**University of Rostock**
Department for Computer Science
Albert-Einstein-Straße 22, 18059 Rostock, GERMANY

**Dissertation**

# *Reflexive Interaction –*
# *Extending Peripheral Interaction by Augmenting Humans*

Denys J.C. Matthies

Submitted in partial fulfilment of the requirements for the degree:
Doctor of Engineering Sciences (Dr.-Ing.)

Submitted: 27.10.2017

urn:nbn:de:gbv:28-diss2018-0085-0

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|---|---|
| Day of Defence: | 19.02.2018 |
| Place of Defence: | Fraunhofer IGD Rostock,<br>Joachim-Jungius-Str. 11, 18059 Rostock, GERMANY |
| Thesis Reviewer: | Prof. Dr. Bodo Urban, *University of Rostock, Fraunhofer IGD*<br>Prof. Dr. Albrecht Schmidt, *University of Munich*<br>Prof. Dr. Katrin Wolf, *Hamburg University of Applied Sciences* |
| Defence Review Committee: | Prof. Dr. Peter Forbrig, *University of Rostock*<br>Prof. Dr. Bodo Urban, *University of Rostock, Fraunhofer IGD*<br>Prof. Dr. Albrecht Schmidt, *University of Munich*<br>Prof. Dr. Katrin Wolf, *Hamburg University of Applied Sciences*<br>Prof. Dr. Thomas Kirste, *University of Rostock (absent)*<br>Prof. Dr. Heidrun Schumann, *University of Rostock*<br>Prof. Dr. Sascha Spors, *University of Rostock*<br>PD Dr. Christian Tominski, *University of Rostock* |

# Abstract

Technology is closer to the human than ever, it exists in various shapes and forms, is omnipresent, while continuously competing for the user's attention. With new opportunities constantly arising, such as mobile computing, we also face challenges, particularly when the user is on the go. Because of mobile devices often demand the user's full attention, control in mobile scenarios can be complicated, inadequate, awkward, risky, or not feasible at all. To overcome these problems, the concept of a *Reflexive Interaction* is presented, which can be seen as a specific manifestation *of Peripheral Interaction*. In contrast, a *Reflexive Interaction* is envisioned to be executed at a secondary task without involving substantial cognitive effort, while enabling the user tiny interactions, shorter than *Microinteractions*, without straining the user's main interaction channels occupied with the primary task. To underline the proposed concept, a series of research studies has been conducted that exploit the unique sensing and motor capabilities of the human body. For this, three body regions (head, body, and foot) have been selected, which all yield specific characteristics. For instance, the region of the head enables facial gesture control, while visual information is perceivable within our peripheral vision. On our body, quick tapping and hovering can be performed, while haptic, thermal, or electrical feedback can be applied on our skin in order to perceive different scales of notifications. The foot enables quick foot tapping gestures as well as the possibility to perceive vibrotactile feedback under the foot's sole. Moreover, in particular the foot, but also the face, generates unique information, which can be utilized to infer on the user's context, such as physical activity or emotional state. The consideration of context information is important in order to determine whether and how a *Reflexive Interaction* can be implemented.

# Zusammenfassung

Technologie ist den Menschen näher als je zuvor, sie tritt in verschiedensten Formen und Arten auf, sie ist allgegenwärtig und wetteifert kontinuierlich um die Aufmerksamkeit des Nutzers. Mit ständig wachsenden Möglichkeiten, wie zum Beispiel dem Mobile Computing, stehen wir auch neuen Herausforderungen gegenüber, insbesondere wenn der Nutzer unterwegs ist. Da auch die Bedienung von mobilen Geräten häufig die volle Aufmerksamkeit des Benutzers erfordert, kann die Steuerung in mobilen Szenarien kompliziert, unangemessen, unangenehm, riskant oder überhaupt nicht durchführbar sein. Um diese Probleme zu überwinden, wird das Konzept einer *Reflexiven Interaktion* vorgestellt, die als spezifische Manifestation der *Peripheren Interaktion* betrachtet werden kann. Es ist vorstellbar, dass eine *Reflexive Interaktion* ohne erheblichen kognitiven Aufwand als Sekundäraufgabe ausgeführt werden kann, während dem Benutzer winzige Interaktionen ermöglicht werden, die kürzer als *Mikrointeraktionen* sind, ohne die Hauptinteraktionskanäle der Primäraufgabe des Benutzers zu belegen. Um das vorgeschlagene Konzept zu untermauern, wurden Reihen von Forschungsstudien durchgeführt, die die einzigartigen sensorischen und motorischen Fähigkeiten des menschlichen Körpers nutzbar machen. Dafür wurden drei Körperregionen (Kopf, Körper und Fuß) untersucht, die alle spezifische Merkmale aufweisen. Zum Beispiel ermöglicht der Bereich des Kopfes eine Gesichtsgestensteuerung, während wir visuelle Informationen im peripheren Sichtbereich wahrnehmen können. Auf unserem Körper kann ein schnelles Tapping und Hovering ausgeführt werden, während haptisches, thermisches oder elektrisches Feedback über unsere Haut wahrgenommen werden kann, um uns beispielsweise in verschiedenen Skalierungsstufen zu benachrichtigen. Der Fuß ermöglicht schnelle Tapping-Gesten sowie die Möglichkeit, vibrotaktiles Feedback unter der Fußsohle wahrzunehmen. Darüber hinaus erzeugt insbesondere der Fuß, aber auch das Gesicht, einzigartige Informationen, die genutzt werden können, um auf den Kontext des Benutzers zu schließen, wie etwa körperliche Aktivität oder den emotionalen Zustand. Die Berücksichtigung von Kontextinformationen ist wichtig, um zu eruieren ob und wie eine *Reflexive Interaktion* umsetzbar ist.

# Contents

# 1. Introduction

## 1.1 Motivation

The access and usage of technology has increased exponentially and technology has and will continue to be an integral utility in our future. However, we still face operation issues, such can the control of smart devices be complicated (e.g., small input space on a mobile screen), awkward (e.g., speech control in a public), inadequate (e.g., short tasks require complex interaction), not feasible at all (e.g., hands are busy with another task), and cause risks (e.g., focusing on a mobile device instead of the road). Here, we must provide alternative interaction concepts, new input, and feedback strategies that consider the users' actual needs and abilities in order to streamline and improve user experience. The *Reflexive Interaction* concept and its correlation to human use of technology is the key factor being presented in this thesis, and can be seen as a specific manifestation of *Peripheral Interaction*. A *Reflexive Interaction* is envisioned to be executed without demanding great cognitive effort and it enables the user to decide and enact an interaction in a second task without straining the user's main interaction channels, which are often hands and eyes. In future, we can use quick, unobtrusive, and nonchalant interaction techniques to enable a new mobile computing while disregarding the requirement of visual attention and make use of a person's ability of peripheral perception and therefore create a potentially safer way for people to use the technology in a public environment. The series of studies presented in this thesis demonstrate novel alternative interaction concepts supporting a *Reflexive Interaction* that include the user's entire body while exploiting its unique capabilities. *Reflexive Interaction* points out new directions and opportunities for a different type of mobile computing that aim to overcome typical interaction issues in mobile computing.

### 1.1.1 Classification

This thesis is intended to be classified in the third wave of Human-Computer Interaction (HCI), while it explores new ways of mobile interaction. Furthermore, the concept of a *Reflexive Interaction* is being proposed, which fills an empty spot in the field of *Peripheral Interaction* [Back13, Hau14]. Moreover, this work also intersects with previously proposed concepts, such as *Microinteractions* [Ash10], *Microgestures* [Wol16], and *Casual Interaction* [Poh17] in the domain of *Wearable Computing* [Man98*].

**Author Keywords:**
Reflexive Interaction; Peripheral Interaction; Wearable Computing; Augmenting Humans.

**ACM Computing Classification System:**
Human-centered computing → Ubiquitous and mobile computing; Ubiquitous and mobile computing systems and tools.

## 1.2 Research Objectives

This section incorporates three subsections addressing problems in current mobile computing (*1.2.1 Challenges Today*), defines concise research questions (*1.2.2 Research Questions*), and demonstrates how these questions are addressed (*1.2.3 Approach*).

### 1.2.1 Challenges Today

Humans have utilized technology in order to expand their capabilities since the stone age. Dating back to the 1960's, Douglas Engelbart [Eng62], utilized computers to extend the intellectual range of a human through the use of computers, Engelbart is one of the forefather of the current HCI technology. Engelbart struggled with making computer technology usable due to the complexity of the user's ambiguous perception and cognition, which he early discovered when developing the first mouse-interface. Controlling a system can result in high error rates due to the lack of User Experience (UX) and also due to misinterpretations of information displayed at the Graphical User Interface (GUI). Moreover, unexpected variables such as environmental influences or the current individual's physical and mental state can also create user misunderstandings. In addition, the computer can also create errors, such as when input is unclear or invalid for technical reasons.

The user's input stands in a repeating interplay to the computer's feedback, which results in what we call interaction. A clear and error-free human-machine dialogue is the main purpose of all HCI paradigms, however, interactions are especially challenging in mobile scenarios [HTS07]. With the development of wearable computers, the designing of interaction concepts for smart and wearable devices such as: smartphones, smart glasses, smart watches, smart bands, etc. has created many opportunities for computing devices to always be accessible [ACL+08] and visible [HLSH09] for their users. This unlimited accessibility enables new interaction scenarios that were less explored in the past, such as computing on the go. However, the future mobile design path is not clear on how to best design error-free interactions with smart devices that would apply to mobile scenarios in real world [BBRS06].

In mobility, we can easily find scenarios where the control of such smart devices would cause problems or not be feasible at all, a mobile device on the hands for example would not be feasible when: «*carrying bags, hanging on in a bus or train, wearing gloves, holding a child's hand, pushing a pram, having full attention devoted to critical working tasks, having unclean hands, doing anything else with one's hands, or if the device is in an in inaccessible location such as a jacket pocket.*» [Mat13]. Speech control can also not be considered to be the best solution due to the possibility of a high level of background noise being present [TWB+13]. Alternative input modalities have to be found, such as gesture control by tracking body parts using optical tracking, accelerometers, or using any other integrated sensors of the aforementioned devices or in combination with other external sensors in order to achieve tracking with low error rates [CWBM08].

**Figure 1. Several situations may; complicate interaction (e.g., a device needed to be operated by a single hand, when a device is buried somewhere underneath many layers of clothes), disable the user to interact with a computational device (e.g., wearing gloves, holding a bike handlebar, carrying bags), or even lead to dangerous situations (e.g., crossing a road, not paying attention to the pram). In particular, visual attention on the device is not desirable when involved in traffic. Moreover, hands should also remain available for real-world tasks to prevent possible dangers. Nevertheless, mobile interaction can be inadequate, create social awkwardness, and be a disturbance (e.g., when being involved in a conversation).**

Nevertheless, the hands-free problem is not the only one we face. Another problem is that the mobile devices tend to rely primarily on users' visual attention. «*However, visual attention is a limited resource and is often heavily taxed by contextual factors in mobile environments.*» [YCFZ12] When involved in traffic as a pedestrian, mobile devices may also create dangerous situations by simply distracting the user's visual focus (*see Figure 1*).

In 2016, Ben Shneiderman et al. [SPC+16] articulated 16 grand challenges in HCI, while he mentions particularly that designing novel input and output interfaces seem to be an ongoing and everlasting challenge. «*As user input continues to shift from keyboards to gestures, speech, and body movements, users will need reliable mechanisms to express their intentions*» [SPC+16]. However, a reliable interaction avoiding misinterpretation on both sides is utopian. Although interfaces may be designed with the greatest care, dynamical contextual influences [HTS07] may negatively influence an interaction. «*Context is any information that can be used to characterise the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves*» [Dey01]. For instance, a changing environment may distract a person's attention and quickly reduce the same senses that are being used for another task occurring at the same time, which is a typical problem within a mobile context [ST94].

Another challenge is the human's deficit in a constant sensing over time. What may taste nicely in the morning may tastes disgusting in the evening. A cross-talk of multiple senses may also play a role.

### 1.2.2 Research Questions

As already introduced, when interacting with computational devices in the context of mobility, such as when the user is on the go and wants to respond to a notification, the control usually requires the user's hand to touch and the eyes to focus on the device. As a consequence, an interaction with mobility often takes the user's full attention and thus potentially creates (1) dangerous situations, such as when being involved in traffic and (2) awkward situations, such as when utilizing speech control when being in a group. Furthermore, the control of a smart device can sometimes be (3) complicated due to the restricted input space that the small screen offers, (4) inadequate, since binary tasks still require complex interactions, and (5) not feasible at all, such as when all interaction channels are already occupied.

These issues occur frequently in the given context of mobility, but could be overcome with new interaction concepts. In order to break down the aforementioned challenges in mobile computing, five Research Questions (RQ) are posed. While these research questions are very general concerns, many other researchers already found possible answers, but which still leave space for substantially different and improved concepts. Therefore, at the end of the thesis, new answers to the research questions from the point of view of a *Reflexive Interaction* and in regard to previous work will be made (*see 6. Conclusion*).

