as *relative* touch interaction, a finger tap (also anywhere on the interface) committed a selection as familiar from existing technology. For all three techniques, the cursor position *before* the finger tap was used for selection, while the selection was committed with the *end* of the tap. All technique were implemented using the same control-display ratio, so that moving a finger from the left to the right edge of the interface resembled the distance of cursor movement from the left to the right edge of the display.

5.2 Mobility

We used three conditions for mobility. For *walking*, participants would walk along a 1.20m wide and 8m long path cornered by tables in an empty seminar room. The path included three side turns and participants would reverse at each end to face an equal amount of left and right turns. We allowed participants to find their own pace where they felt comfortable to move and interact at the same time. For the conditions *sitting* and *standing*, participants were sitting on a chair, respectively standing in the room.

This resulted in 9 combinations (3 *interaction techniques* x 3 *mobilities*) which were presented using a 9x9 latin square for counterbalancing. The dependent variables were *selection time* and *error rate.*

5.3 Target selection

As the wearable display, we used a Google Glass with a display resolution of 640x360px. 8 circular targets were arranged in a 4x2 grid across the display, 160px apart along each axis. Targets had a diameter of 90px and the cursor 80px, respectively, to resemble the size of a finger tip (see Fig. 6). The center of the

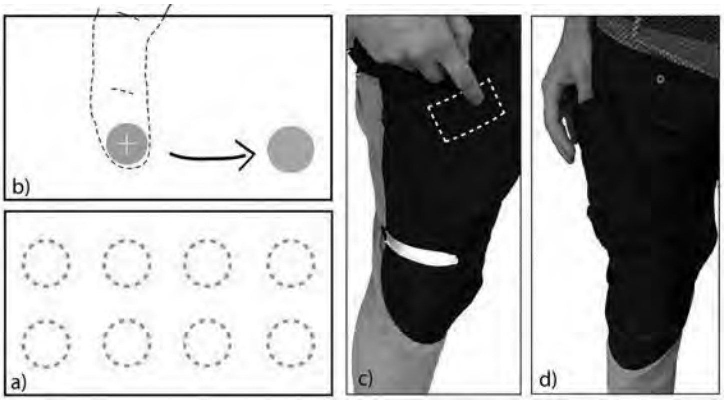

Fig. 6. Target locations were aligned in a 4x2 grid (a). Each target selection consisted of a start and target location along this grid (b). We built a second prototype for the user study that could be strapped ontop of regular trousers. c): Side-view of using the index finger as with *absolute* and *relative* touch interaction. d): Front-view of *dual-sided* touch interaction using the thumb for pointing.

cursor featured a haircross for an actual cursor size of 1px. When positioned over a target, the target was visually highlighted.

For each condition, participants selected at least 56 (8x7) targets, with each target location as the *start* and *destination* of a trial combination. Targets were selected successively after another in random order uniformly distributed with each target selection being automatically the start location of the next trial. We refrained from using a circular arrangement of successive targets (as defined in the ISO9241-9 standard [13]) to make use of the full 16:9 aspect ratio of display and touch interface. If a participant failed to successfully select a target the trial combination was repeated at a later point in time. An intermediate trial was inserted to set the cursor back to a valid start location for the subsequent trial. Intermediate trials were exempt from analysis to maintain a uniform distribution. Each condition was preceded by a random training set of 20 targets for the user to get familiar with the respective *interaction technique* and *mobility*.

5.4 Prototype

We built a second prototype for the study due to hygienic reasons and because of different clothing sizes of participants. An artificial trouser pocket was sewn onto a pair of rainlegs[4] (see Fig. 6). This way, the prototype could be tightly strapped ontop of the participants' worn trousers.

5.5 Participants

We randomly recruited 18 participants (11 male, 7 female) from our institution with an average age of 27 (range: 22 to 36). All but one had an academic background being either students or had studied at the university. All were right handed and used their dominant hand for interaction. Nine of the participants had never used a head-worn display before and only two stated having experience due to previous studies on the subject of wearable interaction. The study took 45 minutes on average and each participant received €10 as compensation.

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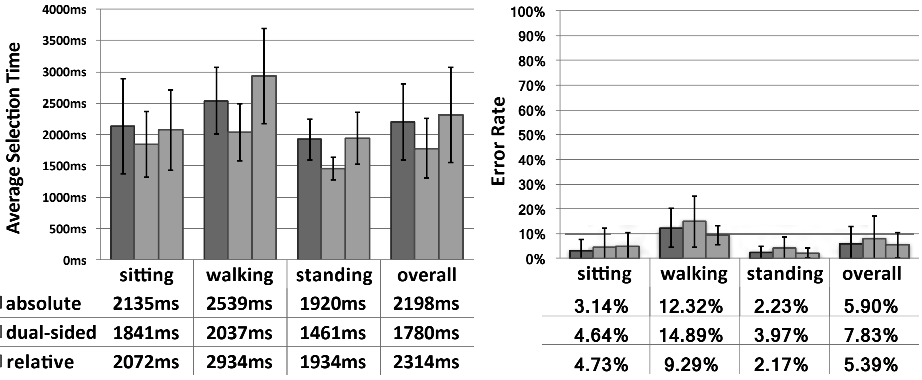
[4] Rainlegs. http://www.rainlegs.com/en/home



	sitting	walking	standing	overall
absolute	2135ms	2539ms	1920ms	2198ms
dual-sided	1841ms	2037ms	1461ms	1780ms
relative	2072ms	2934ms	1934ms	2314ms

sitting	walking	standing	overall
3.14%	12.32%	2.23%	5.90%
4.64%	14.89%	3.97%	7.83%
4.73%	9.29%	2.17%	5.39%

Fig. 7. Average selection time and error rate for the different variables. (+/- standard deviation of the mean). *Dual-sided* interaction was significantly faster than *absolute* and *relative* touch interaction.

5.6 Results

Our analysis is based on 18 participants selecting targets on 8 locations each from 7 different start locations using 3 different interaction techniques under 3 different mobilities resulting in over 9072 selections.

5.6.1 Selection time. For the selection time, a 3x3 (*interaction technique* x *mobility*) repeated measures ANOVA showed significant main effects for *interaction technique* ($F(2,34)=32.200$, $p<.001$) as well as for *mobility* ($F(2,34)=19.212$, $p<.001$). Pairwise comparisons revealed that users were significantly faster using *dual-sided* touch interaction (M=1780ms, SD=470ms) than using *absolute* (M=2198ms, SD=609ms) and *relative* touch (M=2314ms, SD=755ms) for selecting targets (p<.001 for both pairwise comparisons; Bonferroni corrected). As expected, users selected targets significantly slower when *walking* (M=2503ms, SD=627ms) than when *standing* (M=1772ms, SD=383ms) and *sitting* (M=2016ms, SD=647ms) (p<.001 for both pairwise comparisons; Bonferroni corrected).

Under all conditions, users were fastest using our proposed *dual-sided* touch interaction (see Fig. 7). Interestingly this effect became largest when walking, where it was 24%, resp. 31%, faster than *absolute* and *relative* touch interaction, while in the *sitting* condition it was only 14%, resp. 11%, faster. For *absolute* and *relative* touch users would lift their pointing finger for tapping. This way, the finger would point and select alternately. In contrast, with *dual-sided* interaction, pointing and selection is seperated to thumb and index finger, increasing efficiency. Furthermore, *dual-sided* interaction benefited most from hand stabilization at the pocket, which became most apparent under the *walking* condition. When *sitting* this stabilization was less required since users could rest their hand at the horizontal thigh.

5.6.2 Error rate. An error was defined as a selection attempt that did not hit the target. A 3x3 repeatured measures ANOVA showed significant main effects for *mobility* ($F(2,34)=53.602$, $p<.001$). A pairwise comparison revealed that as expected users made significantly more errors when *walking* (M=12.17%, SD=9.17%) than when *standing* (M=2.79%, SD=5.04%) and *sitting* (M=4.17%, SD=6.97%) (p<.001 for both pairwise comparisons; Bonferroni corrected). Unlike for the selection time, the *interaction technique* had no significant influence on the error rate.

5.6.3 Pinching analysis. We furthermore observed and analyzed the tapping behaviour of participants using the *dual-sided* touch technique. We were interested in whether participants would follow the mental model of pinching their thumb with their index finger or if they would touch anywhere on the touchpad to commit a selection. Users had two strategies: 11 participants moved the thumb mainly via wrist joint rotation (left and right) and arm movement (up and down). In this case the hand moved in union and upon tapping, the selection resembled a *pinch-through* gesture (see Fig. 8a). 7 participants instead moved the thumb mainly via its saddle joint. In this case, the other fingers were moved more independently. As a result the tapping finger had a large offset skewing towards the bottom left where the tip of the index finger is located. (see Fig. 8b). This shows that both interaction is feasible: *pinching* the thumb using the index finger with the thumb as a proprioceptive point of reference, but also moving fingers more independently utilizing the high degree-of-freedom of the thumb's saddle joint.

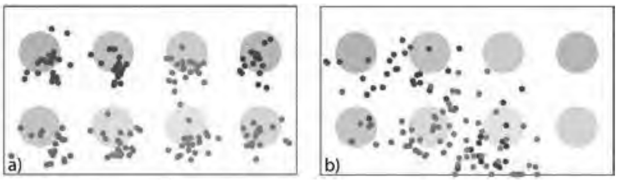
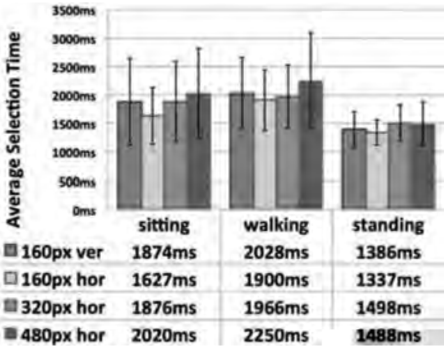


Fig. 8. Landing locations of the index finger when successfully selecting a target with *dual-sided* interaction. Left: A user (P1) following the mental model of *pinching* their thumb, hence the landing location of the index finger is closeby the target location. It is sligthly shifted to the bottom due to the index finger being longer than the thumb (see Fig. 3 and 5c). Right: A user (P8) not *pinching* but tapping anywhere with their index finger, i.e. moving index finger and thumb independently.

5.6.4 Movement within pocket. We looked at selection trials that were based on solely horizontal (160px, 320px, 480px) and vertical (160px) movement of the thumb using the *dual-sided* touch technique. Interestingly horizontal movements of the same distance were faster in all three mobility conditions (see Fig. 9). This suggests that thumb movement via wrist joint rotation (left and right) is more efficient than sliding the thumb slightly more into or out of the pocket to move up or down.



	sitting	walking	standing
▨ 160px ver	1874ms	2028ms	1386ms
☐ 160px hor	1627ms	1900ms	1337ms
▨ 320px hor	1876ms	1966ms	1498ms
▨ 480px hor	2020ms	2250ms	1488ms

Fig. 9. Average selection time of trials based on solely horizontal or vertical thumb movement of the *dual-sided* touch technique. (+/- standard deviation of the mean). For the same distance, horizontal movement performs better than vertical movement.

6 DUAL-SIDED TOUCH INTERACTION

It was shown that using the thumb for cursor-based pointing on a dual-sided touch interface is feasible. It can however not only be used as a cursor, but also as a spatial point of reference for the remaining hand. Hence, we want to explore the capabilities of using the thumb for pointing and the remaining fingers for jointly performed gestures.

For single-sided touch interaction, the capabilities for pointing and joint gestures are very limited due to the pointing finger reducing the degrees of simultaneous movement of the remaining hand. The only finger that can independently be moved over its saddle joint is the thumb. This is utilized in current touch systems for *pinch-to-zoom*, where thumb and index finger are moving with a high degree of freedom. However, when other fingers are concurrently used, they are very dependent on each other and bound to move together, such as when swiping with multiple fingers into the same direction (e.g. for *scrolling*). This limitation in hand motion leads to users either pointing at a target with a finger or performing a complex gesture, but not doing both at the same time with the same hand.

By using the thumb as a pointer in dual-sided touch interaction, the high degree of freedom of the thumb's saddle joint enables independent movement of the remaining hand and by that concurrently performed gestures. Since the thumb is opposing the other fingers, it is not obstructing their movement and can instead serve as a point of reference in the user interface.

6.1 Spatial tapping

Users can use their thumb as a proprioceptive reference for tapping with their fingers. This is used for the introduced *pinching* gesture, where users aim for the thumb for selection. It is however also possible to aim *beside* the thumb. By this, users can willingly tap left or right of the pointing cursor, which can be used as an analogy to left and right clicking of a mouse to increase the expressiveness of a touch selection.

Spatial tapping can be dinstinguished from the thumb via blob size and touch duration. Also, the capacitive intensity of these touches is lower as when pinching the thumb. With the current implemented absolute mapping of touch interface and display, *spatial tapping* faces limitations when selecting targets near the border. This however can be prevented by extending the touch interface or adjusting the cursor-display ratio.

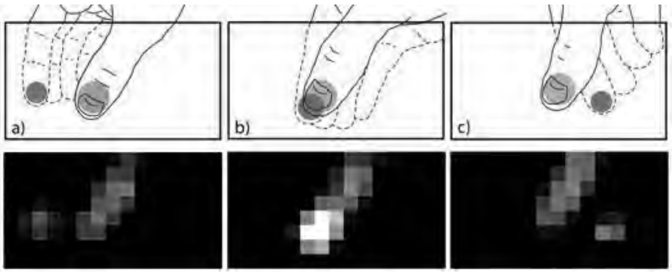


Fig. 10. Users can not only pinch the thumb (b), but also tap left (a) and right (c) of it. The latter enables to *"right-click"* interface elements with the cursor similar to a computer mouse.

6.2 Grab-and-drag

Dragging is a basic operation in many touch-based interfaces to move a target along the display that is pinned to the pointing finger. For the dual-sided *PocketThumb* interface, a target can be grabbed from both sides and then dragged along the display. This corresponds to physical interaction, where the thumb is opposing the rest of the hand and providing force to grab and move an object [23].

The *grab-and-drag* gesture can be distinguished from *pinching*-for-selection by movement of the pinching-blob along the interface.

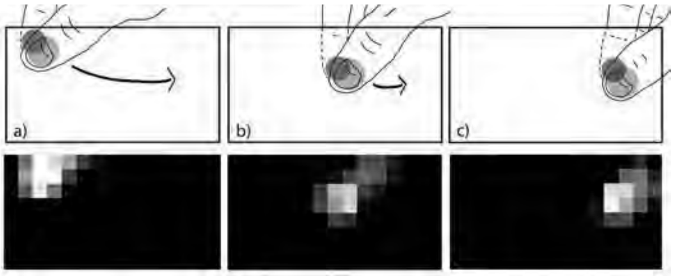


Fig. 11. *Grab-and-drag*. Users can grab (*pinch*) a target and then drag it along the display.

6.3 Pinch-and-circle

When the dominant characteristic of a human grip is *precision*, the gripped object is pinched between index finger and the opposing thumb [23]. This allows to flex and axially rotate both fingers and by that precise manipulations. We utilize this for a *pinch-and-circle* gesture where the user can pinch their thumb and then circle the opposing index finger around it for fast and precise interaction. In an user interface, this allows ro rotate a virtual knob or to quickly navigate through a list by continuous circling without having to lift the finger. The latter resembles continuous scrolling using the click-wheel of an iPod. In contrast, *pinch-and-circle* is performed while simultaneously pointing at a target and thus allows for varying contexts of the gesture.

Pinch-and-circle can be distinguished from *pinching* by the continuous circling movement of the pinching-area (see Fig. 12). This movement can be detected in the sensor image as well as in a computed differential sensor image containing differences to the previous frame. We calculate the imaginary center of the circle movement [20] to identify the angular movement around it.

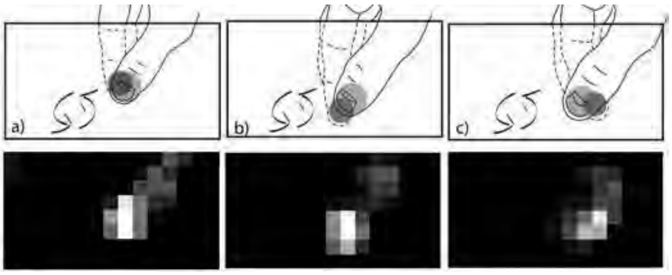


Fig. 12. *Pinch-and-circle* allows for continuous precise manipulation of a target, such as rotating a virtual knob.

6.4 Point-and-swipe

Swiping is commonly used for touch-based interaction to navigate through content such as when scrolling a page or switching through displayed interfaces. For *PocketThumb* users can use their fingers for swiping while pointing with the thumb to quickly navigate through complex menu structures. This can be used to switch the current application (left and right swipe) or to invoke or close menu interfaces related to a pointed target (up and down swipe).

When performing a *swipe* across the thumb, the finger-blob merges with the thumb on the sensor image upon crossing. This is detected by the measured intensity (see. Fig. 13b). The trajectory of the pinching-area resembles the movement of the finger (similar to *point-and-circle*), resolving the ambiguity.

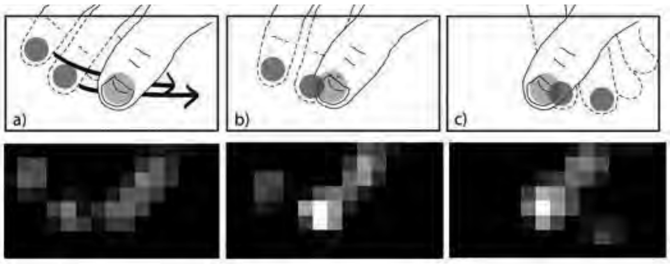


Fig. 13. A user swiping with two fingers while pointing with their thumb.

By performing the proposed gestures (*tapping*, *dragging*, *circling* and *swiping*) with multiple fingers, the input expressiveness can further be increased (e.g. swiping with two or more fingers).

6.5 Limitations

For *PocketThumb*, we utilize a single capacitive layer for dual-sided touch interaction. Using only one sensor for front and back of the interface creates ambiguity which although can be resolved under the assumption that the thumb is the only finger continuously in contact and not moving during finger gestures. Using two individual capacitive layers, as in previous research with handheld devices [38][37], would allow for simultaneous thumb movement, but would also increase the thickness of the interface.

An electronic interface embedded into clothing might raise the question of how the integration of the interface is practicable with varying pairs of trousers (one typically owns more than one pair) and how it might survive the washing process. We believe that the *PocketThumb* interface can be built as an insert of the inner pocket of trousers to be quickly swappable among multiple pairs. This would also allow taking it out before washing.

The trouser pocket as an input location is inherently limited in that not all alternative garments like skirts and dresses contain a pocket. However, we believe that when combining fashion and technology, it is very unlikely to find one solution that aligns with all the great versatility of fashion choices.

6.6 Conclusion and Future Work

PocketThumb is a wearable touch interface embedded into the trousers' front pocket for combined dual-sided interaction utilizing a single capacitive touch layer for rich interaction. The thumb stabilizes the hand from inside the pocket and allows for cursor-based interaction, which in a selection study showed to be more efficient than familiar single-sided touch interaction, especially in mobile conditions such as walking. The input expressiveness can furthermore be increased by using the thumb as a spatial point of reference for finger gestures performed on the front of the interface.

In the future we want to conduct an in-the-wild study to investigate the appropriateness of *PocketThumb* interaction in public. We expect that it is possible to perform subtle selections without drawing attention upon the user, but believe that spacious quickly performed gestures might raise attention. We therefore want to investigate the tradeoff of mobile efficiency and public exposure, and the cost of seamless transition from subtle to rich interaction.

6.7 Acknowledgments

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The Effects of Mobility, Encumbrance, and (Non-)Dominant Hand on Interaction with Smartwatches

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ABSTRACT

Smartwatches are designed for short interactions in varying mobile contexts. However little data is available on how present mobile conditions affect interaction with these devices. In this work, we investigate the effects of mobility (walking), encumbrance (by carrying items like shopping bags) and wearing the watch on the (non-) dominant hand on interaction techniques present with current devices: tapping targets, swiping, and flicking the wrist. The results showed that for tapping and swiping, the outfitted hand had the largest effect on selection time (9.41%, resp. 4.84% slower interaction when the watch was worn on the dominant hand), while for wrist flicking, encumbrance had the largest effect (11.94% slower when carrying bags). The walking condition had the largest effect on the error rate for all techniques. Swiping as an interaction technique was barely affected by any condition, both in terms of selection time and error rate, making it a robust mobile interaction technique for smartwatches.

Author Keywords

Smartwatch interaction; mobility; encumbrance; hand dominance; tapping; swiping; wrist-flicking

ACM Classification Keywords

H.5.2. User Interfaces: Input devices and strategies

INTRODUCTION

Smartwatches benefit from being quickly accessible at the user's wrist. This is especially beneficial in mobile context where access time for short interaction is important [1]. Mobile contexts, however, often have a negative effect on interactions when the user is on the move and potentially having their hands partly restricted by other physical activities.

Encumbrance and Walking

Users in mobile contexts are unlikely to focus all their attention on interaction with their mobile devices and often find their attention shared with other activities such as walking and carrying objects like shopping bags [7]. Ng. et al [6] observed that smartphone users that concurrently hold and carry objects while interacting with their devices are a frequent occurrence in public. In subsequent experiments, they found that users were significantly less accurate at targeting on a smartphone when being encumbered by carrying boxes or shopping bags.

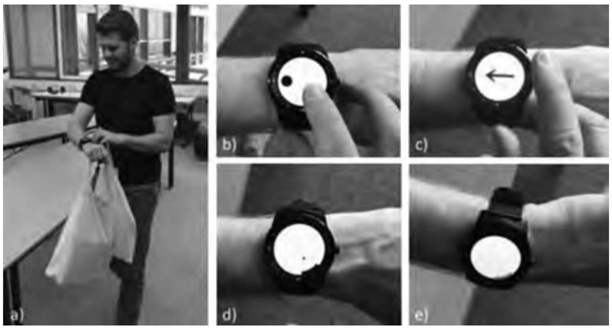

Figure 1. A user selecting targets while walking, being encumbered by carrying shopping bags, and wearing the watch on the non-dominant hand (a). We investigate the effects on tapping to select targets (b), swiping gestures (c), and flicking the wrist (d&e).

While most smartphones support one-handed interaction, many interactions with smartwatches involve and require both hands [8] by passively restricting the watch-outfitted hand in its movement and making use of the non-outfitted hand for touch interaction (notable exceptions are voice input, wrist-flicking and glancing at information). This could potentially make touch interaction with smartwatches even more prone to encumbrance as with devices that can be operated one-handed.