**RQ 1:** *How can we make interaction less attention drawing to enable safer mobile computing?*

**RQ 2:** *How do wearable interfaces need to be designed in order to facilitate low distraction that is also socially acceptable by users?*

**RQ 3:** *How can we simplify and expand interaction modalities at the same time while extending the limited capabilities of a mobile device?*

**RQ 4:** *How can we reconsider interactions for smart devices to enable an adequate input for binary tasks that are feasible when the user is involved in real world tasks?*

**RQ 5:** *How can we increase the user's ability to interact at any time?*

### 1.2.3 Approach

To answer the research questions raised, it is more beneficial to have a variety of differing approaches, which may also lead to multiple solutions. As a matter of fact, there may be no ultimate solution covering all aspects of interaction problems in mobility, due to the great variance of the mobile context [ST94]. For instance, when the user completes daily tasks; situations of usage will change, such as places may change while using a bus. Also other passengers may accidently get involved in an interaction, such as occurring quickly with speech interfaces. Moreover, external objects may also interfere, such as a handle that needs to be grasped or unfavoured light conditions. All these aspects impact the quality of interaction, while alternative interaction concepts need to be multifarious. Therefore, many different user interfaces are being investigated that try to provide diverse answers, namely interaction strategies, that could be applicable in specific mobile scenarios.

Each of the three identified body zones all yield different properties to match the requirements to potentially enable a *Reflexive Interaction*. The three zones (*see Figure 2*) are: 1. the Head (including face and eyes) yields the broadest spectrum of sensation, 2. the Body (including torso and limbs) provides the most degrees of freedom in terms of agility, and 3. the Foot (including toes and sole) possesses the highest potential for unobtrusive interaction. Because interactions consist of input and feedback, both sides of an interaction are being investigated, since they are interdependent.

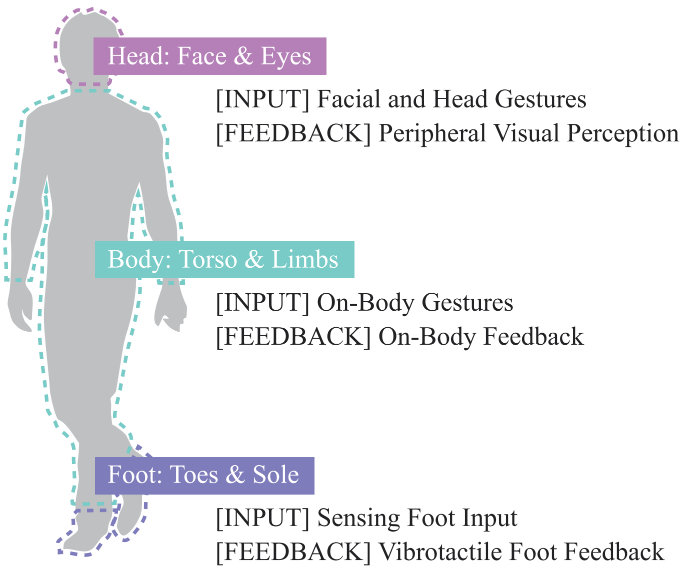



**Figure 2. Three unique areas have been identified and investigated, which are the Head, Body, and Foot. Both the input and feedback strategies are being explored within each area.**

For each body zone an input and a feedback concept is being investigated, which illustrates the concept of a *Reflexive Interaction*. Each section introduces a hand-crafted wearable hardware prototype, which is followed by a user evaluation demonstrating applicability of the developed interaction concept.

## 1.3 Reflexive Interaction

We can categorize the interaction between human and computer in three general classes: *Focused Interaction, Peripheral Interaction,* and *Implicit interaction* (*see also: 2.2 A Typology of HCI*). Later, different aspects and views on *Peripheral Interaction*; how it is understood within the HCI community (*2.3 Perspectives on Peripheral Interaction*), is introduced. Within this theme, a *Reflexive Interaction* would be classified as a subcategory of a *Peripheral Interaction*, while slightly overlapping with *Implicit Interaction*, following Bakker et al. [BHS16] due to the low attention demanded.

### 1.3.1 Positioning to Related Work

In summary, a *Peripheral Interaction* denotes any interaction that is somehow occurring on the periphery of the user in relation to their main task, for example, arranging tokens on a table while briefly interrupting work at the workstation. In a *Peripheral Interaction*, we have these short attention shifts from the main task to a secondary task for either the perceiving of feedback or the providing of input at a secondary task. When sticking within a four seconds threshold, quantified by Ashbrook [Ash10], we can also call this a *Microinteraction*.

Although Bakker [Bak13], Hausen [Hau14], and other researchers provide several definitions on *Peripheral Interaction*, the framework of a *Peripheral Interaction* may still not be absolutely clear. In particular; when does a *Peripheral Interaction* end or become an *Explicit Interaction*? The only answer given here is the fact of floating transitions. That is because human attention is dynamic and may even shift frequently to several other tasks. The works demonstrating a *Peripheral Interaction* presented by Bakker [Bak13], Hausen [Hau14], Ashbrook [Ash10], and Edge et. al. [EB09] have a striking common ground: They work with either external or internal interruptions, while relying on a *Sequential Multitasking*. Therefore, at the moment of interaction, the user's focus of attention shifts over to the secondary task, which can happen within several seconds.

Although task interruptions can sometimes be good, they yield many negative consequences, for instance, increasing error rates [ATH14]. Also it has shown that an increased amount of task interruptions forces the user to unconsciously interrupt more often in other daily routines [DMG11]. Moreover, task interruptions are seen as rather negative in our society, but also by HCI researchers. Instead of technology to become calm and gradually recede into the background [WB97], it becomes more distractive and increasingly louder competing for the user's attention [BDH16]. Previous works, such as from Hausen [Hau14] or Ashbrook [Ash10], try to counteract this by more or less focusing on interruption management, while applying quick sequences of interaction during task interruptions.

In contrast, a *Reflexive Interaction* relies on a *Concurrent Multitasking*, which enables tasks to truly exist in parallel. Because task interruptions do not occur, the parallel secondary task would never exhaust the user's center of attention. A *Reflexive Interaction* would rather follow Brown's strict definition of a *Peripheral Interaction*, to be «*...the reflexive and reactive pre-attentive use of tools and techniques on the periphery of conscious attention*» [Bro16].

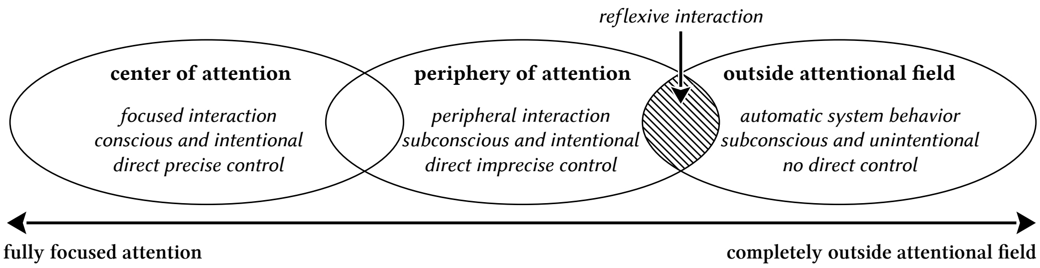



**Figure 3. Bakker et al. [BHS16] use this figure to illustrate the three types of interaction based on the user's involved level of attention.**

Following Hausen's definition [Hau14] of a *Peripheral Interaction*, a *Reflexive Interaction* would be classified on the right edge of *Peripheral Interaction* marginally intersecting with *Implicit Interaction*, which is happening in a pre-attentive way (*see Figure 3*).

### 1.3.2 Definition

**Classification:** A *Reflexive Interaction* can be attributed to a reflexive and reactive pre-attentive variation of a *Peripheral Interaction* which enables the user to interact in parallel with a secondary task without interrupting the primary task.

**Enablers:** A *Reflexive Interaction* is enabled because of the human's capability to complete tasks with divided attention. Divided attention exists because the human possesses several and separate processing systems for reflexes, reactions, and reflections. In addition, information can be simultaneously perceived in the sensor periphery while actions can be executed in the motor periphery. Although the human's attention resources, such as cognitive resources, perception capabilities, and physical abilities are naturally limited, they can be regulated by our attention filters. By reducing the difficulty of a task the attention reduction allows for the extra attention span to be allocated to another task. For example, part of a person's attention can be directed to a secondary task when the mental and physical effort created by the task is minimal, when the user is highly motivated to accomplish a task, when environmental interferences are minimal, or when the tasks are highly familiar to the user.

**Requirements:** Interactions may happen subconsciously due to information being perceivable pre-attentively and when input is provided by a reflexive gesture. This requires a conditioning including a long training phase as well as an interaction design to operate on a standard basis of low complexity information. Thus, an interaction should be accomplished within a fraction of a moment, such as for a duration of about a second. Thus, input gestures are characterized to be very short and feedback would rely on subtle notifications that are scaled to a level that is on the threshold of not disturbing but still recognizable.

Furthermore, the secondary task's feedback and input should be distributed to a secondary interaction channel and not to an already occupied channel.

Moreover, the current context must be considered, such as the user's mental state and activity level, environmental changes, and temporal variables which help determine when the user would be enabled to have a secondary task running in parallel, and coordinate which interaction channels are occupied or potentially available.

**Benefits:** A *Reflexive Interaction* would not allow an interruption of the primary task, instead it opens a quick parallel interaction on a basis of a *Concurrent Multitasking* which enables the user to continue performing the primary task in a limitless manner. The main focus of attention would remain on the primary task while the *Reflexive Interaction* only requires peripheral attention. A *Reflexive Interaction* is minimally noticeable and doesn't interrupt the main directive because it pre-attentively perceives and quickly accomplishes tasks in an automated way. For this reason, a *Reflexive Interaction* is also hardly to be interrupted. Since quick gestures and short notifications often remain unnoticed by other people, they are thus potentially socially acceptable.

**Limitations:** The concept of a *Reflexive Interaction* is not the ultimate solution to all interaction problems because it requires the secondary task to be conditioned closely in a reflexive manner. Moreover, we cannot apply the concept if the input and feedback is greater than two bits. Also in future, more complex interaction would continue to rely on visual feedback and finger input unless mankind developed a sufficient working thought control.

### 1.3.3 Example

To illustrate the workflow of a future system (*see Figure 4*), we assume a simple scenario in which a user rides a bike while we imagine an incoming phone call notification.

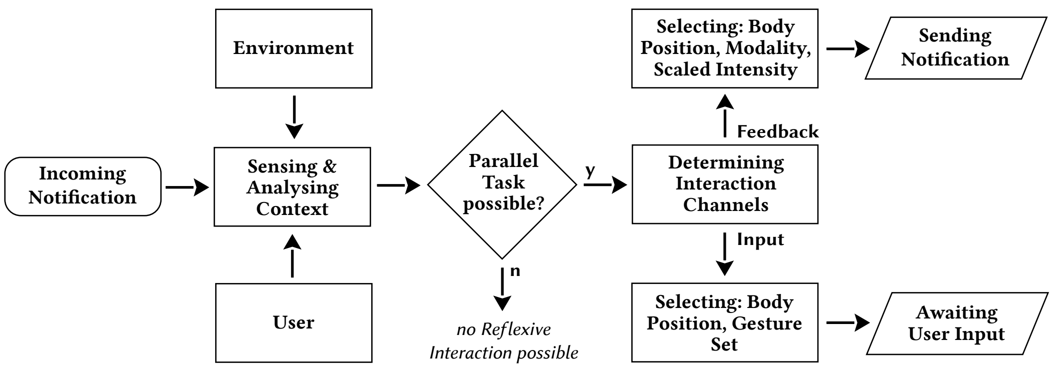



**Figure 4. Flowchart illustrating the theoretical workflow of a system**

In the moment of the call, the system would sense and analyse the current context, such as *environmental variables*. Typical environmental variables are: *location, social aspects, infrastructure, conditions* (e.g., light, temperature, noise, acceleration, ect.), and the *user's* *physical activity* and *mental state*. After evaluating these contextual variables, the system knows if a parallel task is possible, and if it could potentially enable a *Reflexive Interaction*. In the next stage, the system determines the optimal interaction channels usable for a secondary task. To convey the notification, the system selects a body part that is not yet occupied by another task. Moreover, the system picks a suitable modality and scales it to be recognizable by the user, but not disrupting to the user's current sequence of actions. For instance, a simple colour change appearing in the user's peripheral vision for a short moment would be a sufficient indication. Moreover, we assume that the user already created a reflexive action, such as a foot tapping or eye winking which usually skips a request or mutes a disturbing notification such as a call. Because feet are already performing the pedalling function, the user can either quickly respond with an eye wink to mute the call, a head shake to decline the call, or by nodding to accept the call.