(Non-)dominant hand

Most research on touch performance implicitly imposes the use of a finger of the dominant hand [2]. Watches are traditionally worn on the left non-dominant hand, but differences in hand dominance (left-handed) and also personal liking lead to watches not always being worn on the left nor on the non-dominant hand. For smartwatches, the outfitted hand can often be chosen in the settings, for being relevant when it comes to tracking activities. For interaction, we hypothesize that the outfitted hand could have an impact: wearing the watch on the dominant instead of non-dominant hand could negatively affect touch interaction (then performed by the non-dominant hand), but on the other side could also have a positive effect on wrist-flicking interaction (then performed by the dominant hand).

Little data is available on how these conditions affect interaction with smartwatches, even though they span many mobile contexts. For this reason, we investigate the effects of mobility (walking), encumbrance (by carrying shopping bags) and outfitted hand (watch is worn on the dominant or non-dominant hand) for

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typical interaction techniques present with current smartwatches: tapping at targets (mainly used on Apple watchOS), swiping gestures (mainly used on Android Wear), and flicking the wrist (optional on Android Wear).

STUDY

We conducted a user study as a repeated measures factorial design with three independent variables:

Mobility

We used two conditions for *mobility*. For *walking*, participants would walk around an oval shaped table (5.3m long, 2.8m wide) in an empty seminar room (see Fig. 1) and reverse their direction at one end to balance the direction of movement. We allowed participants to find their own pace where they felt comfortable to move and interact at the same time. As a baseline, we used a *standing* condition.

Encumbrance

For *encumbrance*, participants would carry two shopping bags, one in each hand, each weighing 900g. As a baseline, participant would not be encumbered.

Outfitted Hand

For the *outfitted hand*, participants wore the watch either on the *dominant*, or as a baseline on the *non-dominant* hand.

This resulted in 8 combinations (2 *mobilities* x 2 *encumbrances* x 2 *outfitted hand* conditions) counterbalanced with a 8x8 latin square. Each participant undertook these 8 conditions for each of the three interaction techniques (*tapping*, *swiping*, and *wrist-flicking*), completing all conditions of an *interaction technique* before moving to the next one. The order of *interaction techniques* was counterbalanced, leading to overall 24 orders of conditions. Each condition started with a random training set of 8 trials, followed by 36 recorded trials. Participants kept their hand close to the watch during each condition to allow measuring *selection* rather than *access* time.

The dependent variables were *selection time* and *error rate*.

Participants and Procedure

We randomly recruited 24 participants (3 left-handed, none both-handed, 7 female) from our institution with an average age of 24.8 (range: 21 to 44). 11 participants regularly wear watches, of whom 1 left-handed participant stated to wear his watches on the dominant rather on the non-dominant hand. 2 participants stated to have a high level of experience with smartwatches, another 4 participants had experience due to previous studies using smartwatches. For the study, we used a LG G Watch R running Android Wear 1.5. The study took 60 minutes on average and each participant received €10 and a chocolate bar as compensation.

Tapping

For tapping, we used a target selection task with round targets having a diameter of 48dp (~7mm). This corresponds to the minimal button size as suggested by the Android Wear guidelines and is slightly larger than homescreen icons on Apple watchOS (~6.1mm). Targets were selected successively in random order. If a participant failed to successfully select a target, the trial was repeated at a later point in time. We used 9 pre-defined target locations and each location had to be selected 4 times. With 8 conditions and 24 participants this resulted in 6912 selections.

Selection time

For the selection time, a 2x2x2 (*encumbrance* x *mobility* x *outfitted hand*) repeated measures ANOVA (sphericity was met) showed significant effects for *encumbrance* ($F(1,23) = 10424$, $p<.01$, $\eta^2=.312$), *mobility* ($F(1,23) = 21557$, $p<.001$, $\eta^2=.484$) and *outfitted hand* ($F(1,23) = 67513$, $p<.001$, $\eta^2=.746$). There was no significant interaction between the effects. Being encumbered, and walking made selections 2.66%, resp. 4.22% slower, while wearing the watch on the dominant hand had the largest effect (9.41% slower).

Error Rate

For the error rate, a repeated measures ANOVA (sphericity was met) showed significant effects for *encumbrance* ($F(1,23) = 9598$, $p<.01$, $\eta^2=.294$), *mobility* ($F(1,23) = 50221$, $p<.001$, $\eta^2=.686$) and *outfitted hand* ($F(1,23) = 8763$, $p<.01$, $\eta^2=.276$). There was a significant interaction between the effects of *encumbrance* and *mobility* ($F(1,23) = 11385$, $p<.01$, $\eta^2=.331$)

Mobility had by far the largest effect on the error rate, increasing the chance of missing a target from 2.87% for *standing* to 9.67% for *walking*. The *outfitted hand* had the lowest effect increasing the error rate only by 30.3% (in contrast to 226.8% for *mobility* when *walking*)(see Fig. 2).

Swiping

For swiping, participants would perform directional touch gestures (up, down, left, and right). Swiping gestures are frequently used in Android Wear to navigate through applications and notifications and also used in Apple watchOS to navigate within applications or to open and close the notification- or command center.

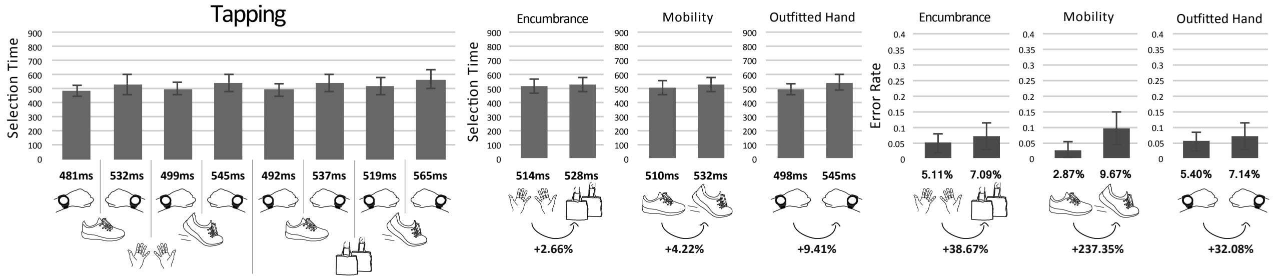

Figure 2. Selection time and error rate for tapping selections. The *outfitted hand* had the largest effect on the selection time (9.41%), while *encumbrance* and *mobility* had comparatively low effects (2.66%, resp. 4.22%). The error rate was significantly increased by all conditions. *Walking* had the largest effect (237.35%), followed by being *encumbered* by carrying shopping bags (38.67%) and wearing the watch on the *dominant* hand (32.08%). We depict the *non-dominant* hand as a left-hand icon and the *dominant* hand as a right-hand icon, albeit the handedness was reversed for left-handed participants.

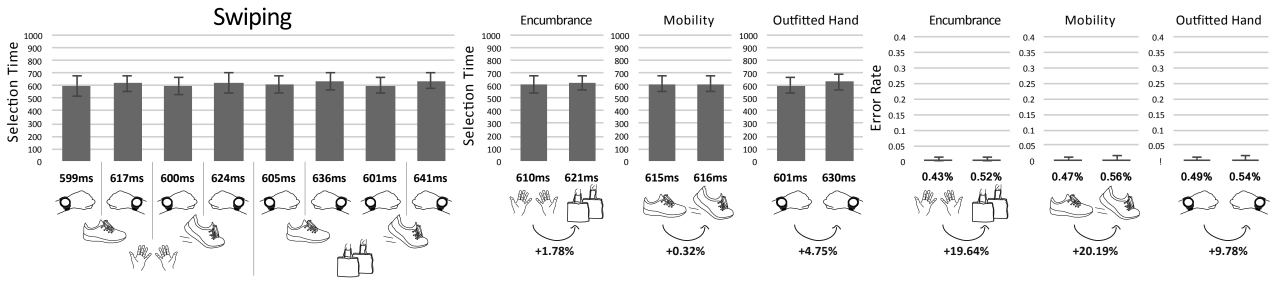

Figure 3. Selection time and error rate for swiping gestures. Swiping was in general barely effected by any condition. The *outfitted* hand had a significant effect on the selection time, but this was only a slight increase (4.75%).

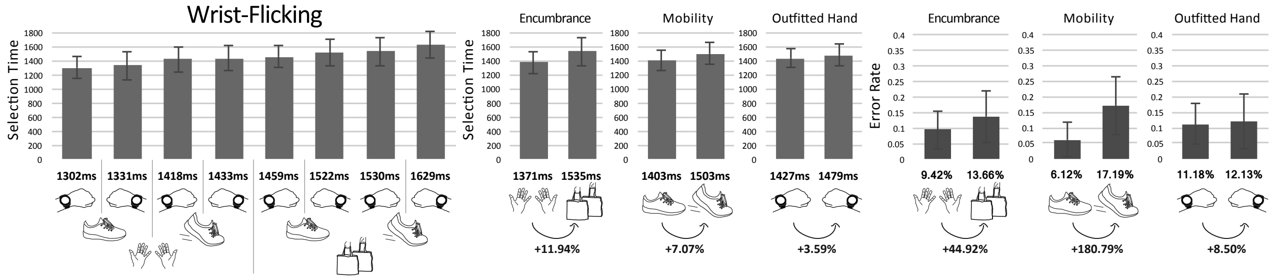

Figure 4. Selection time and error rate for wrist-flicking gestures. *Encumbrance* had the largest effect on the selection time (11.94%), while *walking* had the largest effect on the error rate (180.79%).

The respective swiping direction was displayed for each task with a large arrow on the display (see Fig. 1). As with tapping, trials were conducted successively in random order. We used 4 directions and each directional gesture had to be performed 9 times, resulting in 6912 gestures.

Selection Time

For the selection time, a repeated measures ANOVA (sphericity was met) showed significant effects for the *outfitted hand* ($F(1,23) = 24855$, $p<.001$, $\eta^2=.519$), being 4.75% slower. *Mobility* and *encumbrance* had no significant effects on the selection time (1.9%, resp. 0.3% slower).

Error Rate

A repeated measures ANOVA (sphericity was met) showed no significant effect on the *error rate* for any of the conditions. The error rate remained below 0.6% under any condition (see Fig. 3).

Wrist Flicking

Wrist flicking can be used on Android Wear to navigate through notifications by quickly flicking the wrist inwards or outwards and then back into the starting position. This has the advantage that unlike with touch-gestures on the watch, only one hand is required for interaction. Guo et al. [3] argue that flicking or tilting on a watch could be used for more pronounced interaction. Flicking the watch inwards or outwards can also be regarded as flicking a virtual on-screen cursor to the 12 or 6 o'clock position and back into the middle of the screen. For a more profound flicking interaction we utilize all 12 clock positions with different target sizes (30°, 45°, 90°) (see Fig. 5). Participants would move a virtual on-screen cursor towards a clock position by flicking the wrist in the respective direction (see Fig. 1) and then back into a flat reference position. Each position was selected for three different target sizes by each participant, resulting in 6912 flicking gestures.

Selection Time

For the selection time, a repeated measures ANOVA (sphericity was met) showed significant effects for *encumbrance* ($F(1,23) = 123750$, $p<.001$, $\eta^2=.843$), *mobility* ($F(1,23) = 24341$, $p<.001$, $\eta^2=.514$), and the *outfitted hand* ($F(1,23) = 8780$, $p<.01$, $\eta^2=.276$). There was no significant interaction between the effects. Being *encumbered* had the largest effect and made wrist-flicking 11.94% slower, followed by *mobility* (7.07%) and *outfitted hand* (3.59%). Contrary to the hypothesis, using the *non-dominant* hand was slightly faster than using the *dominant* hand.

Error Rate

For the error rate, a repeated measures ANOVA (sphericity was met) showed significant effects for *encumbrance* ($F(1,23) = 21028$, $p<.001$, $\eta^2=.478$) and *mobility* ($F(1,23) = 88254$, $p<.001$, $\eta^2=.793$). There was no significant interaction between the effects. The *outfitted hand* had no significant effect.

Target Position and Size

We furthermore looked at the different target positions and target sizes (see Fig. 5). Participants were fastest when flicking to the 6 and 12 o'clock position. These could be selected by solely rotating the wrist. Other positions involved movement of the arm (e.g. moving the hand down or up for the 3 and 9 o'clock position). Interestingly the error rate was lowest for the 3, 6, 9 and 12 o'clock positions, which could be due to the remaining clock positions requiring both: movement of the arm (hand up or down) and rotation of the wrist (inwards or outwards). The error rate for 90° targets was quite low (2.20%), while for 30° it was very high (16.25%), suggesting that 90° targets at the 3, 6, 9 and 12 o'clock position could extend current wrist-flicking gestures (which only use 6 and 12 o'clock positions).

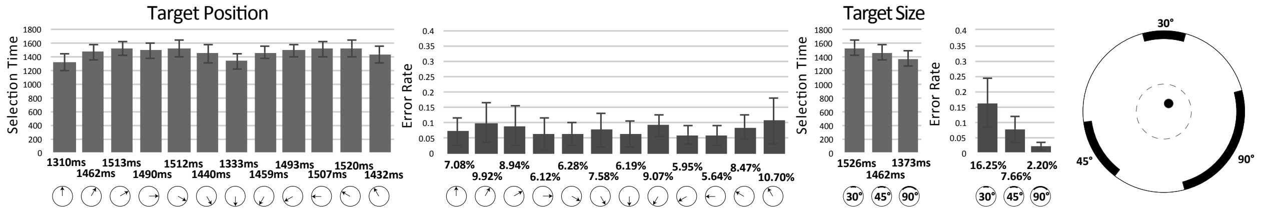

Figure 5. Wrist-flicking gestures segmented into target positions and target sizes. Participants had to flick a cursor (small black dot) from within the center of the display (dashed circle) into the boundaries of an angular target at the edge of the display and back into the center. The 12 clock positions served for target positions. Targets were either 30°, 45°, or 90° in size. Participants were fastest when flicking to the 6 and 12 o'clock position. The target size had a very large effect on the error rate, which was quite low for 90° targets (2.20%), but high for 30° targets (16.25%).

DISCUSSION

The results from the experiment show that mobility, encumbrance, and the outfitted hand have significant effects on interaction with smartwatches which however highly depends and differs for the investigated interaction techniques. Swiping gestures were barely affected by any condition, while tapping was notably affected by the outfitted hand and wrist-flicking by carrying shopping bags.

Generally, users found coping mechanism that made the effects smaller than initially expected, e.g. for tapping and swiping, users could rest their interacting hand on the watch hand to increase hand stabilization. In previous studies on smartphones and encumbrance, Ng et al. [7] found that using two hands for interaction increased the accuracy. In this regard, the cost of requiring both hands for touch interaction with smartwatches can be beneficial for hand stabilization.

Lyons [5] argued that during smartwatch interaction, the watch hand is only partly restricted since it is still free to hold objects. The same however is true for the interacting hand. Since only one finger is required for touch interaction with the watch, the remaining hand is able to grasp objects (e.g. the handle of a shopping bag), so that being encumbered by a graspable object that does not restrain the whole hand only has a small effect. For wrist-flicking however, which requires more active movement of the arm (resp. the wrist), the effect is larger.

The outfitted hand had a large effect on tapping interaction, while it only had a small effect on swiping gestures. Kabbash et al. [4] found that for rough pointing or motion, the non-dominant hand is as good as the dominant hand, while for precise pointing the hands significantly differ. In this regard, directional swiping on a watch can be seen as a rough motion, while tapping requires more precision and hence is more affected. For wrist-flicking, we expected the watch worn on the dominant hand to have a positive effect on interaction. Contrary to this, participants were slightly faster using the non-dominant hand. This might be explained by participants being generally more familiar with a watch worn on the non-dominant hand and having experience in rotating the wrist to glance at the time.

CONCLUSION

Touch interaction with smartwatches involves two hands, but both only partly. In contrast to smartphones that actively need to be held in hand, a watch is attached to the wrist, leaving the watch-hand free to hold objects, but also only partly restraining the interacting hand (requiring only one finger for touch input). The term *two*-handed interaction can thus be misleading. Since both hands can support and stabilize each other, interaction is quite robust to mobility and encumbrance effects. The more precision an interaction required, the more it was affected by mobile conditions, making directional swiping gestures that only require rough pointing, a very robust interaction technique for smartwatches.

The study results showed that each of the interaction techniques was differently affected by different conditions, so that interaction designers that want to extend the interaction capabilities of smartwatches [9] need to be aware of the varying conditions in mobile contexts. Swiping was least affected by any condition, which indicates that designers can utilize swipe gestures when the smartwatch application is expected to be primarily used when being mobile.

ACKNOWLEDGMENTS

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FaceTouch: Enabling Touch Interaction in Display Fixed UIs for Mobile Virtual Reality

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Figure 1. (a) A user interacting with *FaceTouch*, a multi-touch surface mounted on the back of a VR HMD. *FaceTouch* allows for precise interactions which can be used to implement applications such as text entry (b) or 3D modeling (c). Leveraging the sense of proprioception a user is able to blindly interact with control elements such as used in a gamepad to control a shooter game (d).

ABSTRACT

We present *FaceTouch*, a novel interaction concept for mobile Virtual Reality (VR) head-mounted displays (HMDs) that leverages the backside as a touch-sensitive surface. With *FaceTouch*, the user can point at and select virtual content inside their field-of-view by touching the corresponding location at the backside of the HMD utilizing their sense of proprioception. This allows for rich interaction (e.g. gestures) in mobile and nomadic scenarios without having to carry additional accessories (e.g. a gamepad). We built a prototype of *FaceTouch* and conducted two user studies. In the first study we measured the precision of *FaceTouch* in a *display-fixed* target selection task using three different selection techniques showing a low error rate of ≈2% indicate the viability for everyday usage. To asses the impact of different mounting positions on the user performance we conducted a second study. We compared three mounting positions of the touchpad (*face*, *hand* and *side*) showing that mounting the touchpad at the back of the HMD resulted in a significantly lower error rate, lower selection time and higher usability. Finally, we present interaction techniques and three example applications that explore the *FaceTouch* design space.

ACM Classification Keywords

H.5.2. [Information Interfaces and Presentation] : User Interfaces: Input Devices and Strategies, Interaction Styles

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Author Keywords

Back-of-device interaction; Mobile VR; VR interaction; Virtual Reality; Nomadic VR; VR input

INTRODUCTION

Virtual Reality (VR) head-mounted displays (HMD) are having a consumer revival with several major companies such as Facebook, Sony and Samsung releasing their consumer devices this year. In contrast to VR HMDs that are operated by a computer (such as OculusRift and HTC Vive), mobile HMDs have been presented which are operated solely by a mobile phone (e.g. Samsung GearVR and Google Cardboard). These mobile VR HMDs allow new usage scenarios where users can access Immersive Virtual Environments (IVEs) anywhere they want. Based on aspects of nomadic computing [17], we define this as *nomadic VR*.

Due to the omnipresence of mobile phones and the relatively low price, mobile VR HMDs (e.g. Google CardBoard) are expected to penetrate the consumer market more easily. However, current VR input research such as [1] and consumer products are focusing on stationary HMDs and input modalities that would not be available in nomadic scenarios. These include the instrumentation of the environment (e.g. Oculus' positional tracking, HTC VIVE's Lighthouse) or the usage of peripheral devices like 3D mice or game controllers. Hand tracking technology such as the Leap Motion strives for enabling "natural" interaction inside an IVE and lead to a higher level of immersion for certain scenarios (e.g. immersive experiences) but discounts utilitarian interactions such as browsing a menu or entering text, where the goal is on performance and less on immersion. We argue that interaction for VR should not only focus on enabling those "natural" interaction concepts but also enable a "super natural" interaction where users can interact and manipulate the virtual environment with little physical effort and enable interactions beyond human capability.

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We therefore investigate the concept of touch interaction inside an IVE as a first step towards that direction.

Current mobile VR UIs are designed to be operated using *HeadRotation* with a crosshair cursor or a gamepad. Since gamepads are not bundled with any mobile HMD (and do not fit the nomadic usage) the most targeted and used selection technique is *HeadRotation*. This leads to a limitation in the UI design space. With *HeadRotation*, a crosshair cursor is centered in the middle of the view, so that the user can aim at the target by rotating their head and select by using another means of input, such as a button or touch panel at the side of the VR device. The area of view has to be centered around the target location and as an implication, it is not possible to design *display-fixed* user interface elements (e.g. targets that are always at the bottom of the display). For this reason, current UI elements are implemented to be at a fixed location in 3D space (*world-fixed* UI). This forces either the content creator to embed every possible UI element (consider a keyboard for text input) inside the 3D scene or the user to leave their current scene to control UI elements (e.g. Samsung GearVR settings menu).

FaceTouch

To address these shortcomings, we present *FaceTouch*, an interaction technique for mobile VR HMDs leveraging the backside of the HMD as a touch surface (see Fig. 1). Adding touch input capabilities to the backside allows for direct interaction with virtual content inside the users field-of-view by selecting the corresponding point on the touch surface. Users cannot see their hands while wearing the HMD, but due to their proprioceptive senses [20] they have a good estimate of their limbs in relation to their body. Supported by visual feedback as soon as fingers are touching the surface, as well as their kinesthetic memory, users find in *FaceTouch* a fast and precise alternative interaction technique for nomadic VR scenarios that does not require them to carry an additional accessory (e.g. a gamepad).

In order to explore the design space we built a hardware prototype consisting of an Oculus Rift and a 7 inch capacitive touchpad mounted to the backside (see Fig. 3). We ran two user studies to investigate the precision and interaction time of *FaceTouch* for *display-fixed* UIs and measure the impact of the *mounting position* on those factors. In a first user study (n=18) we conducted a target selection task in a *display-fixed* condition showing a possible throughput [22] of ≈2.16 bits/s. Furthermore, we present a selection point cloud, showing how precise users can point at targets relying only on proprioception. In a second user study (n=18), we investigated the impact of the *mounting position* on performance, comparing three different locations (*face*, *hand* and *side*) and showing a significantly lower error rate and lower selection time when mounting the touchpad on the backside of the HMD, justifying our design decision for *FaceTouch*.

CONTRIBUTIONS

The main contributions of this paper are:

- The concept of *FaceTouch*, an interaction technique for mobile VR HMDs allowing for fast and precise interaction in nomadic VR scenarios. It can be used on its own or combined with *HeadRotation* to further enrich the input space in mobile VR.
- Showing the feasibility of *FaceTouch* for *display-fixed* user interfaces, offering a low selection error rate (≈3%) and fast selection time (≈1.49 s), making it viable for everyday usage.
- Comparing three different mounting positions of the touchpad and showing the advantages (≈8% less errors then *hand* and ≈29% less then *side*) and user preference for the *face* mounting location.
- Exploration of the design space of *FaceTouch* through the implementation of three example applications (gaming controls, text input, and 3D content manipulation) showing how the interaction can be utilized in *display-fixed* as well as *world-fixed* VR applications.

RELATED WORK

Our work is related to the research fields of back-of-device interaction, proprioceptive interaction and input techniques for IVEs.

Back-of-Device Interaction

In order to eliminate finger occlusion during touch interaction, researchers proposed back-of-device interaction [14, 18, 35, 2] which leverages the backside of a mobile device as an input surface.

Several implementations and prototypes where proposed which either used physical buttons on the backside [14, 18] or used the backside as a touch surface [31, 35]. Wigdor et al. enhanced the concept by introducing "pseudo-transparency" which allowed the users to see a representation of their hand and fingers allowing the users to precisely interact with the content independent of finger sizes [37]. Furthermore, Baudisch et al. showed that the concept of back-of-device interaction works independent of device sizes [2]. Wigdor et al., applied the concept further to stationary devices such as a tabletop [38]. Without seeing their hands and using only the sense of proprioception, participants interacted with a tabletop display by selecting targets under the table.

FaceTouch extends the field by being the first work utilizing back-of-device interaction in VR. In contrast to existing techniques, the user is completely visually decoupled from their body and by that means not able to see their arms while approaching a target. This forces the user to rely even more on proprioception to interact with the content.

Proprioceptive Interaction

The human capability of knowing the position and relation of the own body and its several body parts in space is called proprioception [3]. It usually complements the visual sense when reaching for a target, but even when being blindfolded from their physical environment, users can utilize their proprioceptive sense especially well to reach parts of their own body, such as being able to blindly touch their own nose [15].

Wolf et al. showed that due to the proprioceptive sense, participants were able to select targets on the backside of an iPad without visual feedback having no significant decrease in accuracy compared to visual feedback [39]. Serrano et al. explored the design space of "hand-to-face" input, where participants used gestures such as strokes on their cheeks for interacting with an HMD [33]. Lopes et al. showed how the sense of proprioception can be used as an output modality [20]. Similar to *FaceTouch*, most work in the field of back-of-device interaction leverages the sense of proprioception. A novelty of *FaceTouch* is that a back-of-device touchpad is attached to the user's body and as a result the user can utilize proprioception while being immersed in a virtual environment. Also the user's hands are not constrained by holding a device and can unrestrictedly be used for touch interaction.

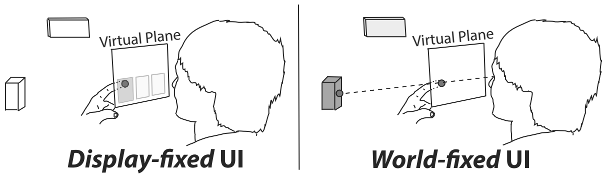


Figure 2. User interface elements for *FaceTouch* can be fixed to both: the *display* (left) and the *world* (right). The virtual plane has a 1:1 direct mapping to the physical touch surface. By touching this plane, users can select *display-fixed* elements on the virtual plane (left) and ray-cast into the scene to select *world-fixed* elements (right).

Further, the use of proprioception was often explored in IVEs [24, 7, 19]. Mine at al. showed the benefits of proprioception in IVEs by letting participants interact with physical props in the non-dominant hand [24]. Similar to this approach, Lindeman et al. used a paddle in the non-dominant hand to leverage proprioception and passive haptic feedback in virtual hand metaphors [19].

Input Techniques for Virtual Environments

Besides novel feedback mechanisms [9, 10], a big part of recent VR research revolves around interaction concepts. The focus of interaction concepts for IVEs in related work is mostly on 3D interaction techniques [1] which can be classified as *exocentric* and *egocentric* interaction metaphors [28], distinguishing between whether the user interacts in a first-person view (*egocentric*) or a third-person view (*exocentric*) with the environment. Our focus will be on *egocentric* interaction concepts of which the most prevalent are the virtual hand and virtual pointer metaphors [1, 29].

The virtual hand metaphor is applied by tracking the user's hand and creating a visual representation of it allowing the user to interact with content within arm's reach [21]. Lindeman et al. presented how using a physical paddle in the user's non-dominant hand to create passive haptic feedback can increase user performance for hand metaphor selection tasks [19]. *FaceTouch* offers the same advantages in terms of passive haptic feedback without forcing the user to hold a physical proxy. To enable virtual hand metaphor interaction with UI elements not in the user's vicinity, researchers proposed concepts such as GoGo [27] or HOMER [4] which apply non-linear scaling of the hand position.

Virtual pointer metaphors rely on casting a ray into the virtual scene to enable user interaction [23]. Several techniques were proposed to determine the ray's orientation which mostly rely on tracking the user's hand similar to the virtual hand metaphor. The orientation of the ray can either be controlled by the hand position and wrist orientation or as a ray cast from the user's viewpoint through the hand [26]. Different approaches combine either both hands [24] or use eye tracking [36]. The *HeadRotation* interaction of Samsung's GearVR can be considered a virtual pointer metaphor where the ray is cast perpendicular to the center of the user's viewpoint.

In contrast to previous work, *FaceTouch* enables direct interaction with content in and outside of the user's vicinity without external tracking or additional accessories (as had been used in [30, 25]) and can be easily implemented in future mobile VR devices. Furthermore, *FaceTouch* offers passive haptic feedback which typically results in a higher selection performance [6].

INTERACTION CONCEPT

The basic principle of *FaceTouch* is to leverage the large unexploited space on the backside of current HMDs as a touch sensitive surface. This allows for the creation of a mapping between the physical touch surface in front of the user and their field-of-view within the IVE. By touching the surface, the user is touching a virtual plane within their field-of-view (see Fig. 2) with the same ratio and resolution as the physical touchpad resulting in a 1:1 direct mapping of physical touch and virtual selection. When aiming for a target, users can see the touch position of their fingers visualized on the virtual plane as soon as touching the surface. We refer to this step as *LandOn*. To commit a selection, we use two different techniques that can both complement each other for different selections. With *LiftOff*, a selection is committed when lifting a finger above a target, while with *PressOn*, a target is selected by applying pressure. Both techniques allow the user to correct the position of a finger on the virtual plane, before committing the selection. User interface elements for *FaceTouch* can be both: fixed to the *display* or to the *world* [8] (see Fig. 2).

World-fixed UIs

In current mobile VR HMDs, such as Samsung Gear VR, user interface elements are fixed within the virtual world and selectable by rotating the head and thereby turning the target into the center of the user's view. This concept of interaction is suitable for UIs which try to immerse the user into the scene. However, it also poses the drawback that only elements within the centered focus (e.g. a crosshair in the center of the display) can be selected and a lot of head rotation is required for successive selections. With *FaceTouch*, *world-fixed* user interface elements can be selected alike, however the user does not have to center their view at the target. It is possible to select targets anywhere within the field-of-view by selecting the corresponding point on the virtual plane. Hence, users can keep their focus wherever they like.

Display-fixed UIs

In addition to *world-fixed* interfaces, *FaceTouch* allows to place *display-fixed* UI elements. These are always attached to the virtual plane and are independent of the users orientation (being always inside the users field-of-view). Examples for this are menu buttons that prove to be useful throughout interaction, such as reverting the last action in a modeling software, opening a settings menu, or virtual controls for gaming applications (more details in the *Applications* section). *Display-fixed* UI elements can be transparent to not occlude the field-of-view or even completely hidden for more experienced users. These kind of interfaces are crucial to realize utilitarian concepts such as data selection or text entry which focus more on user performance than on immersion. Therefore, the rest of this paper will focus on investigating parameters and performances with *display-fixed* UIs.

IMPLEMENTATION

We built a hardware prototype of *FaceTouch* by mounting a 7 inch capacitive touchpad (15.5cm x 9.8cm) to the backside of a Oculus Rift DK2 (see Fig. 3). Even though we do not consider the Oculus Rift a mobile VR HMD since it has to be connected to a computer, it allowed us to easily integrate the rest of the hardware and was sufficient for our study designs. The touchpad is embedded in a 3D-printed case and attached to the HMD via 5 small buttons to enable the detection of finger presses on the touchpad. An Arduino Pro Mini is used to control these buttons. The *side*

Figure 3. The ***FaceTouch*** **prototype. A capacitive touchpad is embedded into a 3D-printed case and attached to the backside of an Oculus Rift DK2 via 5 small buttons that allow for pressure sensing on the touchpad. The side touchpad was only used in the second user study and does not have any buttons attached to it.**

touchpad was mounted on the right side of the HMD to simulate an often used mounting location for HMDs which is considered ergonomic (e.g. GearVR and Google Glass). The *side* touchpad has the same resolution and aspect ratio as the *face* touchpad. The size is approximately 10.8cm x 6.8cm. Both touchpad were picked so that they would offer as much touch space as possible for the mounting position used. Oculus Rift, the touchpad and the Arduino are tethered to a computer running Windows 8.1. The VR environments are rendered with Unity 5.0.1.

DISPLAY-FIXED UI - USER-STUDY

To show that *FaceTouch* can be used on daily basis with mobile/nomadic VR HMDs we ran a user study which simulates the interaction with *display-fixed* interfaces. We conducted a target selection user study for *display-fixed* UIs to investigate parameters relevant for *FaceTouch*. Since users rely on proprioception, we were interested in how accurate and fast users could hit targets of different sizes and locations, especially without visual feedback. Depending on size and distance, we expect users to get close to the target while blindly attempting a selection, but not being able to accurately select the target. For this reason we compared *LandOn*, as a selection technique without visual feedback as a baseline to *LiftOff* and *PressOn*. The latter two allow for the correction of the initial selection by first visualizing the touch location and requiring an additional *commit method* afterwards.

By positioning the virtual touch plane at the actual distance of the physical surface, we expect less interference with the proprioceptive sense. However, the Oculus guidelines [40] suggest *display-fixed* virtual planes to fill out only a third of the field of view leading to less ”eye strain”. For that reason, we were also interested in the effect of changing the virtual plane distance.

Study Design

The study was conducted as a target selection task using a repeated measures factorial design with three independent variables. As independent variables we chose *commit method* (*LandOn*, *LiftOff* and *PressOn*), *plane distance* (*NearPlane*, *MidPlane* and *FarPlane*) and *target size* (*small* and *large*).

Commit method. We implemented three methods to commit a selection. With *LandOn*, a target is immediatley selected at the initial point of contact of a finger. By this, no visual feedback is given prior to selection. *LiftOff*, selects the target that was touched when lifting the finger from the surface, while *PressOn* selects the target below the finger when physical pressure is applied to the touchpad. For *LiftOff* and *PressOn*, a cursor is presented on the virtual plane as visual feedback to represent the finger.

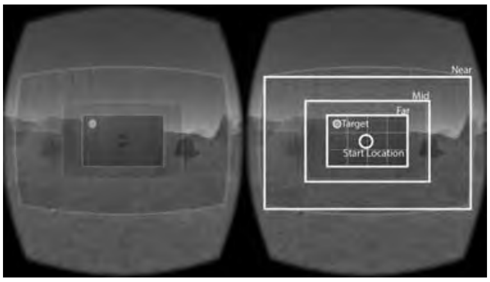


Figure 4. The interface of the ***display-fixed*** **UIs user study, showing the distances of the planes and the arrangement of the targets (for illustration).**

Plane distance. We used three different ratios for the field-of-view and the size of the virtual plane. *NearPlane* positioned the virtual plane at the same virtual distance as the touchpad was attached to the HMD. *FarPlane* positioned the virtual plane at a distance to fill out approximately a third of the field of view, as suggested by the guidelines of OculusVR [40]. The *MidPlane* was positioned in-between *NearPlane* and *FarPlane*, filling out approximately half of the field-of-view.

Target size. The *small* circular targets were picked based on the Android Design Guidelines for the smallest target having the size of 48dp (density-independent pixels) approximately 7.8mm. *large* targets received double the size (96dp approximately 15.6mm).

This resulted in nine combinations (3 *commit methods* x 3 *plane distances*) which were presented to the participants using a 9x9 Latin square for counterbalancing. *Target size* was randomized together with the target position as described in the *Procedure*.

The dependent variables were selection time, error rate and simulator sickness. The latter was measured using the RSSQ (Revised Simulator Sickness Questionnaire) [16]. We included the simulator sickness since we were particularly interested in the subscale ”Ocular Discomfort” and expected the *plane distance* to influence this.

Procedure

For the first user study we only used the *face mounting position*. All participants performed a target selection task whilst wearing the *FaceTouch* prototype and sitting on a chair. Participants were instructed to lean back on the chair and were not allowed to rest their arms on a table to simulate the nomadic scenario. To begin with, participants were introduced to the concept of *FaceTouch* and filled out a demographic questionnaire. Based on the Latin square, each combination (*commit method* and *plane distance*) was presented and explained to the participants. Each participant filled out the RSSQ for simulator sickness before and after completing the target selection task with each combination. Participants were allowed to practice with each combination until they felt comfortable. At the end each participant filled out a final questionnaire comparing the presented combinations.

The target selection task consisted of 12 circular targets arranged in a 4x3 cellular grid across the virtual plane (Fig. 4). Similar to Lubos et al. [21], participants started with selecting the start button before each target which was located in the center of the plane having the target size *small*. This started the timer and randomly spawned a target in the center of one of the 12 cells. This allowed us not having to use a perfect circular arrangement of targets but cover the full surface of the touchpad (also the corners) and still have a fair measurement of time. Each cell was repeated 3 times with both target sizes resulting in at least six targets per cell and at least 72 targets per combination. If a participant failed to successfully select a target the target was repeated at a later point in time (similar to [2] this repetition was not applied for *LandOn* since a high error rate made it impracticable). For each participant, the study took on average 1.5 hours.

Participants

We randomly recruited 18 participants (12 male, 6 female) from our institution with an average age of 27 (range: 21 to 33). All had an academic background being either students or had studied at the university. On average participants had been using touchscreens for 10 years (range: 3 to 12). Eight of the participants had never used an HMD before. Each participant received 10 *currency*.

Results

Our analysis is based on 18 participants selecting targets of 2 sizes on 12 locations with 3 different plane distances using 3 different commit methods each with 3 repetitions resulting in over 11664 selections.

Error Rate

An error was defined as a selection attempt which did not hit the target (selecting the start button was not taken into consideration). Figure 5 shows the average error rate for each *commit method* with each *plane distance* and each *target size*. A 3x3x2 (*commit method* x *plane distance* x *target size*) repeated measures ANOVA (Greenhouse Geisser corrected in case of violation of sphericity) showed significant main effects for *commit method* ($F(1.078,18.332)=634.822$, $p<.001$, $\eta^2=0.97$), *plane distance* ($F(2,34)=8.928$, $p<.001$, $\eta^2=0.24$) and *target size* ($F(1,17)=801.810$, $p<.001$, $\eta^2=0.97$). We also found significant interaction effects for *target size* x *commit method* ($F(1.141,19.402)=437.581$, $p<.01$, $\eta^2=0.96$).

As we expected, pairwise comparisons (Bonferroni corrected) revealed that participants made significantly more errors ($p<.001$) using *LandOn* (M=54.7%, SD=9%) than *PressOn* (M=1.8%, SD=1.9%) and significantly ($p<.001$) more using *LandOn* than *LiftOff* (M=2.2%, SD=1.8%). It is worth pointing out, that the average *LandOn* error rates for the targets close to the start button (target 5 and 6 on Fig. 7) were only at 8%. This indicates that the precision drastically reduces when the user had to cover longer distances blindly.

A second interesting finding was that participants made significantly ($p<.05$) more errors using the *NearPlane* (M=20.9%, SD=4%) compared to the *MidPlane* (M=18.4%, SD=4%). One has to keep in mind that the *plane distance* only changed the visual target size, not the actual target size on the touchpad. This showed similar to prior work [41] that the target size which is presented to the user, significantly influences the accuracy of the pointing, even if the actual touch area stays the same. Finally, we found a significantly ($p<.001$) higher error rate of participants selecting *small* targets (M=25.6%, SD=3.8%) compared to *large* targets (M=13.6%, SD=2.9%).

Selection Time

As the selection time we defined the time between selecting the start button and the target. Only successful attempts were taken into consideration. Figure 6 shows the average selection time for each *commit method*, *plane distance* and *target size*. We excluded *LandOn* from the analysis since it resulted in a too high error rate. A 2x3x2 (*commit method* x *plane distance* x *target size*) repeated measures ANOVA (Greenhouse Geisser corrected in case of violation of sphericity) showed significant main effects for *plane distance* ($F(2,34)=8.928$, $p<.05$, $\eta^2=0.17$) and *target size* ($F(1,17)=345.773$, $p<.001$, $\eta^2=0.95$).

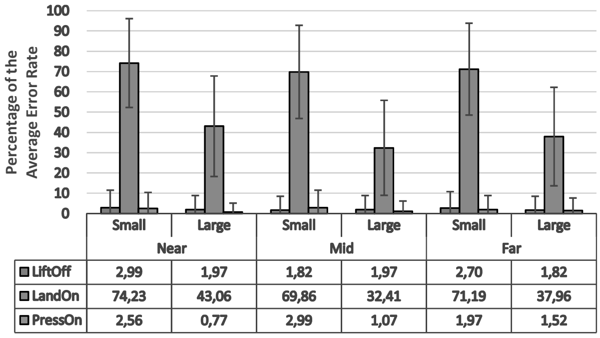
Confirming with Fitts' Law, pairwise comparisons (Bonferroni corrected) revealed that participants were significantly ($p<.001$) faster in selecting *large* targets (M=1.22s, SD=0.17s) than *small* targets (M=1.51s, SD=0.19s). For comparisons, we calculated the mean selection time of *LandOn* (M=0.84s, SD=0.14s). Unlike for the error rate, *plane distance* had no significant influence on the selection time.

Using this data we calculated an average throughput (following the methodology of [34]) for *LiftOff* of around (M=2.16 *bps*, SD=0.28 bps). The average throughput values for the mouse range from 3.7bps to 4.9bps [34] whereas touch has an average of 6.95bps [32].

LandOn Precision

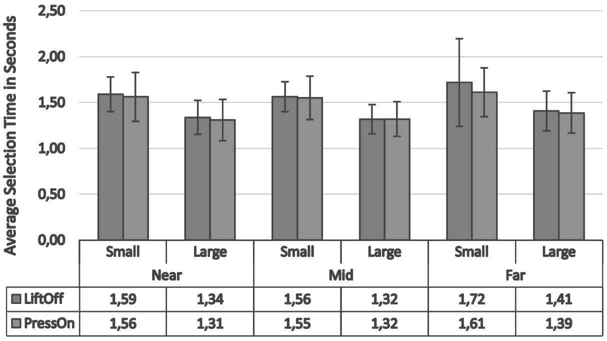
Bonferroni corrected pairwise comparisons of means revealed that within their three attempts, participants' touches resulted in a significantly ($p<.001$) higher amount of overshoots with *small* targets (M=1.44, SD=0.2) than with *large* targets (M=1.19, SD=0.29). Additionally, participants' touches resulted in a significantly ($p<.001$) higher amount of overshoots using *NearPlane* (M=1.6, SD=0.25) than *MidPlane* (M=1.3, SD=0.25) and significantly ($p<.001$) higher amount of overshoots using *NearPlane* than *FarPlane* (M=1.0, SD=0.4). To be able to understand and optimize the interaction using *LandOn*, we did an in-depth analysis of the selection locations. We were hoping to get a better insight into the level of accuracy people are able to achieve using the proprioceptive sense and how participants were using *FaceTouch*. We logged the location participants touched and defined an overshoot as a touch with a distance more than the length of the direct path. A 2x3x12 (*target size* x *plane distance* x *target location*) repeated measures ANOVA (Greenhouse Geisser corrected in case of violation of sphericity) on the number of overshoots (within the three attempts) showed a significant main effect for *target size* ($F(1,17)=24.179$, $p<.001$, $\eta^2=0.58$), *plane distance* ($F(2,34)=17.965$, $p<.001$, $\eta^2=0.51$) and *target location* ($F(11,187)=20.377$, $p<.001$, $\eta^2=0.54$). Furthermore, there were significant interactions between *target size* ×*target location* ($F(11,187)=2.103$, $p<.05$, $\eta^2=0.11$) and *plane distance* ×*target location* ($F(22,374)3.159$, $p<.001$, $\eta^2=0.16$).

To explore the differences between the cells, we numbered each cell of the *target location* (see Fig. 7). Pairwise comparisons of means between each cell revealed significant differences in the amount of overshoots. We could divide the cells in two groups, an overshoot (cells 2,3,6,7,10,11)and an undershoot group (cells 1,4,5,8,9,12), each containing half of the cells. Figure 7 shows the touch locations for *small* targets and *MidPlane* where the centroids for failed and successful selections are represented as a triangle, respectively a circle. One can easily see the two groups by comparing the relation between the success and the fail



	Near Small	Near Large	Mid Small	Mid Large	Far Small	Far Large
▨ LiftOff	2,99	1,97	1,82	1,97	2,70	1,82
▨ LandOn	74,23	43,06	69,86	32,41	71,19	37,96
▨ PressOn	2,56	0,77	2,99	1,07	1,97	1,52

Figure 5. Error rates for the different variables (+/- standard deviation of the mean)



	Near Small	Near Large	Mid Small	Mid Large	Far Small	Far Large
▨ LiftOff	1,59	1,34	1,56	1,32	1,72	1,41
▨ PressOn	1,56	1,31	1,55	1,32	1,61	1,39

Figure 6. Average selection time for the *LiftOff* and *PressOn commit method* (+/- standard deviation of the mean).

centroids to the center. In the overshoot group the fail centroids are always further away from the start location, whereby in the undershoot group the fail centroids are between the start location and the target. This overshooting is related to the distance the users finger has to travel. These findings show that when relying solely on proprioception, users tend to overestimate their movement over longer distances, resulting in an undershooting and underestimate it when the target is close.

In a next step we created a function which calculates the optimal target size so 95% of the touch points would end up to be successful (this is only a rough estimate since the target size itself can influence performance [41]). The optimal target size would have a diameter of around 370px (30.06mm) which is smaller than targets of Wigdor et al. [38]. We assume this is due to the fact that people have a better sense of proprioception in their facial area than with a stretched out arm under the table.