The example demonstrates that a *Reflexive Interaction* is context-dependent and it should consist of short, recognizable but not disruptive scaled notifications which include a short gesture set for a response. It makes sense to offer a gesture set enabled to: respond with, accept, reject, and skip notifications. Using natural body language when assigning gestures, such as head nodding, shaking or a heel kicking (such as to "*kill*" a notification) seems intuitive and is easy to internalize. However, other quickly executable gestures could be conditioned but may require longer periods of training. After internalizing a gesture, the interaction would take place without an increased cognitive load. However, a person may sometimes encounter an involuntary behaviour. For instance, while the user is on the bike he considers himself to be busy and reflexively declines any incoming phone call but then changes his mind after the call has been disregarded. In this case, a designer may enable an option to revoke the user's decision, such as waiting for a second gesture to counteract the first negating gesture.

The idea of a *Reflexive Interaction* proposed in this thesis must be seen as a first sketch of a concept. The aim of the thesis is to pave the way for a *Reflexive Interaction* by exploring the possibilities on a technical basis to augment humans. The implementation of a successful *Reflexive Interaction*, however, yield several challenges. Like described before we are subject to long training phases. Furthermore, a number of new questions arise, such as concerning the optimal number of gestures, social acceptance,... etc. that must be answered in future work (*see also: 7. Summary & Outlook*).

## 1.4 Contributions

This section summarizes the contributions of all subprojects that relate to the idea of a *Reflexive Interaction* and allude to possible future applications suitable for a *Reflexive Interaction*. These contributions can be disaggregated as follows:

### 1.4.1 Head: Face & Eyes

Chapter *3. Head: Face & Eyes* investigates alternative Input and Feedback modalities for the given area of the head. The head can be considered as the most interesting body part, by way of it incorporating all five human senses: Ophthalmoception (Sight), Audioception (Hearing), Tactioception (Touch), Gustaoception (Taste), Olfacception (Smell) and the Equilibrium – the sense of balance.

#### 1.4.1.1 Input

Section 3.1 reveals how to sense facial and head gestures in the ear canal through the use of an unobtrusive ear plug. A *Reflexive Interaction* can be implemented exploiting quick facial gestures for a control of a mobile device. This demonstrates an in-ear headset to control incoming phone calls as well as a smartphone music player by head gestures and facial expressions using a physiological sensor and a gyroscope. Furthermore, a novel gesture set based on facial expressions is being introduced, which has been evaluated with an unobtrusive in-ear electrode setup using various wearable technologies (EMG, CS, ESF). Moreover, a differential amplification EFS is being contributed, applicable in a wearable scenario and sensitive enough towards very small changes in electric fields of the human body in order to detect facial-related and other kinds of micro-gestures. By recognising facial expressions, one can extrapolate and infer on the user's state based on the feelings and emotions of a person, which is an important context information (e.g., to find suitable moments for interaction). These findings can be processed when implementing a *Reflexive Interaction* in a future system.

#### 1.4.1.2 Feedback

In section 3.2, the definition and implementation of a *Peripheral Head-Mounted Display* (PHMD) is being introduced, which major characteristic is in empowering the user to continuously performing real world tasks. Therefore, it was investigated how to perceive visual peripheral information and its trade-offs favouring a *Reflexive Interaction* by arranging the peripheral display at varying positions around the user's field of view with three different kinds of visual stimuli. It has been found that when aiming to design a successful *Reflexive Interaction*, the stimuli is essential. Conveying low complex visual information, such as colour changes, arranged in the peripheral area of the user's field-of-view doesn't disturb the user's main task, but is still recognizable. However, when aiming for short reaction times below a second, the Middle-Center and Bottom-Center positions are preferred.

### 1.4.2 Body: Torso & Limbs

The chapter *4. Body: Torso & Limbs* incorporates two sections investigating on-body input and on-body feedback with wearables. The use of the entire body for interaction instead of just utilizing finger for input and eyes for feedback is not broadly considered yet. The body offers around two square meters of surface, which can be utilized for interaction, such as for touch or sensing, because the skin incorporates a variety of haptic receptors. In particular, the limbs have many versatile options to create input gestures, since they are considered to be the most agile parts.

#### 1.4.2.1 Input

In section 4.1, an interaction concept and a wearable prototype is being presented that enables for identifying the location of tap gestures on the entire body without driving an electrical current through the body. The demonstrated implementation enables the ability to sense soft and long touches with an increased sensing range per sensor unit. Moreover, it supports a number of techniques for eyes-free and hands-free interaction to allow different tapping and hovering gestures even while wearing clothes. A short tapping on and hovering over our body parts enables new interaction possibilities that can be quickly performed without significant cognitive effort in a manner that it favours a *Reflexive Interaction*.

#### 1.4.2.2 Feedback

Section 4.2, focuses on a novel notification concept that presents three studies, which utilizes on-body feedback based on haptic, thermal, and electrical feedback. These studies extend to related works, with the proposition of scalable notifications that go beyond simply notifying the user, and force the user to take action. Providing notifications with different intensities can be useful in several situations, such as when being in a group of people and obtrusive notifications may bother others. While subtle notifications can help here, they may also be quickly overlooked or intentionally ignored without great effort and disruption, these subtle notifications favour a *Reflexive Interaction*. A future system is envisioned to automatically scale the feedback to an appropriate level, based on the urgency of notification or based on contextual factors. Also forcing the user to subconsciously considering a notification, such as by quickly forcing the user's foot to press down the car's pedal, may support a *Reflexive Interaction,* since the execution time of the gestures is being reduced.

### 1.4.3 Foot: Toes & Sole

Chapter 5: *Foot Toes & Sole* is divided into two sections, which introduce foot-based input strategies and vibrotactile foot feedback. Utilizing the foot for interaction is interesting, because it does not occupy conventional interaction channels nor does it attract visual attention. Reactivating the foot as an interaction channel has potential, because it still yields similar amounts of motor-receptors like the hand.

#### 1.4.3.1 Input

In section 5.1, a technical implementation of a wearable insole interface based on capacitive sensing was researched. Furthermore, five applications are presented and contribute: (1) an explicit foot gesture control such as a heel tapping, and weight shifting based on plantar pressure exertion, (2) the recognition of body postures when standing still, (3) the recognition of walking styles, (4) the identification of the user, and (5) a ground surface detection. Making use of simple foot gestures may not disturb the user's main task and thus abet a *Reflexive Interaction*. While the idea of a *Reflexive Interaction* is to provide the user with suitable input and feedback modalities, in order to not interrupt the primary task, it is apparent that a varying context can influence interaction significantly. Hereby, the position of foot can help to infer on context by detecting the user's current body posture, walking activity, and the environment the person is walking through. These new kinds of contextual information can be considered when designing *Reflexive interactions*.

#### 1.4.3.2 Feedback

In section 5.2, several prototypes are presented to evaluate vibrotacile feedback under the foot. Here a comparative study contributes, that the foot is found to be capable in perceiving vibrotactile signals precisely, in fact the foot interface performed slightly better than the wristband and the belt. Moreover, several lab studies are being contributed to the study of vibration patterns known from literature and are being evaluated on and under the foot. Two in-situ studies provide information that vibrational feedback at the foot is successfully tested to be less stressful and capable of being used for an assistive technology. This research indicates the foot to be an interesting position for perceiving feedback, due to the fact that the haptic channel at this position not being occupied yet and therefore enables eyes-free and hands-free interaction and thus fulfils the basis for a *Reflexive Interaction*.

Based on these individual contributions, several implications (*Chapter 6: Conclusion*) can be derived that help answering the afore raised research questions. General findings are summarized in section 6.2 that should be considered for future developments.

## 1.5 Thesis Organisation

This thesis incorporates seven chapters (*see Figure 5*). The motivation of this research is being presented in *Chapter 1: Introduction*. Here, current challenges are being introduced, which we face when interacting with mobile computational devices while being on the go. In reference to these, five research questions have been defined. At next, the idea of a *Reflexive Interaction* is defined, which represents a possible solution to the afore highlighted interaction issues. In *Chapter 2: Related Work*, necessary fundamentals are being introduced to provide an understanding on how we can extend *Peripheral Interaction* by augmenting humans. The following *Chapters 3-5* present investigations on input and feedback around the user's body that favour a *Reflexive Interaction*. These research works are based on papers published at international conferences. *Chapter 6: Conclusion* presents a compilation of most important findings based in the conducted researchers introduced before. Finally, *Chapter 7: Summary & Outlook* closes the thesis with a short recapitulation of presented research and ends with posing future research questions.

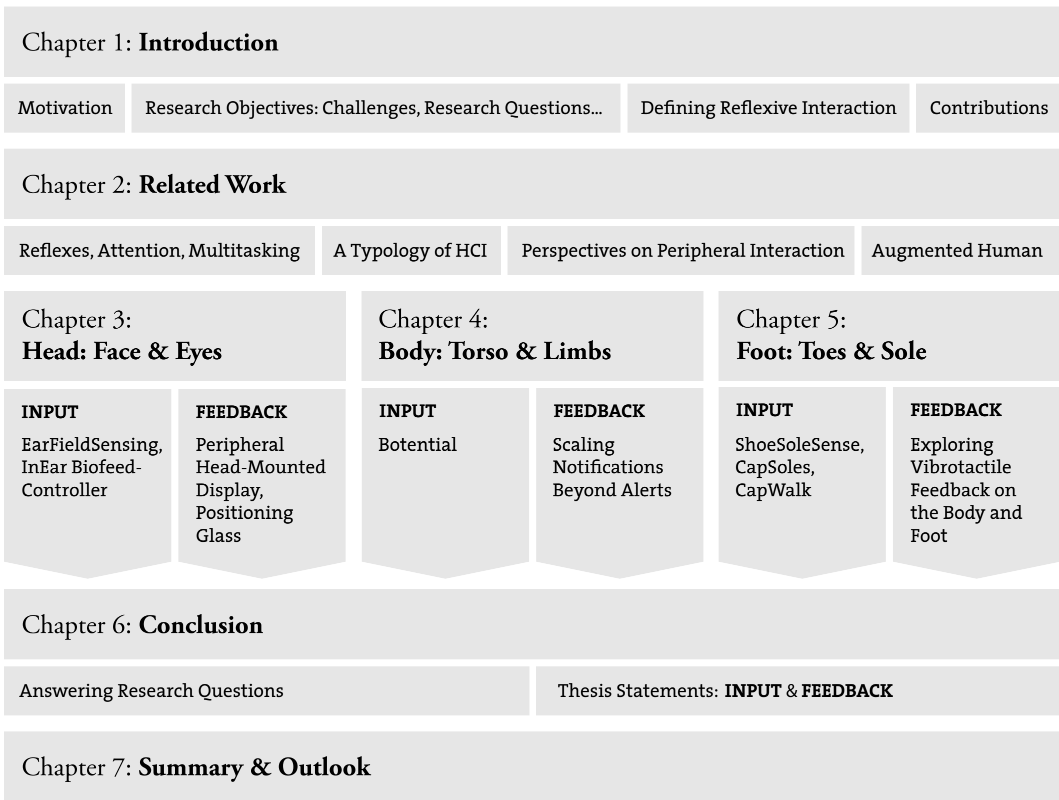



**Figure 5. Structure of the thesis. The idea of a *Reflexive Interaction* is already being introduced in the first chapter, while Chapter 3-5 contains a variety of research papers illustrating the proposed concept.**

# 2. Related Work

This chapter introduces a selection of fundamentals, which are important to gain a complete understanding of the proposed concept of a *Reflexive Interaction*. The first section introduces an overview on the human's ability of paying attention and responding to his environment, which is essential to understand the idea of multitasking (*2.1 Reflexes, Attention, and Multitasking*). To decipher how a *Human-Computer Interaction* functions, previous models and a current typology are being briefly introduced (*2.2 A Typology of HCI*). In the following section, *Peripheral interaction* is being introduced in greater detail, since a *Reflexive Interaction* can be a specific manifestation of it (*2.3 Perspectives on Peripheral Interaction*). The last section provides a historical overview on the evolvement of technology from the past up to how technology is being envisioned to augment the human in future (*2.4 Augmented Human*).

## 2.1 Reflexes, Attention, and Multitasking

The human can be considered as an I/O system that is always switched on: listening to the environment and being capable of action – be it consciously when drawing attention to a task or unconsciously, such as by responding with reflexes. In this section, the most fundamental knowledge and theories are being briefly introduced that underlie the idea of a *Reflexive Interaction*.

### 2.1.1 Human Reflexes and Conditioning

The general definition of a reflex describes a nearly instantaneous reaction, such as a physical movement, in response to a single stimulus or multiple stimuli. Human reflexes can be considered as an autonomous neuro-motor interaction, enabled by neural pathways, also called reflex arcs which act on an impulse-basis before reaching the brain [Gil05, War19]. Therefore, reflexes do not involve conscious thoughts initially, although the result of the reflex, such as the movement of a leg, is consciously perceivable.