Usability Data

In a final questionnaire we let participants rank the *commit method* and *plane distance* based on their preference. Participants ranked *LiftOff* unanimously to be the *commit method* they would like to use (second was *PressOn*). Furthermore, participants (17 votes) voted *MidPlane* to be the most comfortable to use followed by *NearPlane* and *FarPlane*. Commenting on open-ended questions, participants mentioned that they thought *FaceTouch* was a "*great idea*"(P16), worked "*surprisingly well*"(P10), had an "*intuitive and natural interaction*"(P2) and was "*fast to learn*"(P7). Analyzing the simulator sickness data we did not find any occurrence of simulator sickness (M=1.09 ,SD=0.56 on a practical scale of −8.44 to 82.04 [16]) nor significant differences for the different variables.

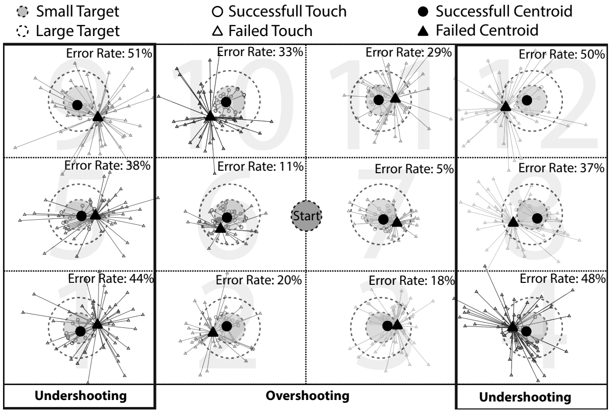


Figure 7. LandOn touch locations (mid distance with small targets) with centroids for failed and successful targets.

Discussion

Our research question for the first user study was to find out if *FaceTouch* is usable for *display-fixed* UIs and how the parameters *commit method*, *plane distance*, *target size* interact with the performance.

LiftOff. The low error rate and overall short selection time shows that *LiftOff* is overall suitable to interact with current UIs for VR HMDs. The UI elements can be picked being even smaller than the *small* targets (7.8mm), since the error rate was around 2.2%. However, calculating the perfect sizes needs further investigation. The touch data for *LiftOff* showed that participants mostly started from the center of the touchpad (on average 460px away from the target location) and did not try to place the initial touch close to the target. So for precise interaction, participants need one reference point where they start their movement and start seeing the position on the touchpad. We leveraged this in the implementation of one of our example applications (Text Entry Fig. 13) by splitting the keyboard into two parts and allowing the user to have one reference point for each hand leading to a reduced overall movement.

PressOn. The overall performance in terms of error rate and selection time of *PressOn* was similar to *LiftOff*, indicating that it would also be a valid choice for interacting with mobile VR HMDs. During the tasks, most participants never lifted the finger from the touchpad preferring to have the visual cue of the current touch location similar as for *LiftOff*. The biggest downside of *PressOn* was that pressing down on the touchpad resulted in the IVE to "*shake*" and led to a higher physical demand. This *shaking* only occurred in the *PressOn* condition, all other conditions had no negative effect since we used a capacitive touchpad that needs no pressure. However, this did not lead to a higher simulator sickness but was reported as being "*uncomfortable*". In a future prototype this can be solved using technology such as "ForceTouch" introduced by Apple.

As expected, *LandOn* performed significantly worse in terms of error rate in comparison to the other two *commit methods*. Nevertheless, it indicated a lower selection time (M=0.84s, SD=0.14s) and has therefore relevance for time critical UIs demanding less accuracy, such as a gamepad (see section *Interaction Scenarios*). Having analyzed the touch data for *LandOn* we are able to give some insights on how users blindly interact with *FaceTouch* and how this interaction can be improved.

The analysis showed that users undershoot for targets which were located far from the starting point (see Fig. 7). In combination with the theoretically optimal target size of 30.06mm, UIs can be optimized for the under-/overshoot. However, this is only valid for interactions which forces the user to select targets over a long distance. After the initial touch to "orientate" on the touchpad, participants have a high accuracy if the moving distance is fairly low (targets 6 and 7 have an average accuracy of 92% using *LandOn*, *large* targets and *MidPlane*). This can be utilized by designers (in combination with a two handed input) by placing two large buttons close to each other to simulate a gaming controller. We utilize this in a gaming application (see section *Applications* and Fig. 12).

An overall surprising finding was that the *plane distance* had a significant influence on the error rate even though the physical target size on the touchpad did not change. *FaceTouch* allowed for the decoupling of the physical target size from the visual target size and showed that the *plane distance* has to be chosen carefully. In our studies *MidPlane* led to the best performance by covering approximately half of the user's field of view (oppose to the Oculus Rift guidelines [40] suggesting to only cover a third of the user's field of view).

In summary, the results support our hypothesis that *FaceTouch* works as an interaction technique for *display-fixed* UIs. The precision and selection time suggests that *FaceTouch* is indeed a viable approach for bringing pointing input to mobile VR HMDs. Furthermore, our findings give design guidelines (which we used ourselves in the example applications) for UI designers on when to use which *commit method* and how to design for each *commit method*.

TOUCHPAD POSITIONING - USER STUDY

After showing the precision which *FaceTouch* offers with *display-fixed* UIs on the *face* mounting position we wanted to explore alternative mounting position of the touchpad and measure their impact on the users performance. We decided to compare three *mounting positions* (*face*, *hand*, *side*). We selected those positions since we expected *face* to have the highest level of perception and therefore the highest accuracy, *hand* because of its comfortable position over long use and *side* as a baseline to compare against the current state of the art of controlling HMDs with a touchpad at the temple (e.g. GearVR or Google Glass). Based on the optimal parameters for *target size* and *target location* we determined in the first user study, we conducted a target selection study with *display-fixed* UIs placing the touchpad either on the back of the HMD (*face*), in the hand of the user (*hand*) or similar to the GearVR on the side of the HMD (*side*) (see Fig. 8). The goal was to determine if placing the touchpad on the backside of the HMD would affect the the proprioceptive cues more compared to the other two positions.

Study Design

The study was conducted using a repeated measures factorial design with one independent variable (*mounting position*) having three levels (*face*, *hand* and *side*). As a selection technique we used *LandOn* and *LiftOff* however did not compare between those since we used different target sizes which were the optimal from the first user study (*LandOn* with *large* and *LiftOff* with *small*). We decided to use *large* for *LandOn* to be able to compare the results for *hand* and *side* with the first study. We omitted *PressOn* from the study since it yield similar results to *LiftOff*. The plane distance was *MidPlane*. The *mounting position* and *commit method* were counterbalanced.

Figure 8. Placement of the touchpads during the positioning user study

The dependent variables were selection time, error rate, usability and workload. Usability was meassured using the SUS questionnaire [5] and workload using the raw NASA-TLX [12]. The touchpad on the *side* had the same aspect ratio and resolution as the *face* but was smaller in size (10.8 cm x 6.8 cm) to fit on the side of the HMD. The mapping from the touchpad on the side to the input plane in front of the user was evaluated in an informal pre-study with several colleges from the institution and set fix for all participants (from the users perspective back being right and front being left). For the *hand* condition the touchpad from *face* was taken out and put into a case which the participant would hold in his non dominant hand an interact using the dominant hand. Other than this, the same apparatus as in the first study was used.

Procedure

The same target selection task as in the first user study for *display-fixed* UIs was used. Participants were able to practice as long as they wanted and started with *LandOn* or *LiftOff* (counterbalanced). Each of the 12 targets were selected three times. After both *commit method* with each *mounting position* was done participants filled out the SUS and NASA-TLX questionnaire. At the end of the study participants ranked each *mounting position* in terms of comfort and could comment on the positioning. The whole study took on average 45 minutes.

Participants

We randomly recruited 18 participants (14 male, 4 female) with an average age of 26 (range: 20 to 36) and all having an academic background being either students or employed at the institute. On average participants had 6 years experience using touchscreens and 7 had experience in using VR HMDs. Each participant received 10 currency.

Results

Error Rate: An error was defined similar to the first study. Figure 10 shows the distribution of the error rate for each *mounting position*. A one factorial repeated measures ANOVA showed a significant effect for *mounting position* (F(2,34)=38.276, $p<.001$, η^2=0.69) using *LandOn*. Bonferroni corrected pairwise comparisons revealed that *face* (M=0.35, SD=0.1) had a significant lower error rate than *hand* ($p<.05$) and *side* (M=0.65,

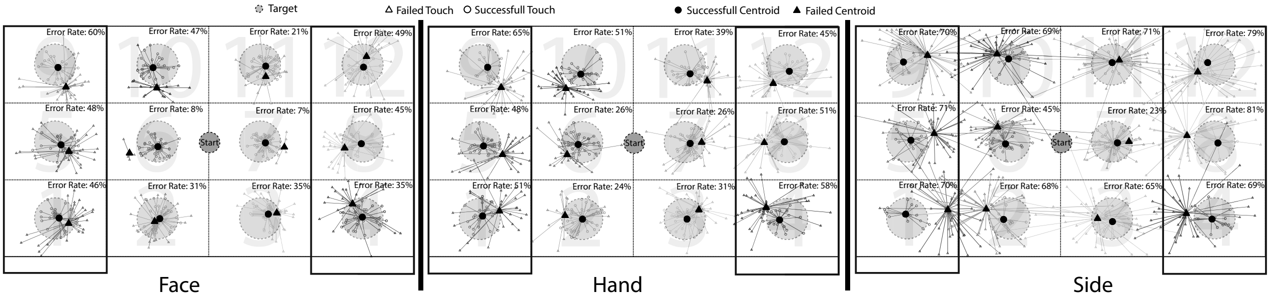
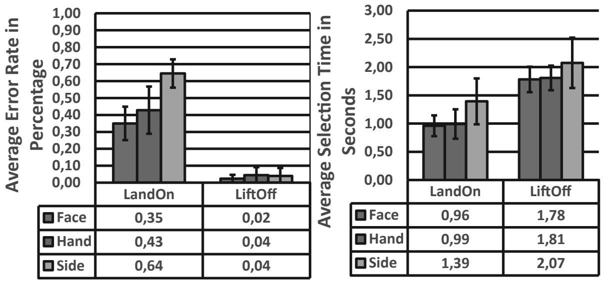


Figure 9. LandOn touch locations for each *mounting position* with centroids for failed and successful targets. One can see the high level of scatter for the *side* position and the relatively low scatter for *face*.



	LandOn	LiftOff
■ Face	0,35	0,02
■ Hand	0,43	0,04
■ Side	0,64	0,04

	LandOn	LiftOff
■ Face	0,96	1,78
■ Hand	0,99	1,81
■ Side	1,39	2,07

Figure 10. (left) The average error rate in percentage for the *mounting position* using *LandOn* and *LiftOff* (+/- standard deviation of the mean). (right) The average selection time for *mounting position* using *LandOn* and *LiftOff* (+/- standard deviation of the mean).

SD=0.09) ($p<.001$) and *hand* had a significant lower error rate compared to *side* ($p<.001$). No significant differences were found for *LiftOff* ($F(2,34)=1.666$, n.s.).

As a further metric for the precision of the touches for *LandOn* we calculated the euclidean distance for each touch point from its target center (see Fig. 9). This gives an estimate of how scattered points were and is a finer measure the just the boolean of hit or miss. A one factorial repeated measures ANOVA showed a significant effect for *mounting position* ($F(2,34)=69.302$, $p<.001$, $\eta^2=0.80$). Bonferroni corrected pairwise comparisons revealed that *face* (M=91,70 px, SD=10.5 px) had a significant lower scatter compared to *hand* (M=110,81 px, SD= 18.40 px, $p<.001$) and *side* (M=160.70 px, SD= 28.84 px). Furthermore, *hand* had a significant lower scatter compared to *side* ($p<.001$). Combining these results with the significant lower error rate showed that participants could easier locate the targets when the touchpad was positioned at the *face*.

Selection Time: Similar to the first study, we measured the time between selecting the start button and selecting the target. Only successful attempts were taken into consideration. Figure 10 shows the average selection time for each *mounting position* using *LandOn* and *LiftOff*. A one factorial repeated measures ANOVA showed a significant effect for *mounting position* ($F(2,34)3.159$, $p<.001$, $\eta^2=0.34$) using *LiftOff*. Bonferroni corrected pairwise comparisons revealed no significant difference between *face* (M=0.96 s, SD=0.18 s) and *hand* (M=0.99 s, SD=0.26 s), but a significant difference between *face* and *side* (M=2.10 s, SD=0.44 s) (($p<.05$)), and *hand* and *side* ($p<.05$).

Usability, Workload and Fatigue: A one factorial ANOVA revealed a significant difference between the *mounting position* for the SUS ($F(2,34)=25.134$, $p<.001$, $\eta^2=0.60$) and NASA-TLX questionnaire ($F(2,34)=29.149$, $p<.001$, $\eta^2=0.63$). Bonferroni corrected pairwise comparisons revealed a significant higher SUS score of *face* (M=79.86, SD=10.72) versus *side* (M=51.11, SD=19.40) ($p<.001$) and *hand* (M=76.11, SD=14.84) versus *side* ($p<.001$). Furthermore, *side* (M=27.11, SD=5.48) had a significant higher workload compared to *face* (M=17.22, SD=4.21) and *hand* (M=18, SD=5.92) ($p<.001$). Overall, *face* had the highest SUS rating and lowest NASA-TLX workload score. This shows that users preferred the *face* location in terms of usability and workload.

To measure fatigue, we let participants state their physical demand on a 7 point Likert scale (subsacle of the NASA-TLX). A one factorial ANOVA revealed a significant difference between the *mounting position* for physical demand ($F(2,34)=8.721$, $p<.001$, $\eta^2=0.34$). Bonferroni corrected pairwise comparisons revealed a significant lower physical demand of *face* (M=3.1, SD=1.7) versus *side* (M=3.8, SD=1.35) ($p<.01$) and *hand* (M=2.2, SD=1.4) versus *side* ($p<.01$).

Discussion

The goal of the positioning study was to measure the impact of the location of the touchpad for *LandOn* and *LiftOff*. The *LiftOff commit method* showed no big differences between the different *mounting positions* even though *face* was slightly better in terms of error rate and selection time compared to *hand* and *side*. Interacting using *LiftOff* benefits from the visualization and therefore does not rely on the proprioceptive sense that much.

The biggest difference for the *mounting position* were found in the *LandOn* condition. Placing the touchpad at the backside of the HMD (*face*) resulted in the overall best result (significant lower errors, scatter of touchpoints and highest SUS and lowest workload). Participants mentioned that they had a better ”understanding” and ”perception” when trying to blindly find the touch points. This probably results from the fact that the proprioceptive sense works better around the facial location and has more cues that the participants know the location of (eyes, nose, mouth etc.). Holding the touchpad in the hands (*hand*) users only have two known relation points, the supporting hand and an approximate of the location from the finger touching. Participants also mentioned it was more difficult to coordinate those two actions (holding still and touching) which is easier in the *face* position. When positioning the touchpad on the *side* participants had to create a mental mapping from the physical touchpad located perpendicular to the virtual floating pad. Participants mentioned that this was inherently difficult (we let participants experience the reversed mapping aswell but noone perceived it as better fitting) whereby placing the touchpad at the back of the HMD (*face*) allowed "almost directly touching" the targets.

Fatigue

One of the big concerns when designing interaction for IVEs is the level of fatigue users will experience when interacting. Hand tracking technology such as the Leap Motion are a negative example here because of the 'touching the void' effect [6]. Furthermore, [11] and [13] showed that having the 'elbows tucked in' or 'bent the arm' results in significant less fatigue than stretching the arm away from the body. However, the last one is necessary for most hand tracking devices since they are attached on the backside of the HMD and the hands must be in their FoV.

Using *FaceTouch*, fatigue occurred after our user studies that took on average over 1h. However, the motivation for FT is that such an interaction is being often used for short utilitarian purposes. Furthermore, when comparing against the currently wide spread touchpad at the temple (*side*), *FaceTouch* resulted in significant lower physical demand. To further increase the comfort of the interaction, participants started already to apply techniques on how to support their arms or heads to avoid fatigue effects (e.g. 'The Thinker Pose', lean back into the chair wrap the non-dominant arm around your chest and rest the dominant arm on it). This position can easily be held over the envisioned period of interaction compared to stretching the arms away from the body [11, 13].

When using *FaceTouch* over a longer periode of time participants mentioned to expand the concept and allow to detach the touchpad and be able to hold it in the hand and using it with *LiftOff*. This would lower the fatique of holding the arm over a longer period and allow for a more comfortable position. However, for small and fast interactions, participants (8) preferred using the *face* location.

These results challenge the current location of the touchpad at consumer VR HMDs such as the GearVR which placed its touchpad at the *side*. The current concept for the GearVR only uses the touchpad for indirect interaction(e.g. swipes). If this would be extended to allow direct touch the positioning should be reconsidered.

APPLICATIONS

To present the advantages, explore the design space of *display-fixed* UIs and show that *FaceTouch* is also capable of being used with *world-fixed* UIs we implemented three example applications (cf. video figure). First, we are going to present a general UI concept which we used to embed *FaceTouch* into VR applications. Afterwards, we present three example applications (gaming controls, text input and 3D modeling) we developed to show how *FaceTouch* can enhance interaction for current VR applications.

General UI Concept

In consumer VR there are currently very little UI concepts to control the device at a general UI level (e.g. control settings inside an IVE). Most devices such as the Oculus Rift and Google Cardboard let the user select applications and content and only afterwards the user puts on the device and immerses into the scene. To change settings the user has to take of the HMD and change those. The reason of which is that VR requires new interaction paradigms incompatible to standard interfaces.

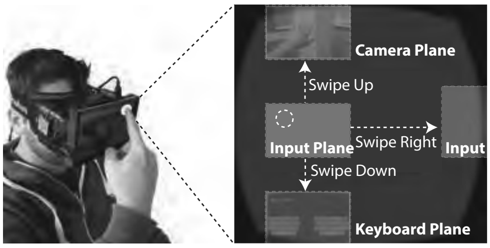


Figure 11. Users can switch through different types of planes (e.g. Keyboard Plane or Pass-Through-Camera Plane) using up or down swipe gestures. Swiping right or left opens the settings of a certain plane. This general model allows to navigate through menus without having to leave the current IVE.

By allowing the control of *display-fixed* UIs, *FaceTouch* enables a new way of navigation through UIs in IVEs without having to leave the current scene (Fig. 11). The virtual plane can be used to place UI elements similar to current smart phones (e.g Android). By swiping up and down users can navigate through different virtual planes containing features such as *Camera Passthrough*, *Application Plane* or *Settings Plane* (Fig. 11). Swiping right and left offers settings or further details to the currently selected virtual plane. This allows for interaction with *display-fixed* UIs without having to leave the current IVE. Since this interaction is not time critical, *LiftOff* or *PressOn* can be used as the *commit method*.

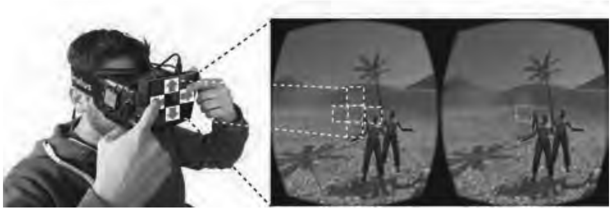


Figure 12. A user controls a first person zombie shooter using *FaceTouch* in combination with *LandOn*. Five buttons for the interaction were arranged in a cross over the full touchpad (the shown arrows are only used to visualize the locations of the buttons and are not displayed in the actual prototype). This allows for decoupling gaze from interactions such as walking.

Gaming Controls

Games that require the user to control gaze and actions independently from each other (e.g. walking whilst looking around) currently demand to be used with a game controller. Using *FaceTouch* in combination with *LandOn*, simple controller elements can be arranged on the touchpad (Fig. 12). *LandOn* seems most suitable for this application, as it delivered the shortest input times while still providing the low accuracy that this type of application requires. In our implementation of a zombie shooter game we arranged five buttons (four buttons for walking and one for shooting) in a cross over the full touch plane of *FaceTouch*. The accuracy of the touches is completely sufficient since users don't have to move their fingers over a great distance but mostly hover over the last touch point (resting the hand on the edges of *FaceTouch*). This allowed users to control movements independent from the gaze without having to carry around additional accessories.

Text Input

Current implementations of applications which need to search through a collection of data (e.g. 360° video databases) on mobile VR HMDs, require the user to browse through the whole library

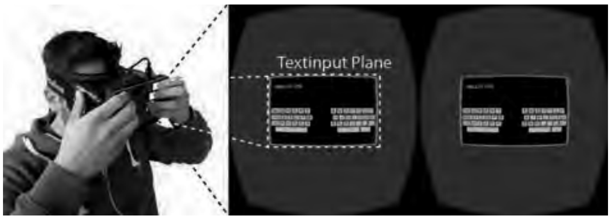


Figure 13. A user is typing text using *FaceTouch* in combination with *LiftOff*. The keyboard is split in half to support the hand posture which is resting at the HMD case.

to find a certain entry. We implemented a simple QWERTY keyboard to input text inside an IVE. Using *display-fixed* UIs, allows for implementing the keyboard without having to leave the IVE (Fig. 13). Since this scenario requires a precise interaction we used *LiftOff* as the *commit method*. In an informal user study we let three experts without training input text (”the quick brown fox..”) resulting in approximately 10 words per minute. This shows the potential of *FaceTouch* for text input in IVEs, which of course needs further investigation.

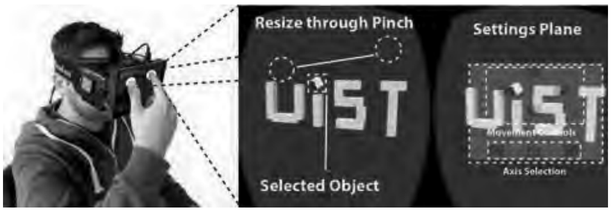


Figure 14. A user creating a 3D model of a UIST logo. The currently selected object is highlighted in a different color. A pinch gestures is used to resize the currently selected cube. The right eye shows a settings plane which can be opened using a swipe gesture

3D Modeling

FaceTouch allows not only to select a certain object in 3D space but to rotate, resize and translate the object by using multi-touch gestures. We implemented a simple ”sandbox” 3D modeling application to show the capabilities of *FaceTouch*. For this application we used the general UI concept which we presented beforehand.

Initially the user starts in a blank environment with their touches visualized. Pushing down on the touchpad (*PressOn*) the user can spawn cubes inside the 3D world. After selecting one cube (*PressOn*), it can be resized using two fingers (pinch-to-zoom) or rotated using three fingers. By swiping down over the whole touchplane (using three fingers) the user can open a virtual plane showing some control buttons (Fig. 14 right). The user can either fly around the model (movement controls) or select the axis he wants to manipulate (e.g. rotate around x-axis).

LIMITATIONS AND FUTURE WORK

One limitation of the current implementation of *FaceTouch* is the weight the prototype puts on the user’s head ($\approx$ 800g). This can be addressed in future prototypes by using more lightweight components. Furthermore, the interaction with a touchpad on the user’s face leads to arm fatigue after a while (similar to the current touchpad at the side of the HMD) which can be counterfeited by supporting the arm and sitting in a comfortable position.

In the future we are planing to enhance the interaction with *FaceTouch* for multi-touch and two-handed interaction (e.g for text entry), further investigating the performance. Furthermore, we are planing to explore how gestural interaction can be further embedded into the concept of *FaceTouch*.

CONCLUSION

Our initial goal of this work was to create an interaction concept which, against the current trend in VR research, focuses on performance for input and not immersion (such as the Leap Motion). We envision touch to become a crucial input method in the future of mobile VR after the first run on ”natural” interaction will wear of and people demand a more comfortable form of interaction on a daily basis (or for scenarios where the level of immersion is not essential such as navigating through a menu or even a virtual desktop). We therefore designed *FaceTouch* to fit into the demand of future mobile VR applications such as quick access to pointing interaction for navigating menus and furthermore the possibility to detach the touchpad and use it in the hands for a longer interaction.

In this paper we presented the novel concept of *FaceTouch* to enable touch input interaction on mobile VR HMDs. We have demonstrated the viability of *FaceTouch* for *display-fixed* UIs using *LiftOff* for precise interactions such as text entry and *LandOn* for fast interactions such as game controllers. Our first user study, besides very positive user feedback, revealed important insights into the design aspects of *FaceTouch* like the right plane distance (*MidPlane*), impacts of various input methods (*LandOn*, *LiftOff*, *PressOn*) and resulting overshooting behavior. Further we provided optimal target sizes for implementing UIs for *LandOn* interaction.

Our second user study compared the *mounting position* for the touchpad and their impact onto the performance of the interaction. We showed that mounting the touchpad on the *face* resulted in a significant lower error rate for *LandOn* (8% less than *hand* and 29% less than *side*) and *LiftOff* (2% less than *hand* and *side*) and the fastest interaction (*LandOn* .96 s and *LiftOff* 1.78 s). The concept of *FaceTouch* can be furthermore enhanced to also support the ability of removing the touchpad from the mounting position and holding it in the hand. By analyzing the touch behavior of users for all positions we give an indicator of how to implement the targets in terms of size and location.

More importantly, *FaceTouch* can be combined with other input techniques to further enrich the input space as has been exemplified by the 3D modeling application. Finally, we demonstrated the large design space of *FaceTouch* by implementing three example applications emphasizing on the advantages of *FaceTouch*. As *FaceTouch* can easily be implemented into current mobile VR HMDs such as the Samsung GearVR, we suggest deploying it in addition to *HeadRotation*. Thereby, for the first time, *FaceTouch* enables *display-fixed* UIs as general UI concept (e.g. for text input and menu selection) for mobile VR as well as combined *display-fixed* UI and *world-fixed* UI interaction for a much richer experience.

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SnapBand: a Flexible Multi-Location Touch Input Band

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ABSTRACT

The form factors of current wearable devices are designed and limited to be worn at specifically defined on-body locations (such as the wrist), which can limit the interaction capabilities based on physical constraints in body movement and positioning. We investigate the design of a multi-functional wearable input device that can be worn at various locations on the body and may as well get mounted onto objects in the environment. This allows users to adjust the device's location to different affordances of varying situations and use cases. We present a *SnapBand* as such a multi-location touch input device that can be quickly snapped to different locations.

Author Keywords

Wearable; multi-location; touch input device; on-body; off-body

ACM Classification Keywords

H.5.2. User Interfaces: Input devices and strategies

INTRODUCTION

For on-body wearable input devices, the form factor specifies the body location the device is worn, each having different properties in reachability. Wagner et al. introduced a body-centric design space [6] showing that different involved body parts lead to different physical contraints in body movement and positioning. E.g. a smartwatch on the wrist requires two hands for touch interaction and restricts movement and position of the watch hand [1]. This can make interaction more difficult to perform, potentially dangerous or even impossible depending on other mobile tasks that simultanouesly involve these body parts, such as biking.

Lyons et al. argued that wearable designer should examine multiple dispositions, i.e. the user's varying poses and physical relationship between them and the wearable device [4]. Users can adjust their pose or the on-body placement of a wearable device for active or passive use, however wearable input devices are mostly designed to be used on only a single on-body location (such as the wrist), which limits the interaction capabilities and constrains the users' poses. In this work, we investigate the possibilities of using an input device that can be used on multiple on- and off-body locations. We present a *SnapBand* as a flexible touch input band that can quickly be snapped to different locations.

MULTI-LOCATION TOUCH INPUT

Depending on varying affordances and use cases, different on - and off-body locations can be suitable for touch input. One solution for this is to integrate touch capabilities into more and more everyday objects and environments [5]. By this, a selection of touch capabilities can be available to users on multiple locations at once. This principle is also utilized for personal mobile devices, such as phones, watches and tablet computers that might be accessible at the same time but embody different affordances.

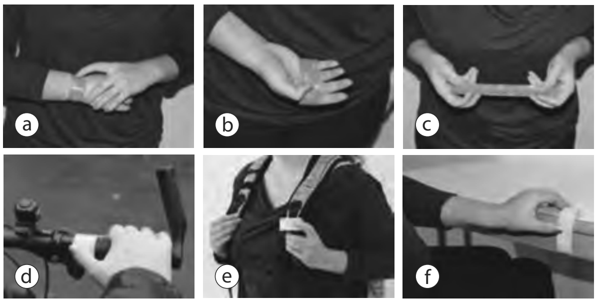

Figure 1. ***SnapBand*** **is a touch input device that can be snapped, worn and attached to multiple on- and off-body locations, such as onto the wrist similar to a smartwatch (a), as a one- or two-handed touch controller (b&c), attached to a handlebar on a bycicle (d), on a strap of a backback (e) or the edge of a table (f).**

We propose an approach that does not require a wide instrumentation of everyday objects and environments, but instead to use a form factor that can be worn or attached to multiple locations within the environment. Such a design could take various forms. An example could be a clipping-mechanism (cf. iPod Shuffle) to allow the input device to be attached to various locations on clothing. Clipping directly onto the user's skin (such as the wrist) however remains unsuitable due to stretching. Ideally, a form factor for a multi-location input device should be comfortable to wear on clothing as well as on the user's skin. We found the *snap band* form factor to be suitable for both.

SnapBand

A *snap band* is a flexible bistable spring band that can have two distinct configurations: In a first equilibrium position the spring band is flat. By slapping the end of the band against a body part such as the wrist or an object such as the edge of a table, a second equilibrium is reached, at which point the band curls into a circular form factor (see Fig. 1). We utilize the *snap band* form factor to enable touch capabilities at varying locations. The act of snapping the device is a transition between multiple interaction dispositions [4] and was shown by its origin as a toy to be a pleasant interaction. *Snap bands* were mostly snapped onto wrists, but could also be attached to other body parts such as arms or thighs or into the environment. When used in the curled configuration, the location is ideally roundish and embraceable by the band. In this position, the band remains in its position and tightens itself by its spring mechanism. It can however also be used in its flat configuration, e.g. as a bimanual handheld input device (see Fig. 1c). Suitable off-body locations are ideally close in range of the user's hands such as the handlebar of a bicycle (see Fig. 1d) or gym machine or the edge of the user's desk (see Fig. 1f). When snapped into location, the band is immediately available for touch input that can be used for a variety of mobile or stationary interaction, e.g. to control smart eyewear, external displays, smart earbuds, a music player or smart home appliances.

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Figure 2. The *SnapBand*-prototype in a flat (left) and curled (right) configuration. A BLE Nano at the end of the band serves as a micro controller powered by a CR2032 coin cell battery.

PROTOTYPE

For the *SnapBand* prototype, a common commercially available snap band was extended with a custom touch input design (see Fig. 2). The base band had dimensions of 22 x 2.5cm which was long enough to wrap around an upper arm, but not too long to not fit a small wrist. For the touch sensor, we used a flexible printed circuit design with a copper coating and active capacitive sensing in shunt mode using the capacitive sensing library for Arduino. A touch resolution of 8x2 pixel showed to be sufficient for a simple 2d touch gesture set of left, right, up and down swiping and tapping for selection. For processing of the touch sensing, a BLE Nano Arduino was mounted to the end of the band. Power was supplied by a CR2032 coin cell battery beneath.

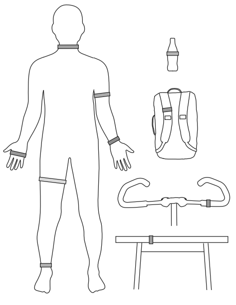
USER STUDY

We conducted a user study to investigate whether the concept of multi-location touch input is suitable and which locations are preferred for interaction. We recruited 16 participants between 19 and 29 years (*m* = 23.6; 8 female) of which all stated to be familiar with touch devices, but having only very little experience with wearables. Participants would use the device within three different use cases: First, participants would use the *SnapBand* as an input device for a head-worn display (a Google Glass). In this use case, the *SnapBand* was worn on the wrist and participants would navigate through a contact list and open and dismiss information. The second use case was using the *SnapBand* as a handheld controller for a (staged) presentation, where participants would show 16 slides of an illustrated story. For the third use case, participants would use the *SnapBand* to control music while simulating a workout on a gym machine (ergometer) where the *SnapBand* was attached to the handlebar. These use cases served to make participants familiar with the concept of multi-location touch input in varying situations. Following this, participants provided feedback using a structured questionnaire with open-ended questions and 5-point Likert scales.

Results

Participants found the concept of using a single device on multiple locations useful (*m* = 4.69, *sd* = 0.46; from 1 - strong disagreement to 5 - strong agreement) and agreed that depending on the use case a different location can be preferable (*m* = 4.56, *sd* = 0.50). The *SnapBand* was seen as a suitable form factor for multi-location input (*m* = 4.56, *sd* = 0.61) and interaction with the device was reported to be easy to learn (*m* = 4.86, *sd* = 0.33).

Participants were asked which advantages and disadvantages they see in the introduced *SnapBand* concept. Appreciated was foremost the versatility (P6) and flexibility (P4, P8, P15) of the input device and that its location can be changed quickly (P10, P16), which was seen as efficient for interaction (P11, P13). The form factor was also seen as lightweight (P3) and easy to transport in a curled configuration (P2, P5, P6). Mentioned downsides were that the device could slip off a location (P12, P15) and potentially get lost (P4, P6, P16) which was seen as a big problem when the device is the only available input device (P1, P7, P8). It was also commented that the band size would always be a compromise and could be too large or too small for some locations (P5, P6, P9).



Location	*User Ranking*		*User Rating*				
			Interaction Length	in public		in private	
	Median	IQR		Mean	SD	Mean	SD
Wrist	**1**	1 - 1.5	2-4s	**4,81**	0,53	**4,81**	0,53
			4-10s	**4,75**	0,43	**4,81**	0,53
Hand Palm	**3**	2 - 4.5	2-4s	**4,19**	1,01	**4,25**	0,97
			4-10s	**3,94**	1,25	**4,13**	1,17
Handle Bar	**3**	2 - 5	2-4s	**4,13**	1,16	**4,25**	1,09
			4-10s	**3,81**	1,47	**3,88**	1,27
Upper Arm	**4,5**	3 - 6	2-4s	**3,75**	1,20	**3,75**	1,15
			4-10s	**3,38**	1,22	**3,56**	1,22
Table Edge	**5,5**	4 - 6.5	2-4s	**4,06**	1,14	**3,75**	1,30
			4-10s	**3,94**	1,14	**3,69**	1,40
Backpack Strap	**6**	3 - 7.5	2-4s	**4,13**	1,17	**3,19**	1,59
			4-10s	**4,00**	1,32	**3,13**	1,65
Bottle	**7**	6 - 8.5	2-4s	**3,56**	1,22	**3,50**	1,22
			4-10s	**3,31**	1,36	**3,38**	1,17
Thigh	**8**	5 - 8.5	2-4s	**2,75**	1,44	**2,94**	1,50
			4-10s	**2,38**	1,54	**2,75**	1,60
Ankle	**8**	6 - 9	2-4s	**2,25**	1,44	**2,44**	1,50
			4-10s	**1,94**	1,30	**2,25**	1,39
Neck	**10**	10 - 10	2-4s	**2,25**	1,44	**2,25**	1,44
			4-10s	**1,81**	1,38	**1,94**	1,39

Figure 3. User evaluation of *SnapBand* input locations. Participants rated whether they can picture themselves using a touch input band on the respective location on a 5 point-Likert scale (1 = totally disagree; 5 = totally agree) under the conditions of interaction length and whether the setting is in public or in private. Participants would also rank the locations for preference.

For the multi-location touch input, participants were asked to rate for a set of 10 locations (6 on-body, 4 off-body) whether they would use a touch input band on the respective location (see Fig. 3) under the conditions of interaction length (c.f., [2]) and whether the usage would take place in private (at home) or in a public setting. Subsequently, participants would rank the locations for their personal preference. Participants overall preferred the locations that they used within the three use cases (*wrist*, *handheld*, *handle bar*). For the on-body locations, acceptance was very similar as reported by Karrer et al. for interactive clothing [3] in that *wrist*, *hand* and *arm* are preferred over body parts more distant to the fingers. Interestingly, while on-body locations were rated lower for a setting in public, off-body locations like the *backpack strap* and the *table edge* were rated *higher*. This could hint at present concerns regarding the social acceptance of on-body locations in public. In this regard, a multi-location input device like the *SnapBand* can enable users to choose and adjust an input location based on *individual preference* of a respective usage situation, including expected efficiency, reachability, comfort and social acceptance.

CONCLUSION AND FUTURE WORK

We presented *SnapBand*, a multi-location touch input band that can be worn or attached to multiple on- and off-body locations. In the future we want to improve the prototype with a higher touch resolution and want to explore possibilities for the device to automatically detect its location based on orientation and alignment. We plan to use this information to infer its intended use case.

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Unconstrained Pedestrian Navigation based on Vibro-tactile Feedback around the Wristband of a Smartwatch

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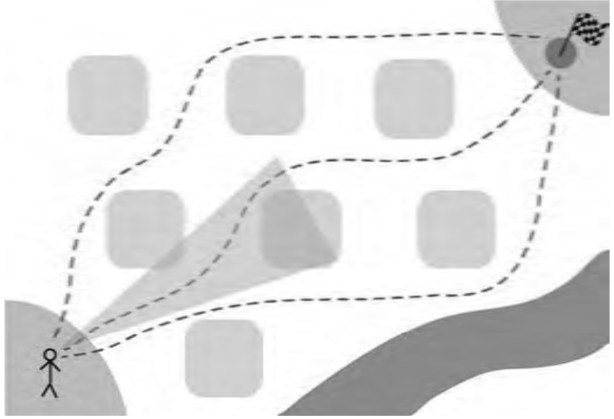

Figure 1: A pedestrian choosing their own way to a target destination.

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Abstract

We present a bearing-based pedestrian navigation approach that utilizes vibro-tactile feedback around the user's wrist to convey information about the general direction of a target. Unlike traditional navigation, no route is pre-defined so that users can freely explore the surrounding. Our solution can be worn as a wristband for smartwatches or as a standalone device. We describe a mobile prototype with four tactors and show its feasibility in a preliminary navigation study.

Author Keywords

Pedestrian Navigation; Vibro-tactile; Wrist; Watch

ACM Classification Keywords

H.5.2 [Information interfaces and presentation (e.g., HCI)]: User Interfaces

Introduction

Pedestrian navigation is nowadays widely available with the prevalence of mobile devices. However, much like navigation for cars, pedestrian navigation is mostly turn-by-turn based and optimized to find the shortest path to a given target, dictating the user's route. This can take away much of the exploratory nature of an individual and has an influence on their behavior [2].

When exploring cities, pedestrians much like tourists, tend to choose their own way based on their personal liking, such as favoring to wander through a historic city part or strolling along a riverside even though this poses a detour. In this regard the journey becomes the objective, while the navigational target is secondary. In these cases, classical turn-by-turn based navigation can take away much of the exploration and enjoyment of the surroundings. We want to reduce the complexity of the navigation task, so that users do not have to spend their visual or auditory attention on a handheld device, but rather get an idea of the general direction of the target and can reassure themselves they are heading in the right direction.

With the current trend of electronic wristworn devices such as fitnesstracker and smartwatches, we envision haptic-feedback around the user's wrist to convey the targets direction. Navigation using vibration is already built into smartwatches, e.g. the Apple Watch uses two different vibration patterns for left and right turns. However, much like on handheld devices this is based on turn-by-turn navigation. In contrast, we provide the user with a general sense of the direction of the target, so the user can find their own way.

We want to complement rather than replace traditional navigation systems in situations where users want to freely explore the surroundings while heading to a target instead of necessarily favoring the shortest or quickest path.

Related Work

Bearing-based pedestrian navigation has already been explored by Robinson et al. [11]. Users can make their own choice by scanning the environment with their handheld device to get vibro-tactile feedback when pointing in the general direction of the destination. In social gravity [16] this approach is used as a virtual tether for multiple users to find and meetup.

In multiple works, belts have been used to convey directional information around the user's waist via multiple vibrators [13] to either constantly vibrate towards the north as a sixth sense [9], or to keep the user on a route by continuous vibration in the direction that is to turn [3]. Erp et al. found that directional waypoint mapping on the location of a belt is effective for navigation, but that coding for distance does not improve performance [14].

Another possibility to code direction is by using different vibration patterns with a single vibrator. In PocketNavigator [10], length and sequence of two tactile pulses are used to convey direction. In Tactons [6], different rythms are used to convey left, right and stop signals. NaviRadar [12] uses a radar metaphor where a radar sweep rotates clockwise. Tactile feedback is provided for each full radar sweep and whenever the sweep hits the direction of the next turn.

Other vibro-tactile navigation techniques use different on-body placements: Meier et al. [8] embed multiple vibrators into the sole of a shoe. Bosman et al. [1] placed a vibrator on both wrists to convey left and right turns on the respective wrist.

Tactor placement on the wrist has been explored by Lee et al. [4]. Using a 3x3 tactor matrix on the back of a potential watch, the vibro-tactile intensity on the outer areas was perceived as stronger as the same stimulus on the inner areas of the wrist. In Buzzwear [5], three tactors got placed in a triangle on top of the wrist. In a thorough user study, intensity was the most difficult parameter to distinguish, while temporal pattern was the easiest. Tatscheko et al. [7] compared placing four tactors underneath a wrist watch against embedding them into a wristband. Around the wristband, a higher perception bit rate was achieved.

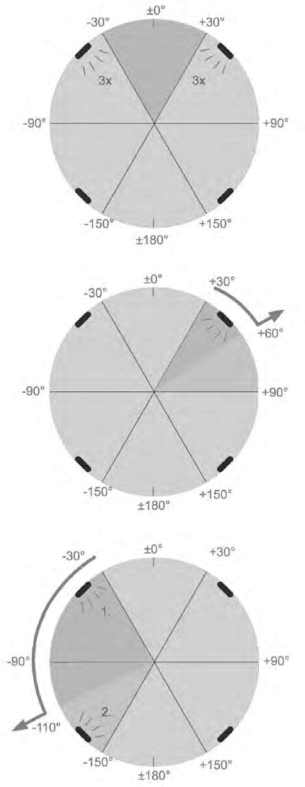


Figure 2: Direction is coded into 6 areas using 4 tactors. Temporal length of the vibration conveys the angular offset of the user to the target. When heading towards the target, the front tactors vibrate simultaneously three times.

Concept

Our bearing-based pedestrian navigation system utilizes vibro-tactile feedback around the wrist embedded into a wristband. While other body locations are possible (i.e. the waist using a belt), the wrist is promising due to the ongoing trend of smart wrist-worn devices. While nowadays these devices contain only one tactor if any at the watch position, it is possible to extend the functionality with smart accessories within the wristband to include multiple tactors around the wrist.

We embedded four vibration motors into an elastic fabric wrist band (see Fig. 3). The elastic band was chosen to include different wrist sizes of participants without having to alter the position of the tactors. For the distance of the sensors, similar to [7], we followed the suggestions of Weinstein [15], which is 38mm on the forearm to differentiate two tactile stimuli. We chose the outer wrist areas for the four tactors (see Fig. 4) as related work suggests that these areas are more sensitive towards the perceived intensity [4]. This accords with our own informal testing with different locations, e.g. in a top / bottom / left / right arrangement it was difficult to differentiate tactile feedback between top and bottom of the wrist, while left and right was easy to differentiate. For this reason we chose top/left, top/right, bottom/left and bottom/right as the four tactor locations (see Fig. 2).

We allocated six distinct directional areas, each occupying 60° (see Fig. 2). The simplest case is the user heading in the correct direction so that the target is within 30° to the left or right in front of the user. In this case, the upper left and upper right tactors vibrate simultaneously multiple times (we chose an arbitrary number of three times). Whenever the user is heading too far in the wrong direction (i.e. further than 30° away from the destination), they will get different information about their drifting. In this case the top left, respectively top right, tactor will vibrate. The duration of the vibration conveys the angular offset, starting from 0.5 seconds for 30° up to 2 seconds for 90°. Whenever the user passes the target (i.e. it is more than 90° behind him), in addition to the top left (or top right) tactor, the bottom left (or right) tactor will join the vibration after 2 seconds for up to another 2 seconds (for the maximum of 150°). By this, the length of vibration is a linear function of angular offset. Also, the addition of the second tactor on the bottom activating is a strong indicator for the user of heading in the wrong direction, so that they might consider making a turn. When facing the opposite direction, both of the bottom tactors vibrate simultaneously multiple times. For the front (and back) the exact angle is not conveyed. This was chosen to not let the user get the impression that they should steer in a straight line to the target, e.g. jaywalking a street, which could pose a threat to pedestrian safety.