We can distinguish between different forms of reflexes, such as natural reflexes, also called *Somatic* or *Unconditional Reflexes*, which are congenital. Although, these natural reflexes are pronounced in any health human, they can be individually strong, as they can get lost in higher ages. For example, in medical research, we classify *Primitive Reflexes* that only occur with newborns, such as: *Asymmetrical Tonic Neck reflex, Babkin Reflex, Galant Reflex, Moro Reflex, Parachute Reflex*,... [Cap78, Zaf04]. Reflexes that can be found in adults, can be grouped in *Myotatic Reflexes* (e.g., *Achilles Reflex, Biceps Reflex, Brachioradialis Reflex*,...) [LS24], which are stimulated mechanically and result in a stretch of a muscle, *Tendon Reflexes* [BD57], which are triggered by striking its tendons, and *Cranial Nerves and Brain Stem Reflexes*, which can be stimulated by nerves (e.g., olfactory, visual...) [Mer11].

Independent from the type, none of the reflexes require the human to draw consciously attention and for the first two groups; motor action is executed in an automated way, also without a conscious processing.

Another form of reflexes has been defined after a great series of Pavlov's experiments in 1928 to 1936, which are denoted as *Conditioned Reflexes* [PA03]. These reflexes are not congenital, but acquired during a life time. A good example of such reflex is illustrated by the well-known dog experiment, in which a bell rang just before feeding time. At some point it has shown that solely the ring of the bell would start the dog's production of digestive secretions, although food may not be served. Building upon Pavlov's theory of *Conditioning Reflexes*, Skinner studied the behaviour of organisms more extensively [Ski66]. This can be seen as the basis for the today's theory of *Associative Learning* [Mac83], which denotes the learning of *Conditioned Reflexes* as *Classical Conditioning,* while extending it with the concept of an *Operant Conditioning* [Ski84]. To better understand the differences between both concepts, some quick examples are being presented:

In *Classical Conditioning,* the response is solely done in a reflexive way, such as the production of the dog's salivation when hearing the bell, or setting the car's blinker when seeing the road marking while willing to make a turn. Here, the response depends on the presentation of the conditioned or unconditioned stimulus – if there is no stimulus, there won't be a response. In contrast, *Operant Conditioning* describes a rather conscious decision to a stimulus, which is often involving longer routines, such putting up an umbrella or washing the dishes to achieve a long-term or sustainable goal. Here, the conditioning is based on a stimulus presented after the response by using reinforcement, such as a reward, and punishment, which can both be positive (presence of a stimulus: e.g., wet clothes) and negative (absence of a stimulus: e.g., no smelly dishes).

Because a successful *Reflexive Interaction* is aimed to be quickly executed by not creating high cognitive demands, it would somehow fit in the continuum of a *Conditioned Reflex*.

### 2.1.2 Human Attention

In 1890, James William originally defined attention as «...*taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others*» [Wil90]. Different speaking; today, attention is denoted as a behavioural and cognitive process of focusing on tasks. While attention can be widely spread, it can also be focused on a single and narrow task. Since, human attention resources are limited by nature, attention can be shared amongst multiple tasks or switched from one focus to another. While we can simply talk of focal and peripheral attention following Juola [Juo16], Wickens et al. [WM07] even speak of five types: focused, selective, switched, divided, and sustained attention. While focal / focused attention is consciously directed to a primary task, we can at the same time recognize abrupt changes occurring in our peripheral perception, such as environmental changes or internal changes without great cognitive effort. This is an important mechanism, which enables us to quickly respond and to quickly switch focus.

### 2.1.3 Attention Theories

There are numerous of different theories on attention, however, all contemporary theories concentrate on the selection process as a means of maintaining focus on the task at hand while being able to accept interrupts. The first model is credited to Broadbent [Bro58], who developed an information-processing model in 1958, which is viewed as a single-channel filter for selecting information. In his model, perceived information is passed into a limited-capacity processor, that processes and stores information in a short-term and permanent memory. Following Broadbent, the attention filter can only be switched between several sources – it doesn't allow sharing, since it is considered to be highly demanding of cognitive resources. While his theory was confirmed for the time being, later other researchers, such as Treisman [Tre64], Moray [Mor59], Norman [Nor68] and Deutsch et al. [DD63], argued that sensory filters may still be on hold and not shut off completely. In 1963, Deutsch et al. discovered that familiar information impacts our conscious perception, no matter of focused attention. Some more decades of research later, different types of experiments made clear that attention can be flexibly distributed over multi-faceted sensory channels [JBCW91, Jon81, Pos80, PC84]. In the early 90's a new aspect comes into play: the investigation on attention distribution over time. Experiments have shown that attention can be interrupted over time based on differing task demands [RSA92]. Moreover, it has been discovered that over time familiarization with a task increases, but which also has a positive effect: if the stimulus is well-known, attention can be quickly reallocated between multiple tasks, although important incoming information can be lost [NM02]. These attention shifts have then been investigated in a broader manner by Redelmeier et al. [RT97] and Strayer et al. [SDJ03, SD07], while focusing on mobile phone use in traffic, such as when driving a car. Although multitasking is within our capabilities, it has shown that attention switching between two demanding tasks, causes high task-switching costs (important information may be lost, reaction time is reduced,...).

While early models only know a single attention filter we, nowadays, decompose a task into having multiple attention filters (*see Figure 6*), such as *Effort*, *Motivation*, *Environment*, and *Familiarity* [WM07], which are responsible for the level of difficulty and thus for the amount of attention required to fulfil a task. Therefore, a *Reflexive Interaction* is favoured when the required mental and physical effort of both tasks are low, the user is motivated, environmental interferences are minimal, and when the tasks are highly familiar with the user.

In terms of human attention resources, we distinguish between multiple attention resources, which we can divide into three parts; *Perception*, *Cognition* and *Action*.

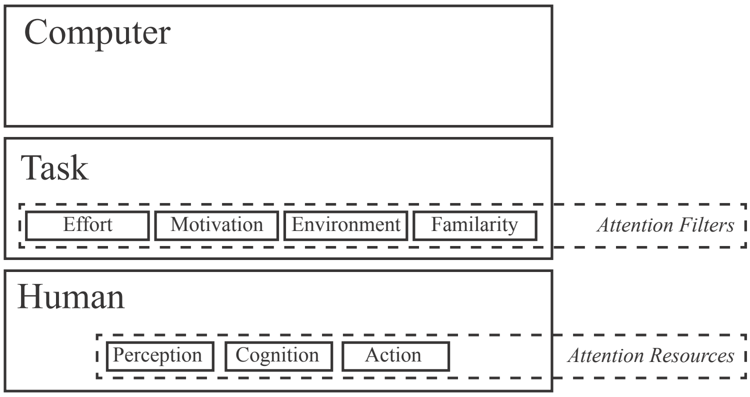



**Figure 6. A simplified model showing four Attention Filters and the humans Attention Resources - based on the theory of Wickens et al. [WM07]**

While all contemporary theories and models on the human cognition agree the capacity of cognitive processing to be limited, Wickens' *Multiple Resource Theory* [Wic02] as well as Van Erp's *Prenav Model* [VV04] brings a new assumption into play. After Wickens, each sensing modality associates its own resources. The stronger the interference of two tasks, the more common resources are claimed by them. Therefore, it makes sense distributing attention to several other channels. For instance, if needed to follow the traffic as a car driver, it would be more demanding having additional directional aids on a visual basis.

Instead, presenting cues of a turn-by-turn navigation in an acoustic or haptic way is likely to produce less cognitive demands. Confirming or rejecting a rout change could be accomplished with a short head gesture, such as nodding or shaking instead of using a manual interaction on a touchscreen, since this interaction channel is already occupied in a driving scenario. This simple example illustrates the benefit of a *Reflexive Interaction*.

### 2.1.4 Multitasking

The fact that our attention resources can be devoted to multiple tasks is the base for multitasking. In a prototypical multitasking scenario, we would have a main task with focal attention and a secondary task accounted with peripheral attention (*see Figure 7*) [Ju016]. Although most experiments underline Joula's theory, it is still questionable whether it may be possible to pay an equal amount of attention to two equally demanding tasks.

There are two theories on how attention resources may be distribute; 1) *Task Sharing*: attention distributes among multiple tasks simultaneously, like displayed in the Figure 7, and 2) *Task Switching*: attention switches rapidly between several tasks. The truth maybe a mixture between both: attention can distribute, but in a high frequency.

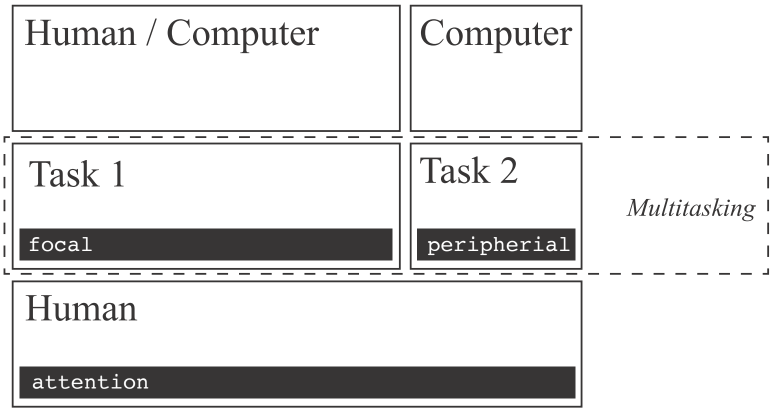



**Figure 7. Simply divided into focal and peripheral attention – based on [Juo16].**

There are two types of multitasking [STB09]; the first one is known under the term of *Concurrent Multitasking* and describes parallel execution of tasks when we use separate cognitive processors for separate processes. For instance, this is where one walks and interacts with a mobile device while having a call, at the same time. The neocortex is thinking about how to correspond to a question, while the cerebellum is coordinating the complex series of reflexes that allows him to walk. In this case, walking is peripheral to conversing. If the user reaches an unexpected obstacle, or if the terrain is rough, then the user may have to switch his conscious attention to figuring out how to walk. Then the conversation becomes peripheral and one either switches into a passive listening mode or introduce filler statements and maybe even loops of previously spoken phrases. One might say «*ummm*» or «*aahh*» or one might repeat own words or even the last words spoken to him. Basically, here the task of walking is brought to the center of your attention, and the task of conversing has been delegated to the periphery. Once past the obstacle, the attention shifts back, which has also been described by Weiser [Wei91]. *(This is a modified example adopted from a personal correspondence with John N.A. Brown.)*

The second type of multitasking is denoted as *Sequential Multitasking*. Here, tasks are executed in an interleaved way over longer periods of time, such as when assembling an IKEA shelf while switching between reading the manual and going back to screwing. Apparently, multitasking is characterized by interruptions, which can be internally or externally [MN86]. Internal interruptions are purely intrinsically motivated, such as a user's mind change. In contrast, external interruptions are caused by environmental influences, such as ringing phone or a notification popping up.

### 2.1.5 Task Interruptions

Interruptions are not necessarily bad, instead they can also have positive consequences, such as stated by Jin et al. [JD09]. For instance, a break can alleviate stress, provide mental stimulation, increase enjoyment of a routine primary task, while it can also improve the user's mood. Jin et al. collected seven distinct categories of self-interruptions which, are labeled as *Adjustment, Break, Routine, Wait, Inquiry, Trigger,* and *Recollection*, while positive as well as negative effects are being summarized.

While internal interruptions in healthy human may yield numerous positive effects, external interruptions are seen as rather negative. A study showed that people who are exposed to many external interruptions have a higher tendency to interrupt themselves more often [DMG11]. Another study by Altmann et al. [ATH14] revealed that short interruptions, no matter if internally or externally, lasting around ~3s doubled the error rate, while interruptions of ~5s even tripled the number of errors, due to the imposed focus switch. Apparently, small interruptions, can substantially distract us, which is a well-known phenomenon in psychology. In HCI, we denote distraction induced by music or a video being played in the background or any other obtrusive feedback by smart devices as *Digital Distraction*.

In 2016, Biskjaer et al. [BDH16] are talking about *«a new type [of Digital Distraction that] has emerged in which the user rendered passive»*, while referring to «... *instant information, reminders, alerts and alarms that seemingly pop up out of the blue and demand the user's attention»*, which seems like to be the opposite of Mark Weiser's envisioned age of calm technology [WB97]. Instead ubiquitous computing to gradually receding into the background, it becomes an increasingly *«hectic, chaotic space in which various digital technologies compete for the user's attention»* [BDH16]. Biskjaer et al. see device-based notifications and the internet's constant stream of social media notifications to be the major cause for that and sees the need to find better strategies to manage the disturbance by smart devices to reduce unnecessary attention attention-drawing. Although, we can meanwhile find additional *Do-Not-Disturb software*, HCI researchers agree that it makes highly sense to reconsider and adapt interaction styles to encounter the growing body of obtrusive technology.