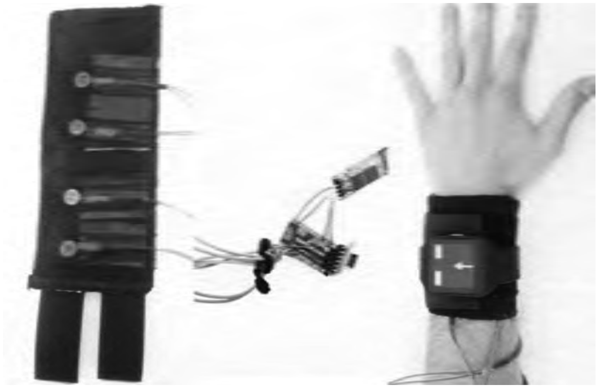


Figure 3: The watchband prototype. Elastic wristband with embedded tactors, Arduino and Bluetooth module for connection and the worn prototype.

Figure 4: Positioning of the four tactors on the top and bottom on the user's wrist.

The frequency of vibro-tactile feedback is based on the directional area and increases the more the pedestrian is heading off-target to raise their awareness. When heading opposite the tactile feedback is displayed every 7 meters and up to 25 meters for the correct direction. In cases where the general direction to a target poses very large obstacles that are difficult to bypass, single waypoints are added. Such cases include rivers that can only be crossed by a bridge in far distance and sparse railroad crossings.

Besides the ongoing vibro-tactile feedback, the user can glance on the watch to get information about the map, and the direction and distance of the target. Also the user can pause and resume the navigation. e.g. for visiting a street shop or sitting down at a cafe.

Implementation

For the four tactors units we used DealMux vibration DC micro motors (3V, 70mA, 12000rpm). Unfortunately, with current commercially available smartwatches, it is not possible to simply attach vibro-tactile accessory. For this reason we used an Arduino Pro Mini 328 5V that powers the tactors and is wired to an HC-06 Bluetooth module to communicate with the watch. We chose a Sony Smartwatch 3 running Android Wear which features a built-in GPS module.

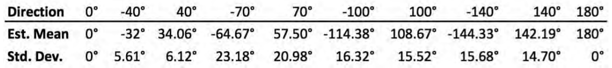
For the tactors, we wanted to make sure that active units are distinguishable. We glued them into the inner side of an elastic fabric bandage and sewed a very thin fabric mesh layer on top (see Fig. 3) so that the tactors were still in contact with the skin when the band was worn. The elastic fabric was chosen to fit multiple wrist sizes in the user study and to prevent vibration of the whole band which occured in testing with more sturdy prototypes. We envision more common looking watchbands with integrated tactors in the future.

User orientation is difficult to detect and can be errenous. With neither the phone, nor the watch being in a horizontal position during walking, magnetometer data is not a reliable indicator for orientation. For this reason, we use the user's recent walking trajectory. This however means, that a user standing still and turning around causes problems for the detection.

Experiment

We conducted a preliminary user study to learn more about the feasability of wrist-worn tactors for unconstrained navigation. We were especially interested in whether participants would be able to navigate to a target with only the general direction provided. We recruited 16 participants (4 female) between 16 and 55 years old (M=26.25 SD=12.93). None was working in areas related to HCI. The study was split into two parts that were conducted after another in two different settings. In the first part, participants were made familiar with the concept, areas and direction of the tactile feedback. They were seated in a quiet room on a table wearing the prototype and were first exposed to the different areas following a defined sequence of angular directions (0°, 30°, 90°, 150°, 180°, -150°, -90°, -30°) 2-3 times in a row until the participant stated to be familiar with the concept. After that, users had to recognize area and angle of a second set of angular directions one time each (0°, 40°, -40°, 70°, -70°, 100°, -100°, 140°, -140°, 180°) and mark their answer for each trial on a sheet of paper. The sequence of these trials was counterbalanced. A sketch showing the six areas and their angular boundaries (similar to Fig. 2) was provided throughout the study. Participants had to wear headphones with music on to prevent audio feedback of the tactors.

Participants could differentiate the six areas very well with an accuracy of 97.5% of identifying the correct direction



Direction	0°	-40°	40°	-70°	70°	-100°	100°	-140°	140°	180°
Est. Mean	0°	-32°	34.06°	-64.67°	57.50°	-114.38°	108.67°	-144.33°	142.19°	180°
Std. Dev.	0°	5.61°	6.12°	23.18°	20.98°	16.32°	15.52°	15.68°	14.70°	0°

Figure 5: Results of the first part of the user study. Participants tended to underestimate small angles and to overestimate large ones.

area that was displayed via tactile feedback. For the top areas, participants slightly underestimated the angles, while for the bottom areas, they tended to overestimate (see Fig. 5). 72% of the overall estimates were within a width of $\pm 10^\circ$ of the displayed angle while 88% were within $\pm 20^\circ$. These first results show that it is possible to estimate the general direction of a target using vibro-tactile feedback around the wristband. In previous work it was found that the vibrotactile angular width does not need to be particularly small and that in fact larger angular widths can help to minimize user frustration [16].

The second part of the user study was a navigation task which was conducted subsequently in the city of Friedrichshafen. The target was unknown to the participants and approximately 450 meters away from the starting position (see Fig. 6). Participants were told to reach the target but to choose their own route as they like to. Since we wanted to learn about the feasibility of wrist-worn tactile-feedback for navigation, we disabled the visual feedback of the watch. All participants reached the target without any navigational help of the presenter. At the beginning, participants started wandering off in different directions. This was due to the target (and target direction) being unknown. However, very soon participants got a good idea of the general direction and headed towards the target on slightly different routes. Most participants took the shortest and quickest path, while a few strolled a little bit off but eventually turned towards the target (see Fig. 6). Participants rated the mental load in the navigation task slightly lower (M=2.44 SD=0.81) than in the previous angle detection task (M=2.94 SD=0.68) on a 5-point likert scale. This suggests that while the exact angle detection requires some concentration, the actual detection during navigation is easier, because the user quickly develops an idea of the general direction that is then getting confirmed which each new vibration. It was observed that the different pattern for the front area triggered assurance and satisfaction with participants increasing their pace when heading in the right direction. Sometimes the vibration was missed. For these cases a possibility was requested to repeat or actively requery the direction. In these situations the watch display that was disabled for the study could be helpful. One suggestion was to use a shake gesture with the wrist to repeat the last feedback. Participants were having small talk with the presenter while navigating which further suggests that the navigation task is not very demanding and liberating the user's attention.

Figure 6: Participants took different routes to the target. While most took the shortest path, some went off for a small detour, but eventually turned towards the target.

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Movelet: a Self-Actuated Movable Bracelet for Positional Haptic Feedback on the User's Forearm

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ABSTRACT

We present *Movelet*, a self-actuated bracelet that can move along the user's forearm to convey feedback via its movement and positioning. In contrast to other eyes-free modalities such as vibro-tactile feedback, that only works momentarily, *Movelet* is able to provide sustained feedback via its spatial position on the forearm, in addition to momentary feedback by movement. This allows to continuously inform the user about the changing state of information utilizing their haptic perception. In a user study using the *Movelet* prototype, we found that users can blindly estimate the device's position on the forearm with an average deviation of $1.20cm$ to the actual position and estimate the length of a movemement with an average deviation of $1.44cm$. This shows the applicability of position-based feedback using haptic perception.

Author Keywords

Self-actuated; movable; wearable; haptic; positional feedback; forearm

ACM Classification Keywords

H.5.2. User Interfaces: Input devices and strategies

INTRODUCTION

Many wearable and mobile devices utilize vibro-tactile feedback for notifications. This feedback however is only momentary, so that users can miss the tactile sensation and need to invest attention. With *positional* feedback, we introduce a sustained haptic stimulus that is continuously available in the background to convey the state of low-bandwidth information. This can be used to gradually display progress, e.g. for pedestrian navigation to gradually display the distance to the next turn, for mobile notifications to provide a sense about the amount of unread messages, or for time scheduling to convey an ongoing feeling about the time left until the next meeting. We generate this feedback by presenting a self-actuated bracelet that can position itself on the user's forearm by being able to move itself up and downwards. The wearer can temporarily feel the movement (similar to other tactile feedback) in addition to an ongoing spatial haptic perception of where the device is positioned.

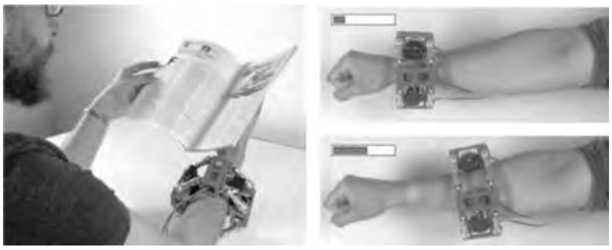

Figure 1. *Movelet* is a self-actuated bracelet that can convey haptic feedback on the user's forearm by movement and positioning.

The contributions of our paper are: (1) a novel self-actuated output device, utilizing the spatial domain of the forearm for *positional* feedback, (2) the concept of sustained background feedback without having to increase an applied stimulus, and (3) the findings of a user study investigating the users' performance in perceiving and estimating position and movement on their forearm.

RELATED WORK

To extend the feedback capabilities of wrist-worn wearables, much work has been done to visually extend the output via additional display spaces [18, 24, 19], or by illuminating the skin around [21]. Visual feedback however requires visual attention. Harrison et al. [10] found that visual alerts on the body work best when positioned on the wrist, but that the reaction time is still very slow (≈ 19 seconds for the wrist).

For eyes-free feedback, vibrations are predominantly being used [16, 3]. Vibration feedback however is working in the temporal domain, so that it captures the user's attention, can be missed when the user is focused and can potentially be disruptive to the task at hand [9]. Thermal feedback can be applied to the skin to feel a change in temperature as heat or cold [29, 26], but strong and fast changing stimuli are required for detection. Another means for tactile feedback is skin drag, where a small physical tactor is mechanically moved to stretch the user's skin, allowing the user to recognize tactile shapes [12, 2]. Alternatively, a tactor can be used to poke the user's skin [13, 23]. This allows for higher bandwidth stimuli, but much like vibrations, the feedback is only momentary.

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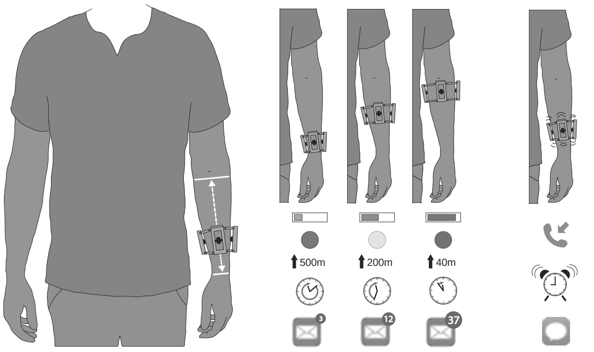

Figure 2. (Left) The self-actuated bracelet can move up and down to position itself on the user's forearm. (Center) The device's position can be used to convey abstract information, such as progress, urgency, distance for navigation, time left until an approaching meeting or the amount of unread notifications. (Right) Fast up and down movements at a location can be used as a means for a temporary notification.

Sustained Feedback
For sustained feedback, pneumatic compression can be applied [20]. Inflating straps can tighten around locations like the wrist much like a blood pressure monitor to generate compression ranged from subtle to forceful [20]. Compression can provide constant background feedback which can ramp up by slowly inflating (or deflating) the device to symbolize progress or to slowly bring something to the user's attention. Similar to thermal feedback however, this requires the applied stimulus to become stronger which with an increased stimulus can be perceived as less pleasant. With *Movelet*, we explore to provide sustained increasing background feedback without an increase in the applied stimulus by using the spatial domain of the user's forearm for *positional* feedback.

Self-Actuation and Smart Jewelry
Self-actuation in Human-Computer Interaction (HCI) was explored to change the affordances of mobile devices [22]. Dementyev et al. envisioned that in the future, wearable devices are dynamic and can move around the body. They introduced Rovables [6], minature on-body robots that can move on clothing via magnetic wheels to serve for input and output and SkinBots [5], on-body robots that can move over skin via two suction legs. Gong et al. presented Cito [8], an actuated smartwatch that can translate, rotate and tilt its face towards the user to address limitations of a fixed watch face.

An important element of jewelry and garments is to appeal and communicate with others. This has been utilized to augment fashion, e.g. a scarf altering its shape to represent emotions and attitude [27] or to dynamically change the color of fabrics on clothing [7] to display abstract information. Kao et al. [15] argued that jewelry and accessories have long been objects for decoration of the human body, but that they remain static and non-interactive. In the future however, smart jewelry could become mobile to vary shape and design [15] as we see an increase in computational jewelry [25]. We envision that such smart jewelry could utilize its motion and positioning as a means of feedback.

Haptic Acuity
Multiple methods have been introduced to measure the haptic acuity of a respective skin region. For the forearm, the haptic acuity was reported by Weinstein [28] as ~3.8cm using the two-point touch threshold (the smallest spatial seperation between two concurrent stimuli) and ~0.9cm using the point-localization threshold (of when a user cannot tell if two successive stimuli were present at the same location). While these methods are useful to compare the acuity of the receptors at different skin regions (in this case the forearm), e.g. for neurological examiniation, they only inform about the haptic acuity, but not about the capability of estimating the *position* of a haptic stimulus.

The localization of a haptic stimulus has so far been limited to multiple vibro-tactile tactors placed on respective body parts, e.g. Cholewiak and Collins [4] used a linear array of seven tactors placed on the forearm and found that the localization (i.e. the identification of the right tactor) was more precise when the stimulus was close to the wrist or the elbow as anatomical points of reference. Jones et al. [14] found that vibro-tactile sensations cause surface waves that propagate across the skin and make the localization of the locus of a vibro-tactile stimulus with tactor distances less than 6cm difficult to achieve. Luzhnica et al. [17] showed that phantom sensations using three vibro-tactile tactos along the forearm can be used to convey continuous values.

In contrast to vibro-tactile sensations, that only reach the fast adapting tactile receptors within the skin during vibration (Meissner's and Pacinian corpuscles), the constant haptic stimulus of *Movelet* via contact force and indented skin also reaches the slowly adapting receptors (Merkel's disks and Ruffini endings). These receptors have already been utilized for skin-stretch displays that utilize the contact force of a small movable tactor to inform directional cues with high accuracies [2, 1]. However this has been limited to direction and tactile shapes during tactor movement. The accuracy in assessing the *position* of a self-actuated haptic stimulus has not been investigated yet.

MOVELET CONCEPT
In this work we present *Movelet*, a self-actuated bracelet that can move along the user's forearm to convey feedback via its movement and positioning. While the movement can be used for momentary haptic feedback to notify the user, the device's *position* provides sustained haptic feedback continuously in the background.

Positional Feedback
The positioning of *Movelet* on the forearm can be seen as an output channel for one-dimensional information. It is thus particularly suitable to convey the state of gradually changing information with a defined endpoint. This can span varying abstract information such as progress (e.g the ongoing completion of a download, a working task, or activity), for urgency (to slowly make the wearer aware when it is increasing), for time awareness (e.g. the time remaining until an approaching meeting), for pedestrian navigation (e.g. the slowly decreasing distance towards the next turn), or for awareness

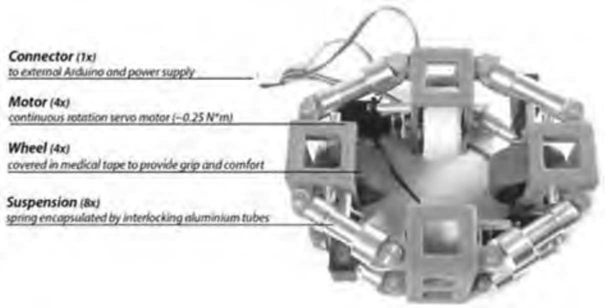

Figure 3. The *Movelet*-prototype consists of four segments that are interlinked, each containing a wheel that is powered by a small servo motor. The interlinkage includes suspension that mechanically expands or contracts to adjust to the varying circumference of the user's forearm. The mechanical wheels were covered in medical tape which showed to provide grip and comfort.

of quantity (e.g. a feeling about the amount of unread emails) (see Fig. 2).

These information can be displayed eyes-free to subtly have an effect on the user. In contrast to other haptic feedback, such as vibro-tactile notifications, the *position* can work as a sustained background feedback that is always available. Unlike visual feedback, perceiving the *position* does not require visual attention and unlike a notification it does not necessarily disrupt the task at hand. These properties can be useful to convey information when the user is engaged in important activities, like a conversation or meeting, where the user then does not get disrupted or has to look onto a display, but can still perceive a feeling about the state of information.

Implementation

For the implementation of the *Movelet* prototype, we first started with design considerations that had to be met to enable self-actuation on the user's forearm. The prototype would need to be capable of moving up- and down the arm and otherwise keep its position, so that a certain amount of pressure or cling to the arm would be required. The arm's shape however heavily differs between users as well as at different forearm position, so that usually the upper forarm has a broader circumference than the user's wrist, which needs to be compensated for by the device. Another importance is that when moving the device along the user's forearm, skin or hair irritations need to be prevented. For the latter reason we designed the prototype so that only little surface area would be in contact with the user's skin.

This led to the design of four mechanical wheels (2*cm* wide; 4*cm* diameter) that contact the user's skin, are evenly distributed around the arm and serve to actuate the device, to stabilize for each direction and to provide the haptic stimulus for the user. To prevent skin or hair irritation we tested different surface materials like plastic, pearl and rubber and found in medical tape the most suitable combination of grip and comfort.

For the *Movelet* to be capable of moving up and down the forearm, the device needed to be able to adjust to the varying circumference from wrist to upper forearm, fit tightly at these different positions and yet be flexible enough to ascend an increasing arm thickness. For this reason, we interlinked the wheel segments via suspension consisting of a spring encapsulated by interlocking aluminum tubes contracting the segments. The design is modular so that users with different arm sizes could wear the device. We provided interlinkage with three different sizes (40, 44, 48mm in length) that could be exchanged for each segment.

Figure 4. (Left) Marker-based camera tracking of movement and positioning. (Center) A user estimating and marking the *Movelet's* position on a previously taken image of his empty forearm, (Right) while his left arm wearing the device is hidden behind a visual cover.

The motorization is optimized to vertically climb an arm and via suspension allowing the device to keep its position and exerting a steady amount of light pressure even though varying arm circumference. Using four continuous rotation servo motors (~0.25 N·m), one for each wheel, the suspension mechanically expands or contracts to adjust to the varying circumference of the arm.

Wheel segments were custom 3d printed, while the interlinkage was custom manufactured consisting of aluminum to optimize for durability, friction and weight. Overall the *Movelet*-prototype weighs 403*g* including the motors but excluding an Arduino and 6V power supply externally connected via wires.

USER STUDY

We conducted a user study to investigate the user's accuracy in estimating the device's position and length of movement on their forearm. So far, studies have been conducted to inform about the haptic acuity of body regions [28], but the accuracy of assesing the position of a self-actuated haptic stimulus has not been investigated yet.

We explored the accuracy of estimating a haptic position using the *Movelet*-prototype and used the user's visual perception as a comparison. Furthermore we were interested in whether this estimation differs for different forearm segments. The user study was conducted as a repeated measures factorial design with the means of *perception* as the independent variable and the participant's estimation of *absolute position* and *relative movement* as dependent variables.

Haptic and Visual Perception

To explore the haptic perception of position and movement, the view onto forearm and device was blocked by a visual cover for the *haptic*-perception condition (see Fig. 4). Furthermore, participants wore noise-cancelling headphones playing brownian noise.

In the *visual*-perception condition, participants would be able to visually observe the device's movement and position by slightly changing their seating posture to be not blocked by the visual cover. With vision as the primary human sense to assess position, distance and movement in the environment, the *visual* perception condition served as a best-case for comparison. We expected the *visual* perception to be more accurate than the *haptic* perception, but were interested in investigating the extent. For a self-actuating wearable like a bracelet, users would in practice be able to visually confirm and complement their haptic perception by glancing at the wearable's position, so that both conditions are important for the usage of a self-actuated wearable.

Procedure

During the study, participants would rest their left forearm horizontally on two cushioned pillars (see Fig. 4). The *Movelet*-prototype would move in-between wrist and upper forearm with outer boundaries chosen, so that the device could not reach wrist joint or elbow to prevent additional cues of feedback. This area was individually identified for each participant and in average had a length of 16.82cm (SD=1.94cm).

For each trial, the device would perform a straight movement to a random position on the forearm. Target positions were randomized following a continuous uniform distribution. We divided the forearm into four equally sized segments and aimed for an uniform distribution of landed segments. Target positions were furthermore constrained to not land within the same segment in sequence and to have a miminum movement distance of 10% of the forearm's length.

The device was automatically controlled and actuated via software utilizing marker-based camera tracking (see Fig. 4) as a ground truth of the device's position.

After each movement of the device, participants estimated the direction and length of the movement first, followed by an estimation of the device's position. Participants were seated so that their left arm wearing the *Movelet* was hidden behind a visual cover, but that they could operate a mouse and computer screen using their right hand (see Fig. 4). For the *visual* feedback condition, participants would slightly change their seating posture so that their vision onto the device was not blocked.

For the estimation of movement, participants would indicate the percentage of movement in relation to the length of their forearm on a slider bar (ranging from 0 - 100% of arm length). For the estimation of the device's absolute position, they were presented a pre-taken image of their empty forearm on which they would place an indication marker for the position. After each trial, participants would then see the actual position as a second marker on the image as well as the actual length of movement as an indication on the slider bar. Trials were conducted consecutively with the previous trial's position being the starting position of the next trial.

The two conditions (*haptic* and *visual* perception) were presented using a 2x2 latin square for counterbalancing. For each condition each participant conducted 40 trials split into two sections with a break inbetween. Conditions were further balanced, by alternating the independent variable after each section break, resulting in an A-B-A-B study design.

This was preceded by three training phases to get familiar with the haptic and visual perception. First, participants got introduced to the *Movelet*-prototype and were allowed to freely move and position the device on their forearm using a joystick. The device was then actuated to pre-defined positions five times, with the participant having to estimate movement and position, while being allowed to watch the device and its movement (i.e. the *visual* condition). Lastly, the device was hidden behind the visual cover to blindly estimate a final training set of five trials relying only on haptic perception (i.e. the *haptic* condition). The noise-cancelling headphones were handed only after the training phases, so that participants were encouraged to ask questions during training.

Participants

We randomly recruited 16 participants (8 female) from our institution with an average age of 26 (range: 21 to 29). 4 participants stated to regularly wear watch-like devices, while 2 stated to regularly wear jewelry on their forearm; 2 were left-handed. The study took 60 minutes on average and each participant received 12 *currency* and a chocolate bar as compensation.