## 2.2 A Typology of HCI

*Human-Computer Interaction* (HCI) is an increasingly important discipline in Computer Sciences. The term HCI itself was first mentioned in a scientific publication in 1976 by James H. Carlisle [Car76]. Nowadays, related terms include: *Computer-Human Interaction* (CHI), *Human-Machine Interaction* (HMI), and *Man-Machine Interaction* (MMI). While HCI lately became a broad and intellectual field, it intersects many research fields, such as perception psychology, engineering, etc. The history of HCI identifies three waves that formed this field of research [HTS07]. Following Kuhn, these scientific revolutions may be denoted as so-called paradigms [Kuh70]. The first paradigm mainly focuses on the optimization of the pure coupling between both entities, the user and the machine, from an engineering and ergonomics point of view. In contrast, the second paradigm, arose from cognitive science, in which researchers then increasingly focus on what is happening at the user's mind during interaction (e.g. how information is being perceived, understood, processed and reproduced). The current and third paradigm of HCI brings another aspect into play: the dynamic context [HTS07]. To better understand human behaviour when interacting with computers, researchers have established different models, which however, often do not cover all aspects such as introduced at the third paradigm of HCI. Well established models are:

- *Gulf of Execution and Evaluation* (1986) – Norman [Nor86]
- *The Structure of Multimodal Dialogue* (1989) – Hutchins [Hut89]
- *A Unifying Framework for Interaction* (1991) – Abowd et al. [AB91]
- *Task Decomposition Model* (2003) – Koubek et al. [KBB+03]
- *Human - Environment Interaction Model* (2003) – Koubek et al. [KBB+03]
- *Cognitive System Engineering Model* (2005) – Hollnagel et al. [HW05]
- *Understanding User Tasks* (2011) – Vu et al. [VP11]

While HCI evolved, new trends of computing arose, which is tried to organize in taxonomies [Gre97] and typologies [DvL15], which are not wrong nor absolutely right, since the viewing angle may just be different. For instance, typologies may follow the logic of material technology [LL13], or rely on the logic of the relation users have towards technology, such as proposed by Dietrich and van Laerhoven [DvL15].

In this thesis, a rather elementary typology is being used that breaks down a human-computer interaction into three types, based on the user's involvement of attention: *Focused Interaction*, *Peripheral Interaction*, and *Implicit Interaction*.

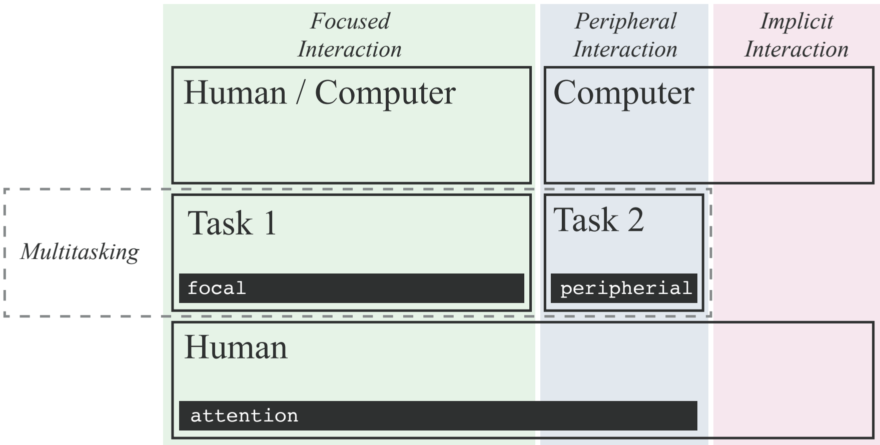



**Figure 8. A model illustrating the relationship of *Focused Interaction*, *Peripheral Interaction* and *Implicit Interaction* based on the user's involvement of attention.**

After Juola [Juo16], we can distinguish two levels of user attention; focal attention, which is demanded by the main task and peripheral attention, which may be demanded by a secondary task running besides the main task. Moreover, interaction between the human and a computer may also happen without the user's attention being involved, although the user may be aware of the result. In the following subsections, these three forms are being briefly explained and underlined with random examples.

### 2.2.1 Focused Interaction

When we think of interaction, we usually think of a focused interaction, which is the most well-known way of interaction in HCI. In a focused interaction, the user's focal attention is directed to a dedicated task.

**Example 1:** Let's imagine a storeman in a storehouse for logistics to use a hand scanner to scan the barcode of his current pick, which could be a package. We assume that the package is being held in the left hand, while the scanner is carried and operated by the right hand. During the pick and scan process, the interaction process is monitored visually by the user. Perception, cognition and action resources are fully devoted to the picking task.

**Example 2:** In another scenario, we assume a pedestrian to walk on a path and willing to send a text message. Therefore, the phone is being fished up the pocket and held by one hand, while the other hand may be used for text entry. Like in the first example, the majority of attention resources are being demanded by the messaging task, while hands and eyes are busy with the phone. A parallel task, such as walking, may co-exists, but does not get focal attention.

### 2.2.2 Peripheral Interaction

Furthermore, there are possibilities to place a second interaction on the edge of the attention focus in the periphery, to minimize the cognitive load and to not distract the user from the primary task. Since attention resources can distribute to other than the primary tasks, we can talk of peripheral attention remaining at a secondary task. While the term *Peripheral Interaction* was shaped under significant influence by Bakker [BvHEO12] and Hausen [Hau12], they allow a *Peripheral Interaction* to also attract full attention for very quick periods of time. However, in a *Reflexive Interaction* greater attention shifts would not occur, and the secondary task would remain with peripheral attention only (*see Figure 8*).

**Example 1:** Let's again imagine the storeman to grasp the package, although this time, a body-worn camera identifies the pick. An artificial intelligence, such as Alexa, would be available to inform about this pick via audio feedback. In a *Peripheral Interaction*, the user is still enabled to walk around, pick and place packages, while also providing input with voice commands. In this example, the user`s attention would shift to Alexa from time to time, in particular when giving voice commands. In another variation, a simple vibration under the foot would signal a wrong pick, while a quick foot gesture could confirm the pick. In this setup, the user`s focal attention can always remain on the package being grasp and on the user keeping track of his surroundings at any time. This scenario can be considered as a *Reflexive Interaction* provided the user is highly familiar with the interaction concept and it is quickly accomplished with a certain automatism by the user. These kinds of subtle interaction can be more convenient for the user, save time, increase efficiency, and be potentially safer, because the user's main interaction channels (which are usually hands and eyes) are not being occupied. Like this, technology moves from the foreground to the background like Mark Weiser envisioned interaction to be desirable [WB97].

**Example 2:** In another mobile scenario, a user may again be on the go, while wearing a *Peripheral Head-Mounted Display*, such as a Google Glass, while running a navigation application showing a map on the display. Small interruptions, by focus switches of the pupil from the real world to the displayed map, would still be considered as a *Peripheral Interaction* following Hausen [Hau14]. In contrast, in a *Reflexive Interaction*, the user's pupil would not be required to focus the PHMD and reading detailed information. Instead, a simple turn-by-turn path navigation could rely on colour changes of the display's background (e.g., blue=turn left; red=turn right), which are also perceivable in our peripheral vision. Moreover, pausing the application would be enabled by a quick eye-wink, instead of raising the finger to the glasses' frame and sliding on it.

### 2.2.3 Implicit Interaction

The term "*Implicit Interaction"* has been initially proclaimed in the year 2000 by Albrecht Schmidt [Schoo], and be the opposite pole to a *Focused Interaction*. *Implicit Interaction* always incorporates an activity recognition component, which tracks the user behaviour and the context. Collected data is then processed and evaluated by an intelligent system and an output is generated. We can talk of an *Implicit Interaction*, as soon as interactions are carried out without demanding the user's attention, which is thus not creating any additional cognitive load – although, the user may be conscious that an interaction may be happening in the background.

**Example 1:** We again envision a storehouse for logistics and a store man to pick a package out of the shelf. While the logistics software is informed about the forthcoming pick, it also receives a broad stream of sensor data providing context knowledge, such as about the current shelf the user is standing in front of. The system is capable of automatically registering the pick without requiring the user to explicitly scan the barcode of the package, while the system fills up the electronic basket in the background.

**Example 2:** Again, in a mobile scenario, we envision a user typing a text message into his smartphone. While this action requires focal attention on the primary task, peripheral attention may be devoted to the user's surrounding, so he doesn't bump into other pedestrians. Based on context information, such as the time of day and the user's vital parameter, an intelligent system may estimate the user's state (e.g., level of tiredness) and thus to increase font size, or to enable a more sensitive auto-grammar-correction.

## 2.3 Perspectives on Peripheral Interaction

Technology permeated our everyday lives, while we can find computers in our pocket, on our wrist, in our cars, and embedded into our cooker. *«The new technology needs to be able to interact with people at multiple levels in order to gauge anyone's current level of attentional focus and task involvement»*, as recently stated by James F. Juola [Ju016]. Any kind of stimuli, be it sound, light, vibration, etc. triggered by ubiquitous technology may interrupt our focal attention due to their potential importance, although, such distraction may be unwanted when performing a critical task or when the user is not in the mood. Here, the concept of a *Peripheral Interaction* comes into play, which aims to minimize or even suppress interruptions, while enabling for the perception of peripheral information presentation and enabling for short inputs that do not create significant cognitive load, nor significantly interrupt the primary task.

The term *Peripheral Interaction* has been shaped over the past few years, which was mainly driven by Saskia Bakker and Doris Hausen with their dissertations [Bak13, Hau14], numerous papers [BvHE10, BvHE13, HBv+13, HBG13,...], panel discussions, workshops [BHS+14], and books [BHvHS15, BHS16].

In 2014, Hausen [Hau14] defined *Peripheral Interaction* to be the interplay between several tasks similar to multitasking, although there is a great difference. In the research field of multitasking, one usually focuses on interruption management, such as finding a good moment to interrupt the primary task with a secondary task [McF02]. *«In contrast, Peripheral Interaction can be applied to both, external and internal interruptions aiming at a reduction of cognitive and visual load and hence the effect of interruptions by embedding Peripheral Interaction into the user's daily routines»* as defined by Hausen [Hau14].

*Peripheral Interaction* is based on Weiser's idea of calm technology, which envisions computers to be seamlessly integrated into all aspects of our everyday lives while being unobtrusive [WB97] and not in the center of our attention. When using computational devices, the user should be *«freed to use them without thinking and so to focus beyond them on new goals»* [Wei91]. To achieve this goal, the idea of *Peripheral Interaction* puts devices into the background of our attention, which is *«inspired by the way we fluently divide our attentional resources over various activities in everyday life... [while] the aim of Peripheral Interaction is to enable interaction possibilities with minimal attentional resources»* [BHS16]. Instead of disrupting the primary task abruptly, following the idea of a *Peripheral Interaction*, the center of attention may seamlessly shift to a secondary task *«when relevant for or desired by the user»* [BHS16]. How this is accomplished, and how other researchers see *Peripheral Interaction* and its variation is introduced in the following subsections.

### 2.3.1 Peripheral Tangible Interaction

In 2009 already, Darren Edge and Alan F. Blackwell introduced *Peripheral Tangible Interaction* to the HCI community [EB09]. *Tangibles* can be physical objects, which embody a digital system state and which can be grasp for the manipulation while being in the focus of the user's attention. In contrast, the new concept of a *Peripheral Tangible Interaction*, allows for an *«imprecise interactions with independently meaningful, digitally-augmented physical tokens»* [EB09]. These tokens can be freely arranged within the periphery of their workspace, in a way that they are away of the normal center of attention, but still ready to be selectively and fluidly engaged with. Edge's and Blackwell's goal, was it to *«design a TUI [(Tangible User Interface)] based on tangible objects that could drift between the focus and periphery of a user's attention according to the momentary demands of their activity»* [EB09] by combining the concept of a *Peripheral Interaction* and engaging tangible interactions.

The authors evaluated their concept on a desk with a computer workstation, which is supposed to demand focal attention and an interactive surface next to the workstation, on which the user had different coloured tokens, which were visually augmented by conventional display halos and optically tracked by a camera. The tokens can be arranged with a single hand, so the other hand can remain at the keyboard continuing the primary task at the computer. The tokens are supposed to represent unfinished tasks and shared documents, which can be used to track and update a task progress and dependencies between tasks. In order to design tangible user interfaces that enable *Peripheral Tangible Interaction*, the authors concluded with a four stages framework [EB09], consisting of: (1) Context Analysis, refining *«design context into a design opportunity»*, (2) Activity Analysis, refining *«a design opportunity into a design space»*, (3) Mapping Analysis, refining *«a design space into a structural design»*, and (4) Meaning Analysis, refining *«structural design into a meaningful design»*. For each step, several affordances are being positioned that further refine the authors' concept of a *Peripheral Tangible Interaction*.

Establishing tasks, such as arranging tokens, on a desk in the periphery of the user's workstation is an interesting approach, although during the moment of interaction, focal attention is clearly drawn by the tokens.

### 2.3.2 Microinteractions and Microgestures

In 2010, Ashbrook proposes the concept of *"Enabling Mobile Microinteractions"* to minimize interruption [Ash10]. He envisions a tiny burst of interaction with a device lasting not longer than four seconds, so the user can return to the primary task [Ash10]. Ashbrook considers motion-based gestures, such as finger gestures on a touchscreen of a wrist-worn device when being engaged in mobile situations. Although Ashbrook did not explicitly mention the term of *Peripheral Interaction* at that time, *Microinteractions* still fit into that continuum following Hausen's [Hau14] definition.

In 2011, Wolf et al. [WNRM11] mentions the term *"Microgestures"*, which fit well into the concept of *Peripheral Interaction*. Wolf et al. defines *Microgestures* to be finger/hand gestures, which are distinguished into three classes: palm-, pad- and side-grasp gestures. While each gesture has its uniqueness in terms of execution style, it may also demand a different level of attention. Wolf [Wol16] envisions such *Microgestures* to be executable in the motor periphery, while the hand is performing a non-precise action, such as when holding a mobile device, digital camera or grasping a steering wheel.

Although it has shown that users can often not divide their motor abilities, especially when performing more than one high precision task, there are other tasks allowing for the user to execute in parallel, such as steering a car and controlling the gas and break at the same time. Wolf, particularly focuses on hands-busy mobile situations, in which the user is walking, driving a car or riding a bike. In mobile multitasking, such as when reading a short message when involved in traffic, it can quickly occur that two or more tasks compete against each other, *«which always requires splitting motor and attentional resources between a primary and a secondary task»* [Wol16].

Wolf distinguishes three different uses of *Microgestures*, such as when being (1) part of the focused activity, for instance when playing a music instrument like a clarinet, (2) as an extra flourish, for instance when ringing the bell while cycling and (3) as a separate embellishment, for instance tapping the rhythm of the radio song at the steering wheel.

*Microgestures* yield the potential to better exploit the unused resources of the user's hand in many everyday situations, especially when hands are busy, such as when grasping a handle or carry a bag. Following Wolf [Wol16], *«finger motions offer a much bigger input design space than is has been taken advantage of»*. On top of that the execution of finger movements are comparably quick gestures and often remain unnoticed by thirds and are thus potentially social acceptable.

While on the one hand, finger gestures are very promising for a *Peripheral Interaction*, on the other hand there are not the ultimate solution, because there may also be situations, in which *Microgestures* are not appropriate, such as when attending a meeting, or not feasible, such as when playing tennis.

### 2.3.3 Casual Interaction

In 2013, Pohl et al. [PM13] proposes the idea of a *Casual Interaction*, which is somewhat related to *Peripheral Interaction* since the user can be engaged in multiple tasks. The striking difference between both concepts is that a *Casual Interaction* can gradually move away from a focused task to a casually way of execution, while reducing focal attention. Apparently, the precision of task execution is then also reduced. To illustrate this concept Pohl et al. describes a touch-sensitive colour picker, that can be: (1) touched for fine-grained control, (2) hovered for setting at least the brightness and hue, and (3) gesticulated in greater distance for an abstract control. In another example, Pohl et al. describes a smartphone control in a mobile scenario, in which the user can accomplish: (1) precise touch input on the screen, while needing to come to a standstill, (2) around-the-device interaction, which may still slow down the runner when interaction, and (3) speech input, which may not hinder the running performance, but which only yields a minimal feature set.

Another difference to *Peripheral Interaction* is that the user can make an active choice of engagement level, and therefore, «*the system is relieved from determining that level itself*» [PRM14]. While interacting casually can be triggered un-/consciously there are three reasons: (1) social constrains, for instance the system is not socially acceptable in the situation, (2) mental constrains, for instance the user is tired, and (3) physical constrains, for instance when wearing gloves.

While «*Casual Interactions are particularly appropriate in scenarios where full engagement with devices is frowned upon socially, is unsafe, physically challenging or too mentally taxing*» [PM13] the proposed focused-casual continuum potentially enables smooth transition to a *Peripheral Interaction*. However, designing a system, that gradually scales attention, such as by varying the distance between the user and the device, yields many technical implementation and design questions, as also pointed out by Pohl et al.

### 2.3.4 Peripheral Proxemic Interaction

In 2016, Vermeulen, Houben and Marquardt [VHM16] summarize how to facilitate transitions between interaction outside the attentional field, the periphery and center of attention by means of a so called *"Proxemic Flow peripheral floor display"*. In their works, the authors combine *Peripheral Interaction* with *Proxemic Interaction*. The term *Proxemics Interaction* has been mainly shaped by Ballendat et al. [BMG10], Marquardt [Mar11], and Greenberg et al. [GMB+11], which means an extension of the classic vision of context awareness and the uses proxemic relationships (distance, orientation, movement, identity, location) to mediate interaction between people and digital devices, such as handhelds and public displays. The authors designed *Proxemic Interactions*, in which it should be possible for a system to fluently move between the periphery and center of attention. In a user interaction, such as with public displays, a fluent transition is desirable to avoid unintended actions, undesirable results and difficulties in detecting or correcting mistakes. *«When the system is doing something that could potentially be surprising or disturbing to the user, Peripheral Interactions could subsequently transition to the center of attention to make the user aware of what is happening»* – Vermeulen et al. [VHM16].

Moreover, information fitted in our peripheral attention, such as light cues at the floor could indicate action possibilities and information on action possibilities and opt-in and opt-out mechanisms. The authors also demonstrate halos on the ground, which (1) indicate the tracking quality of a single or multi user, (2) reveal interaction history, (3) establish borders, and (4) invite for interaction with light waves. While halos improve peripheral awareness of spatial movement and help to evaluate the state of the world, *«all the floor visualizations are shown in the user's periphery and do not require constant attention»* [VHM16]. Based on these research activities, Vermeulen et al. generalize their findings in two design patterns that help when transitioning between *Focused* and *Peripheral Interaction*:

*Slow Motion Feedback*, which can make the user aware of what is happening outside their attentional field, while manipulating *«the time frame in which the system executes actions to realign it with the time frame of the user»* [VHM16]. For example, an ambient light dims slowly down, so the user can notice a system change, while being possibly able to still intervene.

*Gradual Engagement Pattern*, which describes how interfaces should be designed to gradually engage users by progressively revealing connectivity and possible interaction functions of inter-device proximity. To implement that, three stages are being sketched [VHM16]:

(Stage 1) *Awareness – «Background information supplied by the system provides awareness to the person about opportunities of potential interest when viewed at a distance»*, (Stage 2) *Reveal – «The person can gradually act on particular opportunities by viewing and/or exploring its information in more detail simply by approaching it»*, and (Stage 3) *Transfer – «The person can ultimately engage in action if desired.»* While stage 1, doesn't require a lot of attention, stage 2 would demand significantly more attention, and stage 3 would in any case require the user's focal attention.

Similar to Bakker et al. [BHS16], Vermeulen et al. [VHM16] see *Peripheral Interaction* to be overlapping with *Focused Interaction*. In contrast to other works exhibiting *Peripheral Interaction*, Vermeulen et al. mainly concentrate on the aspect of the user's ability to perceive information visually in a peripheral way, such as demonstrated with halo floors and ambient light. While displaying peripheral information to any time, the user is always able to perceive the systems state and while focusing on slow motion patterns, transitions to a focused task can be very fluid as described, such as when the user decided for an intervention. Vermeulen et al. findings also apply to any other scenarios when interacting with computers.

## 2.4 Augmented Human

While in the previous sections we learned about human capabilities and types of interactions, this section provides a historical overview on the evolvement of technology from the past up to how technology is being envisioned to augment the human in future. The *Augmented Human*, also referred as *Human Enhancement*, is the humans' «*...constantly attempted to improve themselves through technology*» [Ste13] to overcome physical and mental limitations.

### 2.4.1 Augmenting Human Intellect

While the idea of augmenting the human goes very far back in time, in our recent past, in 1962, Douglas Engelbart [Eng62] articulated the term *Augmenting Human Intellect*. While Engelbart understood that the complexity and urgency of solving problem grow faster than the ability to solve the problems, his aim was to somewhat extend and support the human's ability to approach complex problems, to gain an understanding of certain needs, and to derive solutions. Therefore, he pursued the goal of providing the human with an individually adjustable machine to take over monotonous and repetitive tasks and to facilitate more demanding works. In 1962 [Eng62], he published a framework that defines four basic augmentation means, which should be extended: (1) *Artifacts* – physical tools for manipulation, (2) *Language* – how we divide the world into concepts, (3) *Methodology* – the organization of goal-centered activity, (4) *Training* – the conditioning needed to bring the user's skills in using means (1), (2), (3), so they are effective. Besides contributing a theoretical concept, Engelbart developed an implementation that follows his vision of an *Augmented Human*. In 1968, he presented the *"mother of all demos"*, an oN-Line-System, a remote collaboration hypertextsystem with a graphical user interface that can be manipulated with a wooden mouse. Engelbart's inventions count to the most impactful ones in the history of HCI.

When we today speak of *Augmenting Humans*, we think of human-computer interfaces as natural extensions of our body, mind, behaviour, and perception. This is also denoted under the term of *Assistive Augmentation* [HSMN17]. While our senses are the dominant channel we use to perceive the world, with technology, we can actively increase the human's range of perception. If having impairments or being healthy, humans often find themselves at the limits of their sensorial capabilities, which is often caused by contextual factors. In addition, technology can bring information into the foreground, and thus create a new awareness while visualizing hidden information of our surroundings. Following Pattie Maes [Mae17], *Augmented Assistive Technology* can help us to become more efficient and to become what we want to be. Maes [FGS+17] envisions that: (1) New sensing technology will make a future system more aware of the user's current context and state, (2) Artificial intelligence will interpret this information and look up relevant information and will provide proactive personalized information, and (3) Augmented reality will integrate relevant information and interfaces into our physical experience.

### 2.4.2 Beyond Wearable Computing

In 1997, term "*Wearable Computing*" was first mentioned by a research group at MIT Media Labs [Man97], while the two most famous pioneers in this field are Steve Mann and Thad Starner [Sta99]. In those times the main focus of *Wearable Computing* was more on *Augmented Reality* (AR); how to «*perform a seamless interaction between the virtual and physical environments*» [SMR+97] by using *Head-Mounted Displays* (HMD) and cameras, to enrich the user's competence and life-style. Today, *Wearable Computing* looks different, since the smart devices, such as smartphones in particular, penetrated and changed the user's life [BBRS06]. Meanwhile current phones, watches, wristbands, HMD's such as Google Glass, and other wearables may be considered as *Wearable Computers*, since they also have an integrated processor, and memory, although not all of Mann's affordances [Man98*] and signal paths[1] are matched with all types of wearables. Nonetheless, wearables already penetrate every spot of the human body while augmenting human intellect as envisioned by Engelbart. As a matter of fact, wearables today already allow for an extension of competence, while they complement the senses and capabilities of man. For instance, wearables provide us with the ability to connect ourselves to a global network and to easily access [MHAU15] unlimited resources of continuously produced knowledge, making us much smarter. Wearable technologies enable for collecting and accessing a great variety of heterogeneous user data, such as vital or activity data, which are being translated into human-readable information [HMU15]. While the quantization of ourselves can substantially increase the human's awareness, it can help us to improve our behaviour.

In 2016, Tony Fernandes wrote an article on *"Human Augmentation: Beyond Wearables"* [Fer16], in which he denotes the *"Implant Hype"*, to be the next step after *Wearable Computing*. While wearables posses the upside to be easily upgradable, replaceable, controllable and removable, implants may not fit into this continuum, since they truly penetrate the human body. Therefore, implants may usher a completely new era of computing; the «*next step on the evolutionary path of computer technology*» as envisioned by Fernandes [Fer16]. Undoubtedly, implants have already permeated our everyday lives, for example Pacemakers, which belong to the category of so called *Neurostimulators*. This type of implant basically penetrates our nervous system without the user being consciously involved. Another type of true implant is the so called *Neuromodulator*, which, for instance, makes use of deep brain stimulation. This is already being used in therapy, such for detecting tremor behaviour and emitting electrical stimulation to reduce Parkinson disease. Moreover, also for healthy users, future implants will provide new levels of convenience and while they will help to understand ourselves better, while quantizing bio-signals, sharing and crowd-sourcing such data via cloud-based services in a very new way – Fernandes speaks provoking of *"the internet of us"*. Although implants yield enormous potential, there are still issues also summarized by Fernandes [Fer16], such as: «*1. Entering the*

[1] Wearcomp.org: *http://wearcomp.org/wearcompdef.html*

*body means complications»* – thinking of infections, stress, and unforeseen discomfort, *«2. Battery power drives almost everything»* – life time is a very critical point, while batteries can also create danger, *«3. Can't be easily upgraded»* – which is especially true for hardware, although software updates may be possible, *«4. The next hacking target»* – since no system is absolutely secure, and *«5. The ethical question»* – what happens if we lose control of the implant and personal data and what if one cannot afford a necessary upgrade?