Results

Our analysis is based on 16 participants overall estimating 1368 movements and positions. Marker-based camera tracking was used as the ground-truth for all measurements. One participant's data (P9) had to be removed from the evalation due to the results of both conditions averaging as outliers. We recruited a 17th participant as a replacement. Overall 5 estimations of position and movement were removed as outliers. All outliers were detected by using the modified Z-score by Iglewicz and Hoaglin [11].

Movement

Participants were able to indicate the correct movement direction for all but 3 trials (99.8%). Movements had an average duration of 1.61 seconds and an average length of 7.61cm. The average deviation of the users' estimation of movement length to the actual length of movement for the *haptic* perception was 1.44cm (SD=0.37cm) and 1.18cm (SD=0.46cm) for the *visual* condition, so that using their vision, participants were 0.26cm (18%) more accurate. A paired t-test showed that the difference was significant ($t(15)=2.99, p<0.01$).

We further seperated movements into directing *upwards* (towards the elbow) and *downwards* (towards the wrist). Participants were slightly more accurate (~8,8%) in estimating upwards movement (M=1.38cm) than downwards movement (1.50cm) under the *haptic* condition. This was potentially due to upwards movements taking slightly longer time (1.63s vs 1.52s) and participants using the duration as a cue for the distance. For the *visual* condition, participants were also more accurate (~16,4%) in estimating upwards movement (M=1.08cm; M=1.26cm). Since the participants' forearms

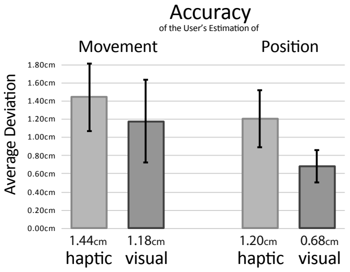

Figure 5. Accuracy was measured as the average deviation of the user's estimation to the actual movement length, resp. position. Participants were less accurate when blindly estimating movement and position in comparison to visually observing the device. Since vision is the primary human sense to assess the environment, a significant difference in accuracy between *visual* and *haptic* perception was expected. The difference was smaller than anticipated and only 18% for estimation of movement length and 43% for the estimation of position.

would be facing away (see Fig. 4), the upper forearm was closer within the user's field of view.

Position

For the estimation of the device's position, the average deviation to the actual position was 0.68cm (SD=0.18) for the *visual* perception and 1.20cm (SD=0.31cm) for the *haptic* perception, so that using their vision, participants were in average 0.52cm (43%) more accurate. A paired t-test showed that the difference was significant (t(15)=6.35, $p<0.001$).

For further analysis, we divided the forearm into ten equally sized segments. Participants were more accurate at the outer regions, i.e. wrist and upper forearm, than within the middle of the forearm (see Fig 6). This can be explained by wrist and elbow serving as positional landmarks for the user, which could benefit the user's perception as points of reference when the device was close to either cue. Also, users could benefit from haptic experiences at the wrist by previously wearing watches and jewelry. The upper forearm had a distinctive haptic feeling in that the *Movelet* was mechanically expanding to adjust to the arm's circumference, which could help as an additional haptic cue for the upper forearm.

For the *haptic* perception, 60% of estimations for the position fell within an area of 2.36 cm along the center of the device, while an area of 6.05 cm along the center covered 95% of all estimations (see Fig. 7). For an average forearm length of 24 cm, this implies that 4 distinct target positions could be placed along the arm without an overlap to be reliably distinguishable by the user. For the *visual* perception, 95% of all estimations fell within an area of 3.57 cm, so that when glancing at the device, user's could distinguish ~6-7 distinct target positions reliably.

QUALITATIVE FINDINGS

Participants were encouraged to provide feedback about their perception. Multiple participants stated that estimating the position blindly was more difficult than under the visual condition, but that estimating movement was easier. While the results do not confirm that users were more accurate under the *haptic* condition for assessing movement, participants were nearly as accurate. A possible explanation is that for estimating the length of a relative movement, a temporal demand is involved that requires the user's attention. Under the *haptic* perception condition, participants would focus on the haptic stimulus during movement, while under the *visual* perception they would primarily trust in their visual assessment of new and previous position, which involved having to memorize the previous position of the device.

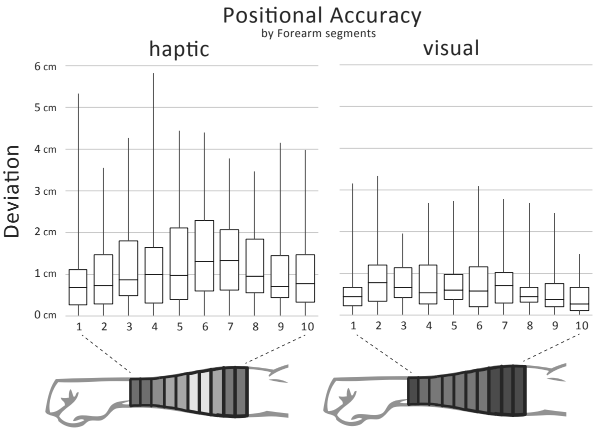

Figure 6. We divided the forearm into ten segments for further analysis of the accuracy of the users' estimated positions. Participants were most accurate at the outer forearm segments where wrist, resp. elbow, could serve as anatomical points of reference. Whiskers within the box plots represent the minimum and maximum deviation of the user's estimation from the actual position.

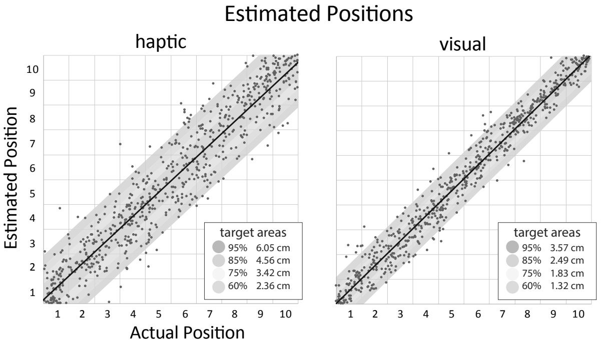

Figure 7. All user estimations for the device's *position* in relation to the actual position of the device as measured by the camera tracking.

Participants were asked which advantages and disadvantages they see with the introduced *Movelet* concept. Appreciated was foremost that users do not need to look at the device (P4, P5), especially in situations where it is not possible to look at (P1). Also, that information can be perceived incidentally in the periphery (P11), which might give users the impression of an additional perceptual sense (P3). Mentioned downsides were that the device might conflict with clothing such as long-sleeves (P15) and that sudden movement could have an irritating effect on the wearer (P11).

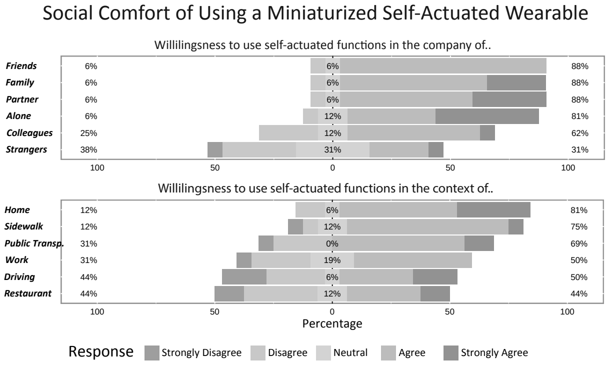

Figure 8. Participants were asked about their willingness to use the functions of a miniaturized self-actuated wearable. There was assent for private social contexts. In public scenarios some participants disagreed and were afraid the device might draw unwanted attention.

Social Comfort

In regard to social comfort, participants were asked in which social contexts they would be willing to use the functions of a self-actuated miniaturized wearable (see Fig. 8). Participants were assenting for private social contexts (e.g. alone, or with family and friends), and rather divided for public scenarios where the device could draw unwanted attention. To prevent unwanted attention, a self-actuated device should therefore prevent sudden and quick movement. Within the user study, our *Movelet*-prototype would quickly move towards a target position, however, we envision slow and unobtrusive device movement in the future, so that neither users nor bystanders are getting irritated.

Haptic Pressure

Participants rated the device's pressure on the arm neither as too weak (M=1.75; from 1 - strongly disagree to 5 - strongly agree) nor as too strong (M=2.06). The pressure allowed a localization of the device on the forearm (M=4.06), but was not always perceived as evenly distributed (M=2.5). One participants with a thin wrist joint (P6) mentioned that at the wrist position, the fourth wheel at the bottom was too loose and did not pressure the arm anymore. While the device's pressure allowed for localization, a more evenly distributed pressure around the arm could be realized by electronically synchronizing the applied force on the suspension.

DISCUSSION

The haptic acuracy in users' estimations of position and movement was higher than expected. The visual perception was significantly more accurate for the estimation of movement and position, but the difference (18%, resp. 43%) was less than expected considering that vision is the primary human sense for assessing movement and positioning in the environment.

A temporal demand was not involved for the estimation of the position, so that it was perceived as overall less demanding by the participants. As an implication, the *Movelet* is better in conveying a current *state* of information than in conveying the quantity of a *change*. Yet when using *positional* feedback, the *Movelet* is conveying both: Users can feel a *change* in information via movement and then have a continuous haptic feeling of its *state*. While the movement is temporary and can be missed, much like a vibration, the position enables sustained background feedback continuously available to the user.

While the haptic perception in average deviates only 1.20cm from the actual position, segmenting the forearm into distinct target areas would enable only four distinguishable target areas along the arm with a high distinction rate (95% success rate along 6.05cm, see Fig. 7). For this reason, the *Movelet* is less suitable in conveying *different* information depending on its position, and more suitable in conveying the *state* of a single information where knowing the exact quantity is less important than getting a close estimation about its extent, e.g. having a good sense about the time left until the next meeting or about the amount of unread notifications (see Fig. 2).

CONCLUSION

Movelet is a self-actuated bracelet that can move along the user's forearm to convey information via its movement and positioning. Using *positional* feedback of a self-actuated wearable is a novel means for a sustained haptic stimulus. In a user study, we found that users can blindly estimate the device's position on the forearm with an average deviation of 1.20cm and estimate the length of a relative movement with an average deviation of 1.44cm. This enables continuous *positional* feedback of abstract information that can be used to gradually display progress, such as the remaining time towards a meeting or the quantity of unread notifications. The accuracy is well suited to map progress that does not require the exact value, but a close feeling of its extent continuously accessible to the user.

FUTURE WORK

In the future, we are planning to conduct user studies comparing positional to vibro-tactile feedback under distraction to show that the user's attention does not need to be focused on the haptic perception when using *sustained* feedback of a self-actuated device rather than *momentary* feedback of vibro-tactile tactors. In this regard, we also want to explore how quickly users can assess the position when attending another main task.

Furthermore, We want to extend the capabilities of *Movelet* to enable for user input. Similar to rolling up sleeves, users could grab and reposition the device on their forearm to change or reset information. To enable this, the device has to be able to detect its position. Our user study was relying on camera tracking, but a more mobile approach could be realized by measuring the current expansion of the device when calibrated to the circumference of the user's forearm.

For positioning, we also explored to include the upper arm to be reachable by the device. The bridging of the elbow joint for angled arm postures as well as the increasing cirumference however introduced technical challenges that yet need to be resolved. The varying circumference of the user's arm also led to technical challenges regarding miniaturization that we want to address in future work. Technical considerations are needed for shrinking the form factor to make self-actuated wearables more practical. Hereby, *positional* feedback could be used on a variety of different body parts built into many kinds of self-actuated wearable form factors. The high haptic acuity of the finger [28] for example, makes it a promising location for a miniaturized self-actuated movable ring.

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inScent: a Wearable Olfactory Display as an Amplification for Mobile Notifications

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ABSTRACT

We introduce *inScent*, a wearable olfactory display that can be worn in mobile everyday situations and allows the user to receive personal scented notifications, i.e. *scentifications*. Olfaction, i.e. the sense of smell, is used by humans as a sensorial information channel as an element for experiencing the environment. Olfactory sensations are closely linked to emotions and memories, but also notify about personal dangers such as fire or foulness. We want to utilize the properties of smell as a notification channel by amplifying received mobile notifications with artificially emitted scents. We built a wearable olfactory display that can be worn as a pendant around the neck and contains up to eight different scent aromas that can be inserted and quickly exchanged via small scent cartridges. Upon emission, scent aroma is vaporized and blown towards the user. A hardware - and software framework is presented that allows developers to add scents to their mobile applications. In a qualitative user study, participants wore the *inScent* wearable in public. We used subsequent semi-structured interviews and grounded theory to build a common understanding of the experience and derived lessons learned for the use of *scentifications* in mobile situations.

Author Keywords

Olfaction; scent-based notification; wearable device; olfactory display

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION

The sense of smell is an important information channel that is strongly linked to emotions and memories. The stimulus of a scent can evoke memories that are more emotionally loaded than memories elicited through other senses. Contextually distinctive odors are especially good retrieval cues [11]. Furthermore, long-term odor memory is unusually well preserved beyond other sense memories [11]. Pleasant odorants can improve mood [1], may affect the quality of life and there is suggestion that a reduced odor perception can be linked to mental discomfort [25].

Figure 1. The *inScent* prototype worn on a necklace.

When perceiving the environment, smell is often an essential part of the experience, e.g. smelling the leaves and trees when strolling through a vivid forest, or the familiar and intimate smell of the own home. But also indepentently, artificial scent is used to create or enhance experiences. Perfume gives oneself a pleasant personal scent, while for instance Mercedes-Benz offers a package to their premium cars that adds digitally adjustable fragrance to the air conditioning system. In aromatherapy, essential oils are used for expected personal well-being and many cosmetic products contain fragrances. Human perception of smell is highly variable with people varying in their general olfactory acuity as well as in how they perceive specific odors [15]. This makes it difficult to design for particular experiences equally among users. Nevertheless, smell inherently contains information about the state of things in our vicinity, like the smell of a burning fire [14].

The unique properties of olfaction as a modality make smell-based interaction a promising field for HCI. We want to utilize artificially emitted scents to invoke emotions and experiences for users in everyday life situations by presenting *inScent*, a wearable olfactory display that can be worn as a pendant on a necklace (see Fig. 1). The primary use case is to complement and amplify received mobile notifications by using scent as an additional *emotional notification channel*. We call this *scentification*. Messages of the life partner can be emphasized

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by emitting a pleasant relating scent such as flowers or the other persons perfume aroma to reflect the emotional link to this person (see Fig. 6). Another example is using the alerting properties of smell to subtly remind of an upcoming event (e.g. a meeting). Our device contains up to eight different scent aromas in exchangable scent cartridges that can be used for different applications and use cases. Upon emission, a scent aroma is vaporized. A small fan within the casing flows air through the device and gently blows scent towards the user's nose.

The main contributions of this papers are (1) a novel unobtrusive, wearable and miniaturized olfactory display that allows passive amplification of received notifications with scents, (2) the presentation of an open source hardware and software framework that allows developers and researchers to add scents to their mobile applications and use cases, and (3) a qualitative user study investigating the users' perception of *scentifications* in public.

RELATED WORK

Kaye encouraged the HCI community to use aromatic output [13] and to explore the symbolic properties of smell in his thorough work [14]. He suggests that the peripheral qualities of scent make it ideally suited as an ambient and calm display. As a conclusion, users are better able to find meaning in the *quality* of different distinguishable scents than in the *quantity* (i.e. intensity) of single scents.

Obrist et al. [23] collected smell experiences and the accompanying emotions via user stories in a large scale online study. Smell was i.a. associated with memory and remembering past events, as a stimulus and desire for more, and as a means to detect immediate events (such as a gas leak).

Applications for Smell in Human-Computer Interaction

Computer generated smell has already been used in a wide variety to enhance the experience and immersion in multimedia. First attempts date back to the 70's with the Sensorama simulator using smell among other modalities such as vibrations and wind to increase the immersion of a motion picture [10]. Ghinea et al. [9] showed that olfaction significantly adds to the user multimedia experience. Nakamoto et al. [20] used scents for an interactive virtual cooking game. For smelling screen [16], odor can be distributed on a display screen by fans on the corners, so that users can lean forward to smell and find the virtual odor source. With the MetaCookie+ [21], it was shown that the perceived taste of food can be altered by changing appearance and scent.

Brewster et al. used smell for memory recall of photos in digital photo collections where users could tag and search by different odors [5]. The properties of different output modalities as a notification mechanism were explored by Bodnar et al. [4]. They found that olfaction is less effective in delivering notifications but also produces a less disruptive effect in the primary task.

For SensaBubble [26], sight and smell are combined in a projected mid-air display. Generated bubbles are filled with fog that contains a scent relevant to the displayed notification. The user can first see the notifcation and then smell it upon bursting the bubble, so that the information is changing its modality.

Scent can also be used to express unique identity. For Sound Perfume [7], a personal sound and perfume is emitted during interpersonal face-to-face interaction. Whereas for Light Perfume [8], the idea is to stimulate two users with the same visual and olfactory output to strengthen their empathic connection.

Kaye defined scent used to convey information, where the scent is environmental and semantically related to the information conveyed, as a 'smicon' [14]. Examples were to use ambient smell to convey whether the stock market had gone up or down, using scent as a personal reminder (e.g. the smell of baby powder to be reminded of picking up the kids) or as a tool to provide presence awareness and a feeling of connectedness in relationships.

Scent Generation Methods

Unfortunately unlike other modalities like vision, dimensions of smell are not as well understood and cannot be coded as easily as color [13]. With our current knowledge, humans have approximately one thousand different kinds of olfactory receptors [27] in contrast to four kinds of receptors for vision. Up to now, no systematic abstract classification scheme could be established [13], so that scents are classified by resemblance with entities, e.g. the smell of a lemon. This is a problem for creating arbitrary scents on demand and leads to olfactory displays being limited to defined sets of scents. With *inScent*, we allow the user to decide which scents resemble relevant personal information by designing small scent cartridges that are easily exchangable (see Fig. 5).

For computerized scent generation, scented air has to first be made from the stocked form of odor material and then delivered to the human olfactory organ, i.e. the nose. Scents can be released by either natural vaporization, accelerated by air flow, by heating or by atomization [31]. Natural vaporization implies that high-volatile chemical substances are released over time as ambient scent due to air exposure such as with worn perfume. This releasing process can be accelerated by feeding fresh airflow. Heating can be used to release larger quantities of chemical compounds. Some compositions however can be denatured by high temperature. By atomization, a fine mist of scent is emitted, e.g. by a sprayer, diffuser or by using ultrasonic waves. However, much like sprayed perfum, the fine mist of atomized scent is adhering to surfaces and then continuing to naturally vaporize over time, making it less appropriate for *scentifications* that rely on temporary scent delivery. Heating has the advantage that very small vessels can be used to carry the odor, that intensity and timing can be controlled by the heating duration and that scents can be generated almost instantaneously [22]. For these reasons, we used vaporization by heating of essential oils mixed with highly viscous carrier liquids. An axial fan is used to deliver the scented air towards the user.

Olfactory Displays

Olfactory displays in related work are mostly stationary. With stationary emission it becomes challenging to create localized rather than ambient odor [29]. Yanagida et al. [32] built a remote air cannon launching small toroidal vortexes of scented air towards the user's nose tracked by computer vision. This however had the problem that users would feel an unnatural airflow when the vortex ring was hitting their faces. As an improvement with SpotScents [19], two air cannons were used to let two scent vortexes collide at a target point in front.

To simplify scent delivery, users can actively move an olfactory display towards their nose. For Fragra [18], the device is mounted on the user's hand, for Scent Rhytm [6] on the user's wrist, while Brewster et al. [5] used multiple graspable smell cubes each containing different odors. This however implies that the user actively has to initiate the delivery process by moving the scent towards their nose instead of passively receiving scent by the system, making it inadequate for scent-based notifications.

Warnock et al. argued that the inherent trait of olfaction as a modality is that notifications are slow to deliver [28]. To minimize and synchronize delivery and exposure time Noguchi et al. [22] used pulse ejection, whereby scents are only emitted for very short periods. The user however has to be positioned immobile in front of the stationary device.

In wearable systems so far tubes have been used to convey scented air towards the user's nose [30][21]. These are designed for virtual reality and are arguably too invasive for everyday life contexts.

Choi et al. [7] built a perfum actuator into a pair of 3d-printed glasses. The actuator was located behind the ear and emitting ambient scent by melting solid perfume. The scent-emission however could not be evaluated due to technical issues with the system. Multiple commercial attempts have been made to create smell devices (e.g. DigiScent's iSmell), however most were stationary and none was truly wearable yet to be used by users to passively receive scents throughout the day in mobile situations. Scentee [12] is a mobile scent dispenser that can be attached to the earphone jack of a smartphone and thus be carried along. However only one aroma is contained and the user has to actively held the device in front of their nose.

McGookin et al. developed Hajukone [17], an open source olfactory display to enable researchers to replicate the device for scent-based use cases. Similar to invasive solutions [30][21], however, the large form factor restricts users from wearing the device in public. Amores et al. [2] build an olfactory display that is wearable and releases scent throughout the day to affect the wearer's mood and wellbeing. The device is small and fashionable, but limited to a single scent to have an effect on the user.

WEARABLE OLFACTORY DISPLAY

We introduce *inScent*, a wearable olfactory display that allows users to passively receive multiple computer generated scents in mobile everyday situations. We utilize this to investigate the use of scents to amplify notifications, i.e. *scentifications*, in public scenarios.

To built a wearable device, a lot of design challenges have to be faced, starting from miniaturization and a small form factor up to battery usage and connectivity. We miniaturized an olfactory display as much as possible while at the same time enabling developers and researchers to replicate the device. All files are made available as open source. The utilities used in our work can be found in a well-equipped research facility. We believe that with industrial effort the device can be miniaturized even further.

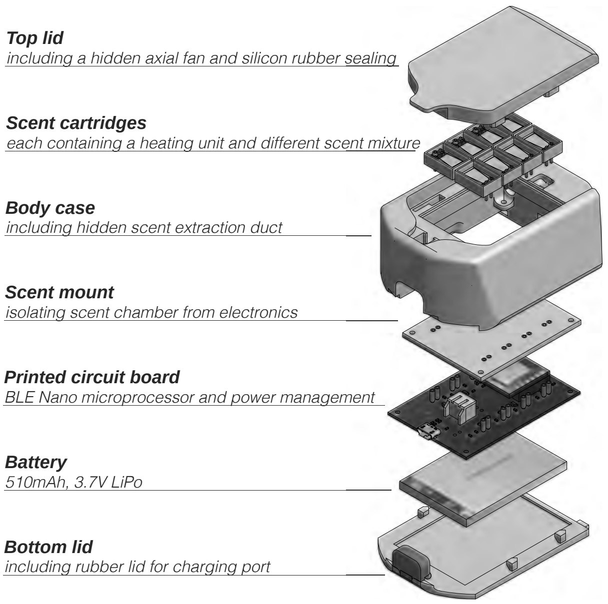

Figure 2. Overview of the assembly of the *inScent* prototype.