### 2.4.3 Human Computer Integration

In 2016, Umer Farooq and Jonathan Grudin [FG16] introduced a new term *Human Computer Integration* in the ACM Interactions magazine (issue vol. XXIII.6.), which experienced great echo in the HCI community. According to the article, we are in the middle of an interaction-to-integration continuum leading to an *"era of man-computer symbiosis"* [FG16]. While a conventional human-computer interaction can be rather considered as a stimuli-response from the user, the authors define *Human Computer Integration* as something that goes beyond that level, implying a partnership between human and computer. While technology yields the power to augment the human's senses and capabilities, Pattie Maes speaks of a fourth-generation computer, which we will live in symbiosis with. She also envisions the computer to be integrated into such an extent that it will provide a natural extension of our bodies that is always on, augments our experience, and helps us to realize ourselves. Maes recently said: *«We should embrace the fact that we are now cyborgs and we will forever be cyborgs»* [Mae17]. She denotes *Human Computer Integration* to be the next era in computing, because it is *inevitable*, *necessary*, and *desirable* [FGS+17].

Maes explains the *inevitability* based on the historical grown development of interaction forms. While, in earlier times, interaction has been location-depended, desktop computing evolved into a mobile and on-body computing [Har13]. The computer has come closer to the human body than ever and will move even closer. Integration is also inevitable because in/out-put modalities develop, for instance, we moved from punch cards to complex GUIs and alternative UI, such as speech interfaces. Further in future, the user's body will be more involved, because we are capable of using more than just fingers for input and eyes for output. Another reason why integration is inevitable, is because application scenarios are continuously expanding. While we used computers for mathematic calculations, the use of computers transitioned over to personal work, communication, entertainment, socializing, learning, and personal growth, future applications will be deeply integrated into our lives and enable physical and mental health improvement.

The *necessarity* of a *Human Computer Integration* is motivated by three aspects, following Maes. The first aspect is attention; current computing is still too attention drawing. Controlling computational devices require a complete attention shift from the real world to computational tasks. Moreover, the necessarity can be motivated by the limited in/output bandwidth. *«Why don't computer understand [and interpret] more what we want?»*. Computers are still in the need to be improved to be better estimate us and to provide us with the wanted information. While sensors and actuators need to be improved, a logical context sensitive AI is necessary. In addition, *Human Computer Integration* becomes necessary because current multitasking is not supported in a sufficient way. Still, short attention spans are required by different UIs that fight for our attention, but distract our main tasks.

Furthermore, Maes justifies the future penetration of *Human Computer Integration* based on the user's ***desirability***. It is desirable to improve learning, it is desirable to expand our perception, making relevant information available, and supporting us when making decisions. Moreover, it is desirable to improve memorization, help us with interaction and improving our health and wellbeing.

The inevitability of *Human Computer Integration* seems logical, and unstoppable, nevertheless, some established researchers raised critical voices. For example, Ben Shneiderman, has expressed skepticism, since the term may communicate a wrong vision to users and designers and while it may also imply technology to possibly take over. In contrast to Farooq and Grudin, Ben Shneiderman sees the term integration rather critical [FGS+17] and emphasize that *«Computers are not people, people are not computers» and «Human thinking and creativity is not calculation»*, therefore, we may not speak of a symbiosis. According to Shneiderman's argumentation, he doesn't see a partnership, while human and computers should not be equally treated. Shneiderman's concerns and fears are understandable, while we can agree that many other ethical issues will need to be broader discussed still.

# 3. Head: Face & Eyes

This chapter is divided into two sections, which basically investigates alternative Input and Feedback modalities for the given area of the head.

The first section presents a research called "*EarFieldSensing*" [MSU17], which systematically investigates the recognition of facial- & head- gestures using different types of electric sensing by electrodes placed inside the ear. In 2015, I created the idea, concept and study design, while this final work was conducted in collaboration with Bernhard A. Strecker, who was mainly driving the implementation and evaluation under my supervision. The project has been published as a Full-Paper at *CHI 2017* (Ranking: A1, Acceptance Rate: ~23%), while it received an Honorable Mention. The second work is called "*InEar BioFeedController*" [Mat13], which demonstrates the technical feasibility of an implementation of a facial-/head- gesture interface into an audio headset for a Smartphone control. To measure signals in the ear canal was born during a conversation with Robert Schleicher in 2012. This work has implemented and published in a frame of a Work-in-Progress at *CHI 2013* (Ranking: A1, Acceptance Rate: ~44%).

The second section proposes the definition of a "*Peripheral Head-Mounted Display*" (PHMD) for Near Field Displays. Factors we need to consider when designing Peripheral Information on such displays are being introduced. Moreover, a broad study is being introduced, in which different stimuli for a visual peripheral perception hast been tested with Google Glass. This section features two publications, "*Properties Of A Peripheral Head-Mounted Display (PHMD)*" [MHAU15], which was published together with my Marian Haescher, Rebekka Alm, and Bodo Urban at the *HCII 2015* (Ranking: B2, Acceptance Rate: not reported). Ideation, concept and implementation was my exclusive responsibility. The second paper, "*Positioning Glass*" [CPMZ16], has been created in a co-working process with Soon Hau Chua, Simon T. Perrault, and Shengdong Zhao and published at the *ChineseCHI 2016* (Ranking: not reported, Acceptance Rate: ~38%). While the idea, concept and inistial study design has been created by myself, the final study has been implemented by Simon T. Perrault and ran by Soon Hau Chua.

## 3.1 [INPUT] Facial and Head Gestures

To pave the way to perform a successful *Reflexive Interaction*, it is useful to waive on the primary interaction channels, such as not using hand hands, nor demanding visual attention. Instead, we can make use of facial and head gestures that can be executed in a quick way to enable control of a secondary task without any interruption. Therefore, a novel input method for mobile and *Wearable Computing* using facial expressions and head gestures was developed. In this section *EarFieldSensing* (*EarFS*) is introduced, which represents a systematic investigation of measuring facial activity inside the ear canal. Finally, the *InEar BioFeedController* is presented, which illustrates a mobile prototype demonstrating a real-time implementation of a gesture set enabling for a *Reflexive Interaction*.

Facial muscle movements induce both electric field changes and physical deformations, which are detectable with electrodes placed inside the ear canal. The chosen ear-plug form factor is rather unobtrusive and allows for facial gesture recognition while utilizing the close proximity to the face. In the first part of this project, 25 facial-related gestures have been collected, while the performance levels of several electric sensing technologies (EMG, CS, EFS, *EarFS*) have been compared with varying electrode setups. The developed wearable fine-tuned electric field sensing employs differential amplification to effectively cancel out environmental noise while still being sensitive towards small facial-movement-related electric field changes and artifacts from ear canal deformations. By comparing a mobile with a stationary scenario, it has been found that *EarFS* continues to perform better in a mobile scenario. Quantitative results show *EarFS* to be capable of detecting a set of 5 facial gestures with a precision of 90% while sitting and 85.2% while walking. In the following, detailed instructions are provided that to enable replication of this low-cost sensing device. Applying it to different positions of our body will also allow to sense a variety of other gestures and activities.

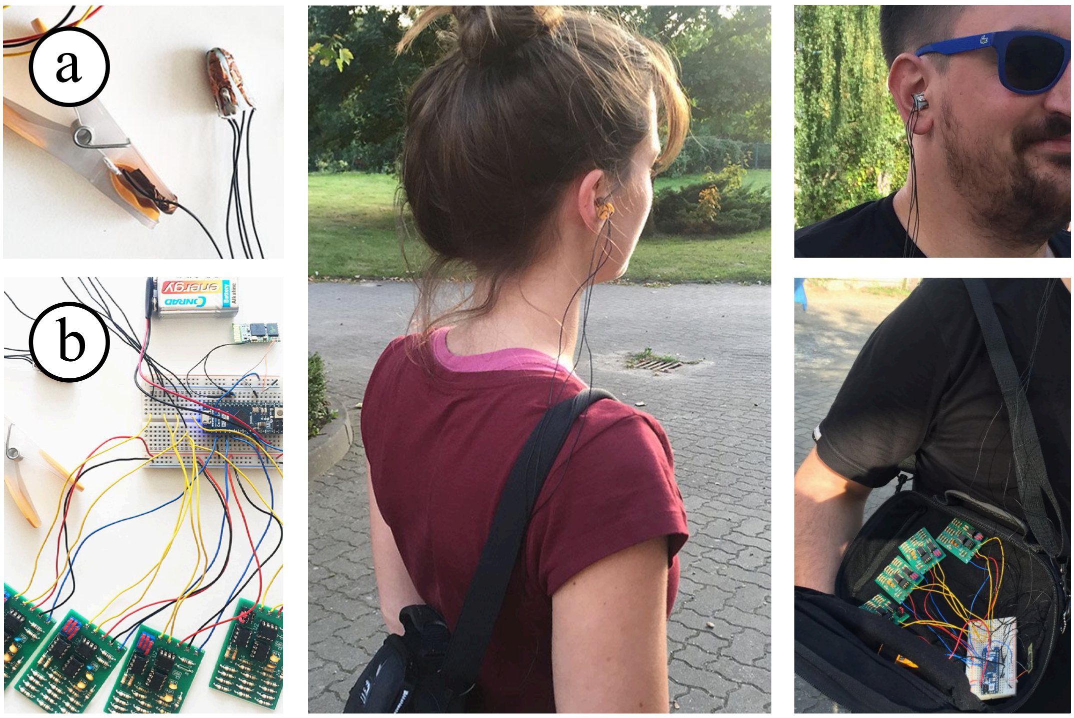



**Figure 9. *EarFS* is a wearable electric field sensing device which enables to sense mobile facial-related gestures. It consists of a) an ear plug plus a reference electrode (a clothes peg that has to be attached to the ear lobe), and b) four sensing shields that are connected to an Arduino which runs on a 9V battery supply and transmits data via Bluetooth.**

### 3.1.1 Introduction

In Human-Computer Interaction, wearables become increasingly important, which is indicated by the prevalence of smart devices such as glasses or watches. Their tendency to engage the center of attention still hinders the interaction to become truly mobile, though. Therefore, one should reconsider how to access and to interact with technology. In 1998 already, Steve Mann stated that wearables should be: «*Unmonopolizing of the user's attention: [...] One can attend to other matters while using the apparatus, [while it should be] unrestrictive to the user*» [Man98*]. Mann envisions wearable computers to provide situational benefits while not obstructing the user and enabling him for subtle multitasking. In contrast, most of the current interaction concepts still do not provide these qualities. Users are often distracted by current smart devices, such as mobile phones, as they usually require the user's full attention while involving the user's hands and eyes. For instance, rejecting a phone call or switching between songs on a music player forces the user to take out the device, which unnecessarily demands visual attention and occupies at least one hand. However, *EarFS* enables the user to have these interaction channels available for a primary task. This is especially relevant for critical tasks, such as when being involved in traffic. Therefore, we make use of a facial expression and head gesture control.

While some facial gestures are also subtle, we enable a shifting of *Microinteractions* [Ash10] to the periphery of our attention [Hau14], which matches the properties to enable a *Reflexive Interaction*. In this research, we demonstrate:

- a broad gesture set based on facial expressions, which has been evaluated with various in-ear electrode setups using different wearable technologies (EMG, CS, EFS, *EarFS*);
- a differential amplification EFS (*EarFS*), applicable for *Wearable Computing*, that is sensitive enough towards very small changes in electric fields of the human body to detect micro-gestures, such as facial expressions.

### 3.1.2 Related Work

Facial-expressions, have been widely investigated in the area of affective computing [Pic95]. Affective computing can be described as a system being able to recognize, interpret, process, and simulate human affects. Human affects can be expressed through our faces, which has been extensively investigated starting in the 1970s by Paul Ekman. In one of his fundamental works, he established a facial action coding system (FACS) which is still the ground-truth database for all facial movements and their associated emotional states [EF77]. Nowadays, we are able to use facial-expressions to determine the frustration level of a user. In terms of technology, two different major setups exist: (1) contact electrodes, which are attached to the face, such as electromyography (EMG) [Haz03] or piezoelectric sensing [SFP99], and (2) proximity sensing, which is often vision-based [GWB+13]. Still, utilizing facial expressions for gesture input has not been extensively investigated yet, as we will illustrate.

#### 3.1.2.1 Facial Expression Control in Medical Context

A major field for application in a medical context is the support of patients, such as those suffering from locked-in syndrome [SD05]. A common solution is eye tracking (mostly based on vision/camera [MR07] or electrooculography (EOG) [GOT93]), which can be considered as a facial expression approach. These solutions often include a displayed software keyboard on which the user focuses his vision on in order to enter text [MR07]. Other use cases include steering a wheelchair by gaze, as already demonstrated by Gips [Gip98], who distributed several EOG electrodes onto the face around the eyes. Furthermore, eye blinks can be used as a binary input in order to provide locked-in patients who are unable to control their eye movements with the ability to communicate. Eye blinks can be detected with several technologies, such as electroencephalography (EEG) [YZJ+13], or in an optical way [AM10]. Those text-input systems usually combine a typical P300 speller in scanning mode.