Form Factor

Miniaturization is a challenge in wearable computing, especially for a device aiming to emit different chemical compounds. A small size and low weight is needed to make the device suitable for daily use, while the limited space must be sufficient to contain aromatic substances and a scent emitting technique that is efficient in both, scent delivery and energy consumption. We decided to build the device in a form factor so it can be worn as a pendant around the neck. Other possible on-body locations could include integration in a shirt collar, a shirt pocket, or into a pair of glasses, however this would require further miniaturization.

For replicability, the casing (8.4 x 5.9 x 3.1 cm) was 3d-printed using an *Ultimaker 2* and PLA filament. The main body serves as a mounting device for the other components and represents the core element of the casing (see Fig. 2) containing the scent chamber, ventilation system, control unit, power management and battery. We made sure that the system is reasonably sealed using a locking system (see Fig. 4), but still allowing users quick access to the scent chamber by opening the top case lid.

Vaporization by Heating

Vaporization by heating is used for scent generation to be able to control timing, duration and quantity of the scent emission which is important for the use of *scentifications*. High temperature required in a small device worn at the user's body poses a safety risk, so that we had to be careful with the design decisions and materials used in the scent chamber.

The heating process for each scent aroma is conducted within the respective scent cartridge (see Fig. 5). Scent cartridges are designed to be simply producible and feature a modular design. They are very small (10 x 15 x 5 mm), can be filled with different scent aroma tailored to the user's and application's needs and are quickly exchangeable and pluggable into the device on the fly. Cartridges are designed to be flat but with a

Figure 3. Left: The *inScent* prototype with opened top lid. Up to 8 scent cartridges can be plugged in. Each cartridges contains highly viscous scented liquid soaked into glass fiber to deter leaking. Right: Normally, scent emission is not visible to the eye. For this photo, we highly increased the amount of glycerol to make the scent emission visible as smoke.

wide surface area to increase the evaporation efficiency. Each cartridge incoperates a wire as a heating coil. We use Kanthal A-1, a ferritic iron-chromium-aluminum alloy that is often used for electrical heating elements since it can withstand high temperatures and is simultaneously characterized by a high electrical resistance. As a downside it is not solderable. This is why two clamps are used to hold the coil in place. The clamps are soldered to two pin heads which serve as a plug to connect to the mainboard and hold the cartridge in place.

An absorbing layer consisting of glass fiber is located underneath the heating coil (see Fig. 5). It absorbs the scented liquid and consistently delivers liquid to the heating coil. In addition it prevents the scent cartridge from leaking. Glass fiber cord is favorable over other absorbing material such as cotton pad, due to high resistance to temperature (over 1300°C) and because it is odorless.

The scented liquid is a mixture based on aromatic substance, high-proof alcohol and carrier liquid. Initially, the aromatic substances (ethereal oils) are pre-diluted with ethanol. Subsequently, the solution is mixed with a carrier liquid consisting of glycerol and polyethylene glycol (PEG). Both carrier liquids are highly viscous. In conjunction with the liquid mixture being soaked into the absorbing layer (i.e. the glass fiber), the high viscosity prevents leaking from the scent cartridge. For easy access and due to space limitations, all cartridges share a common scent chamber. McGookin et al. [17] argued that scents must be contained individually to prevent scent mixture and natural vaporization over airflow. We didn't face these problems by carefully choosing the intensitiy of the aromatic substance, so that natural vaporization does not expose a perceivable amount of molecules, but that when heated enough scent is released to have an effect on the user. The mixing ratio was determined experimentally and was for instance 5% aromatic substance, 20% ethanol, 50% glycerol and 25% PEG for the scent aroma *orange*. The amount of aromatic substances can vary due to human olfaction perceiving different odors at varying intensity (e.g. we used only 2% aroma for *mint*). For mixing liquids a pipette and micro test tubes were used.

To seal the scent chamber from the top lid, a silicon rubber sealing was casted (see Fig. 4) using a 3d-printed negative mold and a two-component silicone. This represents an important safety factor. The silicone is thermally stable up to 180°C and insulates the lid's PLA filament from heat emission. For safety reasons we also isolated the scent chamber from the in-built electronics and battery by an extra layer (see Fig. 2).

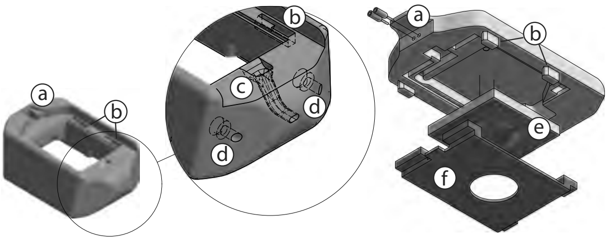

Figure 4. Detailed view of body case (left) and top lid (right). The top lid slides into the fan connector (a) and locking system (b). Scent is emitted over the extraction duct (c). The mounting (d) can hook a necklace. An axial fan (e) vacuums scented air from the scent chamber into the extraction duct (c). Silicon rubber (f) seals the top lid with the body case and serves as a thermal protective layer.

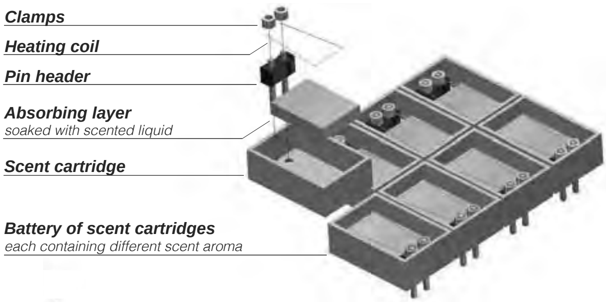

Figure 5. Overview of the scent cardriges with integrated heating units.

Scent Delivery

After vaporizing scented aroma, the scented air has to be delivered to the user. A small axial fan[1] (30 x 30 x 3 mm) is embedded in the top lid and vacuums the vaporized scent from the scent chamber and exhales it into a scent extraction duct (see Fig. 4) on the upper side of the device facing the user's head. The fan maintains a static pressure of 88.18Pa, corresponding to 17.74l /min at a low noise emission of 28.7dB(A). Even smaller (down to 10 x 10 x 2 mm) fans were tested but they provided insufficient air pressure for the user to smell the scents. For scent emission, the fan, as well as the heating coil in the scent cartridge are powered for 5 seconds. Scented aroma vaporizes almost instantly in the scent chamber, but then takes a few seconds bridging the distance to the user's nose.

Power management

The axial fan operates between 2.0 - 6.0V and has very low energy consumption of maximal 72mA resulting in a low battery drain. For power supply we built-in a Lithium-ion Polymer (LiPo) battery that provides 3.7V and a nominal capacity of 510mAh. The battery has small dimensions (34.5 x 52 x 3.5mm) but provides a maximal discharge current of 1020mA making it suited to meet the high discharge requirements during the scent release.

For *inScent* to be able to receive *scentifications* from a connected mobile device and to then drive the scent release, a *BLE*

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[1] Sunon UB5U3-700 `http://www.sunon.com/`

Figure 6. A user receiving a message of her parthner (a). She smells his scent (b) and in pleasant anticipation reaches for her phone (c) to read his message (d).

Nano[2] was integrated. It has a low power consumption and is one of the smallest Arduino microcontroller on the market that incoporates Bluetooth Low Energy (BLE) functionality.

We manufactured a double-sided printed circuit board (PCB) to mechanically support and electrically connect all electronic components. The conducting paths are designed to support both high current frequencies and currents up to 2A. This enables individual voltage values between 0 and 3.7V through pulse width modulation (PWM) signaling with different currents. The board features a slot for each scent cartridge over which the *BLE Nano* is capable of measuring current. This enables polling each slot to detect plugged-in scent cartridges. However, by itself the *BLE Nano* has only a limited output voltage of 3.3V and an output current of 0.5mA which is not sufficient to directly power a scent cartridge to release scent. This is why the slots draw the power directly from the battery which is switched by a transistor.

The board can be powered via battery or micro-USB. In addition, an integrated linear charge management controller allows charging the battery via the USB-port. The controller has an integrated current sensor to prevent the battery from overvoltage and thus overheating.

Including all components, the *inScent* wearable weighs 102g, can be used multiple days without recharging the battery and each scent cartridge contains aroma for approximately 70-100 *scentifications* (depending on intensity). All assembly files, instructions and software are made available as open source at `https://www.uni-ulm.de/?inscent`

SOFTWARE FRAMEWORK

To be able to use the *inScent* wearable in daily life and to open new application areas we built a comprehensive mobile software framework for the user's phone running on Android (ver. 5.1). The framework runs as a background service that can be accessed by one or multiple applications. It is in charge of the control flow of *scentifications* including the connection with the device. For a developer, the development of a new scent-based application is simple by implementing an existing interface and installing the *inScent* framework on their phone.

Scented notification

The framework allows to automatically amplify the phone's native notifications with emitted scents. A developer can define multiple trigger and events such as the name of the sender, the content of a message or a particular application (in any combination). Also timing conditions are possible (e.g. 5 minutes before a specified calendar event).

Remote service

To also enable remote control for developers, we implemented a GCMService that allows the sending of push notifications over Google Cloud Messaging (GCM) direcly to the running background service . This enables access to the framework from outside the phone and allows for its integration into other systems independently of system platform or programming language. External systems are able to remotely emit scents for varying use cases. It is also possible to remotely change the device configuration (e.g. to integrate new events)

To release a scent from any application implementing the interface, it just has to send a message to the background service:

```
sendCommand(new Command(commandType,slot,intensity));
```

Commands are validated by the service and additionally on the *BLE Nano*. Messages with invalid slot number or intensity are withdrawn. This way, the system can prevent misuse. It also validates whether the addressed cartridge is inserted.

We developed an exemplary application implementing the interface that we use for the user study that allows the user to release different scents via large icons in a user interface and the instructor to remotely send messages and emails that trigger scents related to the respective incoming notification.

USER STUDY

We conducted a qualitative user study to learn from a first-hand user perspective about *scentifications* in wearable contexts in public. In previous work it was shown how scents can be used as notifications to convey information (e.g. [14][4]). These systems however were stationary and emitting *ambient* scents. In contrast, we want to investigate the properties of personal *mobile* scents. For our user study, participants wore the *inScent* prototype while walking through a heavily frequented university as a public scenario and received a scripted set of different notifications on a phone that each triggered an additional scent. Subsequently, in semi-structured interviews, we asked participants about their impressions and concerns and used grounded theory to build a common understanding of the experience to learn about the use of scented notifications in wearable contexts.

Procedure

We recruited 16 participants between 20 and 31 years (M=26.13; 7 female). The study lasted about 60 minutes and started and ended in an office room where the participant was made familiar with the *inScent* prototype and the concept of *scentifications*. Beforehand, we asked for any medical condition, e.g allergies against certain scents or having a cold, that could negatively affect the participant or the perception of smell. We handed over the wearable device and a complementary Android phone running the background service.

Four different scent aromas were used (flowers, mint, lavender and lemon) and inserted as scent cartridges into the device with help of the instructor. The first scenario for the participant was to manually trigger any of the four scent aromas via an app on the phone as *Ambient Smell*. This also served to familiarize with the four scent aromas. Afterwards

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[2] BLE Nano `http://redbearlab.com/blenano/`

Figure 7. A participant wearing the *inScent* prototype in public during the user study. As an assignment, they would buy a chocolate bar in the university cafeteria. Participants received an enforced *scentification* while lining up and another while at the cashier.

the participant was asked to individually assign the given scent aromas to four scenarios that were used for scripted *scentifications*:
(1) *Scented Message*. Received messages of an important person (e.g. the life partner) were complemented with a scent to reflect the emotional link to this person. The person would send multiple messages throughout the study such as asking when the participant comes home.
(2) *Scented Reminder*. Calendar events were complemented with a scent to subtly remind the user for the next task in the user study.
(3) *Scented Event*. The user eagerly awaits the delivery of an important parcel. The scent would be released for updates with the delivery process.
(4) *Time Sense*. A scent to trigger a feeling for the passing of time. We used a scent indication every quarter-hour to guarantee at least 3 events during the study.

These scenarios were to help participants understand the concept of scented notifications. We restrained to four scenarios with four scents to make it easier for participants to quickly accommodate.

After assigning scent aromas, the participant put the *inScent* wearable around their neck and the phone into their pocket. The instructor was also wearing a (functionless) *inScent* wearable to lower the inhibition level and a phone to control the user study. Instructor and participants then left the office room and strolled through the university as a public setting that is heavily frequented. The route was guided by the instructor and equal for each participant. It included two elevators, various corridors, three floor levels and dwelling for a while at three open locations with many bystanders. This part of the user study lasted around 15 minutes and included 12-15 scripted *scentifications*. In addition to emitting a scent, the participants phone would vibrate and the content of the scripted message was displayed (e.g. the partner's message). Part of this setting was for the participant to walk into the university cafeteria, to get into line, and to buy a chocolate bar. The presenter forced a *scentification* when the participant was lining up, another when paying at the cashier and another when standing within an elevator (with other people). Other *scentifications* were scripted over time. During this study part small talk was used to distract the participant from solely trying to smell.

Following this, a semi-structured interview was conducted in the office room for at least 30 minutes and audio recorded. The interview started with remarks and comments that came up in the previous study part. Themes that were explored spanned possible improvements for the prototype, benefits and limitations, social acceptance, application scenarios, scents in everyday life and the perception of scent in general. Participants received €8 and a chocolate bar for compensation.

Analysis

The analysis process followed an open coding approach [24] by two researchers. The audio recodings were transcribed into text files. We used initial coding along the study process on the transcribed text and generated 120 initial codes on user statements, followed by holistic and subsequently axial coding grouped into 31 axial codes. Codes are emphasized in text.

Design

Participants appreciated the amulet form factor as masking the scent emitting device as being **jewelry**. A **fashionable design** was noted to be important. However, as fashion changes with context "I wear different jewelry every day" (P12) there was also the notion of reaching for a **subtle design**. With that in mind our prototype received compliments, nevertheless, an ideal device was desired to be smaller and to weigh less. There was worry what **impression on others** is made by the design and form factor, especially whether the device exposes itself as scent emitting "I don't want to be referred to as an esoteric" (P15), "I fear that people might stare at me" (P1). Thus, the design should be **unobtrusive to others**.

Subtlety

Scents diffuse and can be smelled by bystanders depending on intensity and dispersal. Therefore, participants preferred scent notifications to be **subtle in intensity** "if the scent was incredibly penetrating and unpleasantly smelling, I would be really ashamed" (P8). On the on hand, participants were worried about the **smell perception of others** "I have the feeling people can be bothered. Like when wearing too intense perfume" (P6). On the other hand, some participants stated they wouldn't mind leaving a scent. Locations with little air circulation such as offices, meeting rooms or elevators were mentioned to most likely let scent affect other people. Multiple participants stated they didn't think of a negative impact on bystanders "I cannot imagine that anybody would be annoyed by a light breeze of pleasant scent" (P8). In general, the scents were perceived as **pleasant** and **non-disrupting**. "The scent is more subtle... (in comparison to other notifications). It is rather a subtle polling than an interrupt" (P6), "I think it is a very pleasant kind of notification, especially if one doesn't want to be interrupted and rather stay focused" (P7).

Our prototype had a fan that could faintly be heard in quiet surroundings such as the empty office room. An ideal device should be **noiseless** to support subtlety.

Scent aromas could easily be dinstinguished, however, participants often had problems remembering the assigned scenario. In this regard, participants did not build a strong association of scent and the respective meaning over the course of the user study. One exception was the flower (ylang-ylang) scent aroma which was assigned to the *Scented Message* of the life partner by all participants. Scent aromas could not be perceived by the instructor, even though being close-by the participant throughout the study. One notable exception was when walking directly *behind* the participant. When in motion, scents were generally more difficult to perceive by the participant. When walking with a fast pace, the resulting air draft would pull most of the scent over the user's shoulder. As a result, participants would slow their pace when getting a notification (i.e. when feeling the vibration). This suggests that motion detection would be helpful to adjust the intensity [3] by creating a stronger air flow.

Control

Participants mentioned prefering to receive *scentifications* at familiar or personal places over public ones. To be comfortable with the device, they wanted to feel like being **in control** of when a scent can be emitted and when not. This behavior might change over time, when the user becomes more familiar. Ideally the device is aware of its context. Nevertheless, it should allow the user to easily *silence* its scent features, which was not implemented with our prototype but a requested function.

Contrary to feeling the need to be in control, participants appreciated the emission of scents being a **background activity** that can subliminally work on the user.

Pollution

Since scents linger and can add up in intensity, a high frequency of *scentification* can be perceived as **smell pollution**. **Overuse of smell** within a short amount of time is therefore a rather bad idea so that frequency should be controlled, e.g. a *Scented Message* would only trigger for the first message of a conversation instead of for every new reply. Also other people might have **allergies** to certain smells so that smell extent should be limited.

In some contexts, *scentifications* are prone to **superimpose smell** that is part of a pleasant experience "When eating I don't want to perceive other smells" (P4) "I wouldn't wear it when I am going out to eat with someone" (P3). On the other hand, the device can be used to **cover unpleasant smell** "I like to be able to adjust the ambient smell" (P11). Depending on context, emitting a scent can create or disrupt a smell experience, which leads back to the user's desire to be in control.

Scent as a different notification channel

Using scents for digital notification was seen as being **novel** "It is a completely different channel that is unknown to you" (P8), "It is a novel experience" (P15). It allows for "**multidimensional feedback**" (P6) in combination with audio, visual or tactile stimulations. One participant (P16) stated that she was overwhelmed by getting so many visual and audio stimuli in a crowded and noisy environment that it made it difficult for her to perceive smell leading to a **sensory overload**. In contrast to other modalities for notification, such as sound or vibration, smell was generally seen as more pleasant and positively connoted.

Reliability is important when it comes to conveying information. Depending on context however *scentifications* could be missed or misinterpreted. In one case, a bystander peeling an orange led to the participant checking his phone in anticipation of a notification. Another participant (P1) claimed to be bad at identifying different smell. As a conclusion important information shouldn't be solely conveyed by smell, so that smell functions as an **additional channel**. Becomming **accustomed** to certain smells can be positive to build up strong associations to the underlying information, but also negative when a user is getting less sensitive to it "When smelling it every day my senses could deaden to it" (P2).

In contrast to other notifications, scents have the inherent property to **linger**. The scent is getting stronger over a short period of time when getting emitted and then slowly disperses and getting weaker. This is unlike the *hard* event of a vibration or ring tone and was mentioned as being favorable by participants "It is not a hard event, you slowly realize its presence. It is not an alert but rather an impression that emerges" (P9).

Scent is very personal

Scents are perceived differently in intensity, liking and association by each person. **Individualization** allows each user to find their personal taste. With our prototype this was enabled by easily exchanging scent cartridges, but also by inserting up to eight scents at once. Ideally a wide variety of these is offered so that every user can find their **individual scents**. Individual scents can allow you to build a very **personal association** and coding to information "Scents can ultimately be very well coded. Even when a bystander can smell the scent they still don't know its meaning. Only I have this information" (P8). However much like the user being able to build a strong association, this might be possible for related persons. For example, for a *Scented Message* friends or office neighbors might be able to **decode the meaning** after a while by context and continued exposure.

Utilizing Emotions

Scents have a very strong link to emotion, thus *scentifications* can be used to add an **emotional channel** to information. Emotional response to a certain smell however is individually different so that it is probably better to let the user decide over a scent than having it assigned by a developer: "The smell of Lavender has a strong connection to our wedding" (P8). A *scentification* can create a **pleasant anticipation** of an event "It is really nice that you get pleasantly thrilled first when smelling the message and then when you read it" (P10).

Scents can also be used to actively **set** or to **support a mood**. Participants suggested they could use scents to animate or reduce appetite, enhance concentration, or to get an relaxant or refreshing effect, i.e. using the device as a mobile personal aroma lamp.

Keyfindings

The study has shown that *scentifications* can be used to convey information in a wearable context. From the findings we can learn that social acceptance, as with other wearable devices, is a crucial factor and that potential users feel uncertain whether bystanders can perceive scents and how they might react. For this reason the overall design should aim for subtlety and unobtrusiveness. Bystanders during the user study did not show indication for perceiving scents, which suggests that subtly using scents in mobile scenarios is feasible.

Smell is inherently different from other output modalities by its traits. It is less reliable, but also perceived as less-disruptive and can be very pleasant. Individual scents can add anticipation and emotion to the moment of being notified and entail a very personal meaning. For this reason, *scentifications* should not act as an replacement for other output modalities, but rather complement to convey addtional meaning, i.e. to *amplify* a notification. During the study multiple participants mentioned feeling generally more aware of the smell of different places than usual. They experienced this as very positive, so that *scentifications* do not only superpose the sense of smell but might help in stimulating its cognition. Moreover, participants were excited about this novel way of passively perceiving information, illustrating that the use of scent in wearable context offers promising possibilities for human-computer interaction.

CONCLUSION AND FUTURE WORK

inScent is a wearable olfactory display that allows the emission of scents throughout the user's day as a mobile amplification for notifications. Users can individually assign scents to applications and use cases using modular scent cartridges, while developers and researchers can create novel scent-based applications for wearable contexts using the introduced hardware and software framework. The potential of scent-based notifications has been investigated in a qualitative user study in public. Our findings offer guidance to design scent-based applications for wearable contexts.

In the future we want to conduct longer qualitative user studies by letting participants wear the device over the course of several days to learn how users adapt to scent-based applications in the wild. Also we plan on conducting quantitative indoor and outdoor experiments. We assume that outdoor conditions, e.g. wind and ambient smell, will make scent recognition significantly more challenging. During testing, we used smoked scent to track and optimize the scent delivery process (see Fig. 3). This caught our interest in investigating purposefully emitted scented smoke as a cue for users and bystanders. So far we focused on enhancing notifications. Scents however could also be used to help keeping and recalling memories. By this, users could actively use a distinctive smell when experiencing a nice situation to later help recalling this event. Other possible use cases for *inScent* span more traditional applications like multimedia enhancement and immersion in virtual reality.

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