#### 3.1.2.2 Sensing Technologies for Facial Activity

Technology-wise, there are various ways to detect facial expressions. In the following, we provide a rough overview:

##### 3.1.2.2.1 Optical Sensing

The most commonly used technology is a vision-based camera tracking of facial expressions [FL03]. Obvious expressions, such as frowning, mouth movements, head movements, etc. are detectable with high precision [BLFM03, CXH03]. Although visual processing presents one of the most effective techniques, it yields drawbacks: cameras are quickly affected by bad lighting conditions, camera-based systems are usually bulky or stationary, and very small movements, such as tongue gestures, cannot be detected sufficiently.

##### 3.1.2.2.2 Electromyography (EMG)

The most rudimentary action is a binary on/off-switch, which can be achieved by measuring an emerging action potential, such as caused by contracting muscles. This has been demonstrated by San Agustin with an EMG headband that detects a frowning or a tightening of the user's jaw [SHHS09]. In *TongueSee* [ZGTR14], 8 EMG electrodes have been attached to the cheeks and throat to detect tongue muscle movements. This setup enables the user to perform 6 different tongue gestures with an average accuracy of 94%.

##### 3.1.2.2.3 Electroencephalography (EEG)

With EEG we usually measure neuro-activity on the cortical surface or within the brain by so called Brain-Computer Interfaces (BCIs). We can use BCIs as a control in two ways: by either utilizing a clean data stream or by using "*artifacts*" which are created through muscle activity, such as by nose wrinkling, eye blinks, and other facial expressions [MW11].

Matthies et al. [MAH+12] utilize eye winking, ear wiggling, and head gestures, such as nodding and shaking to control a handheld with Emotiv's mobile EEG headset. Since an EEG headset is bulky and hardly applicable in realistic scenarios, an in-ear headset consisting of a hacked NeuroSky EEG system and two gyroscopes was presented, which enables the same gesture set [Mat13]. A similar setup, a foam earplug with two electrodes, has recently been used to classify sleep stages [NAR+16]. In our opinion, an ear-plug form factor is the least obtrusive setup.

#### 3.1.2.2.4 Electrooculography (EOG)

With EOG Glasses, eye gestures, which are basically tracked eye-movements, could control smart environments such as suggested by Bulling et al. [BRT09]. Other researchers, such as Ishimaru et al. [IKU+14], used EOG goggles to roughly identify chewing, talking, eating, and reading with an accuracy of 70%. Manabe et al. attached EOG sensors to a pair of headband headphones [MF06] and to an in-ear headset [MFY15] in order to sense eye gestures. We believe that placing electrodes into an in-ear headset is rather unobtrusive and apparently offers great sensing potential.

#### 3.1.2.2.5 Capacitive Sensing (CS)

Rantanen et al. [RNVL10] presented a capacitive sensing glass which is capable of detecting a frowning and a lifting of eyebrows to execute click-events with an average accuracy of 82.5%. In 2013, Rantanen et al. [RVS+13] furthermore introduced a face-hugging device which consists of 12 electrodes. They found the activation of four different muscle groups to be detectable with a proximity sensing. While these results are impressive, wearing a face-hugger is rather obtrusive since it almost covers the whole face.

#### 3.1.2.2.6 Electromagnetic Sensing

In 2006, Fagan et al. [FEG+08] placed seven magnets on the lips, teeth and tongue that cause a significant change in the magnetic field when performing mouth-movements. 6 Dual axis magnetic sensors were mounted on a prepared pair of glasses, which enabled a detection of 13 phonemes with an accuracy of 94%, and 9 words with an accuracy of 97%. Even though the physical setup is quite bulky and obtrusive, the results are impressive. In 2014, Sahni et al. [SBR+14] attached only one magnet onto the tongue and utilized the built-in 3 axis magnetometer of Google Glass plus an in-ear piece measuring the optical ear canal deformations in order to detect tongue and jaw movements. They report to be capable of distinguishing 11 sentences with 90.5%.

### 3.1.2.3 Head Gestures in Activity Recognition

Especially in Human Activity Recognition (HAR) the head can play an important role, since it provides very characteristic movement and orientation patterns [Pol06]. However, there is only very few work, which takes the head as a potential position for HAR into account. In 2000, Madabhushi et al. [MA00] presented a system to distinguish different human activities by analyzing the head in different monocular gray scale image sequences, and achieved decent results. Further research demonstrates a human fall detection and gear behaviour with sensors attached to the head, such as described by Lindemann et al. [LHS+05] and Menz et al. [MLF03]. A first real step towards inertial sensor based HAR was successfully performed by Hanheide et al. [HBS05], who built a smart glasses prototype. The system was capable of distinguishing several motions and gestures via an integrated camera and accelerometer. Later, Windau and Itti [WI13] revealed a situation awareness system consisting of a pair of glasses and an IMU with an accelerometer and a gyroscope that was able to discriminate 20 different activities with an overall accuracy of 81.5%. Lately, Ishimaru et al. [IKK+14] demonstrated an HAR implementation for Google Glass. By analyzing the blink frequency, using the integrated infrared proximity sensor, and head motion patterns, the team was able to recognize up to five different head activities (including watching a movie, reading, mathematical problem solving, sawing and talking) with an overall accuracy of 82%.

Head mounted sensors, such as in glasses, headgear, or even hearing aids, yield the advantage of being fixed and always available while performing everyday activities. As a matter of fact, such devices are worn for longer periods of time in comparison to smartphones while enabling a seamless recording of personal data without interruption. While former study outcomes on head mounted inertial sensors already indicate the head as a sensor position to have great potential, there are also drawbacks being indicated. Prior research reveals that we face a trade-off between having an obtrusive hardware setup providing quite meaningful features versus unobtrusive hardware setups that are limited in features and recognition precision. However, it is to believe that it must be possible to find a more advantageous solution compared to those presented before – a device that is unobtrusive (such as an in-ear plug) and that still provides a reasonable feature set that can be executed in a quick and almost unconscious way in order to enable a *Reflexive Interaction*.

### 3.1.3 “EarFieldSensing”

We present EarFieldSensing (EarFS), an improved electric field sensing device capable of sensing electrical changes in the ear canal by an in-ear electrode setup. We think, hiding a sensing device in a subtle ear plug is less obtrusive than other approaches demonstrated in literature. Also, using facial expressions for input enables for hands-free and eyes-free interaction, which is safe when operating devices, such as a smartphone, while being involved in traffic.

#### 3.1.3.1 Contribution

As an essential part of this work, we developed an improved electric field sensing for which we provide technical details to enable reproduction of our sensing technology.

To gain insights into the performance level, we conducted a lab study to compare previous technologies with a gesture set of 25 facial-related gestures. Compared technologies:

- Electromyography – EMG (Shimmer3[2]),
- Capacitive Sensing – CS (FDC2214 Texas Instruments[3]),
- Electrical Field Sensing – EFS (hacked OpenCapSense [GBB+13]),
- Improved Electrical Field Sensing – *EarFS*.

A comparison of technologies in a stationary setup can reveal theoretical performance differences, but does not reflect reality, such as when the user freely moves around. Therefore, we conducted a second study in which we present more insights into performance differences in a mobile context. As a result, we found *EarFS* (*see Figure 9*) to outperform other evaluated electrical sensing technologies when it comes to the recognition of facial-related gestures in mobility while walking.

#### 3.1.3.2 Background

In this subsection, we describe the reason of being able to sense various facial muscle movements and head gestures by placing a sensor piece into the ear canal.

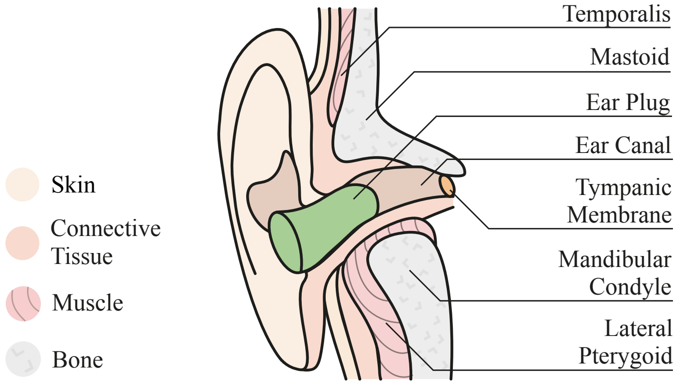



**Figure 10. An ear plug enables the experience of deformations and changes in an electrical field while resting in the ear canal.**

When talking of the ear canal, we mean the tunnel between Mastoid and Mandibular Condyle (*see Figure 10*). Facial expressions, such as yawning, cause an opening of the mouth which is triggered by a contraction of the Lateral Pterygoid. This process causes the Mandibular Condyle to slide forward and thus a tiny void is created, which is then filled with the surrounding tissue. A change in volume and deformed tissue creates a very different electrical field, which is detectable. Even eye movements and head movements are perceivable, although the electrical change is comparably small. As we quickly figured out, movements of the jaw are quite easily perceivable. Other muscle activities, such as raising

[2] Shimmer3 EMG Unit:
*http://www.shimmersensing.com/images/uploads/docs/Shimmer3_ECG_EMG_Specification_Sheet_Revision_1.7.pdf*

[3] Texas Instruments FDC2214: *http://www.ti.com/lit/ds/symlink/fdc2214.pdf*

eye brows, are apparently triggered by other muscle groups (e.g. Frontalis) located on the forehead. Still, we can sense these activities in the ear, because many facial muscles are connected with the Temporalis, the biggest muscle of the head, which forwards mechanical and electrical artifacts towards the ear canal.

*Performing a manual self-test: putting the pinky inside our ear, while executing facial expressions, lets us sense these deformations.*

#### 3.1.3.2.1 Nature of Signals

In a spot so small as the ear canal, we measure compound electrical activity (white sensor noise, environmental noise, potential changes from muscle activity, characteristic signal peaks from ear canal deformations, and very tiny signals from neural activity such as from brainwaves). As mentioned before, ear canal deformations inducing changing electrode-skin contact play a major role. As a matter of fact, increasing skin-contact gradually decreases the electrode input impedance and leads to a transition in signal contributions, e.g. the action potentials' share of the total signal increases.

### 3.1.3.3 Mobile Sensing of Facial Expressions

The application of facial expression recognition via an in-ear-positioned electric field sensing is challenging and far more delicate than just recognizing hand/arm gestures. This is due to the electric field changes that are brought upon by facial muscle movements, which are much smaller in magnitude. Especially in a mobile situation, artifacts caused by walking are crucial. Nevertheless, we envision a facial gesture recognition in mobile scenarios that works independently from side-actions, such as walking, running, biking, jumping and sitting. For the example activity of walking, the user's body experiences a periodically changing capacitive coupling to ground, which substantially impacts an electric field sensing on any part of the human's body. Unfortunately, it is hard to anticipate the frequency of the signal caused by walking or running since speed levels are likely to change when the user, for example, hurries to catch a bus. Therefore, it is hard to target specific frequencies for filtering out. Moreover, these frequencies are rather low and can typically range from anywhere in between 1 to 5 Hz, which are the same frequencies that carry information of facial gestures.

### 3.1.3.4 Technical Solution

The first step of *EarFS* is to isolate electric field changes brought upon by facial gestures as effectively as possible while simultaneously reducing environmental artifacts, such as caused by walking. As mentioned before, an option would be to filter out periodical signals which are reappearing over a longer period of time. However, this does not solve the problem since parts of the unwanted artifacts may also overlap with signals stemming from facial expressions. A simple filtering of artifacts would possibly erase signals of facial gestures as well, because they are too marginal in amplitude in comparison to the artifacts' signal strengths. In fact, as long as artifacts occur on the signal we cannot amplify these comparably small facial gestures. Otherwise, the operational amplifiers would saturate and low magnitude facial gestures are prone to disappear in the signal. Therefore, we eliminate these high magnitude artifacts early on by isolating them beforehand and subtracting them from the original signal with a dual electrode approach as described next.

#### 3.1.3.4.1 Differential Amplification using a second Electrode

Our solution uses a second "*reference*" electrode that needs to be placed relatively far away from the face. We then feed a difference / instrumentation amplifier with the two signals, the one gathered from the reference electrode, and the other from the in-ear electrode. This way, common-mode signals stemming from walking artifacts, which are similar on the whole body, are likely to be filtered out or at least substantially reduced. It is important to note that the placement of the reference electrode is crucial, because any limb movements may affect signals. By attaching the reference electrode to the waist, for example, the arm would create a change in electrical field while nearing or passing the reference electrode

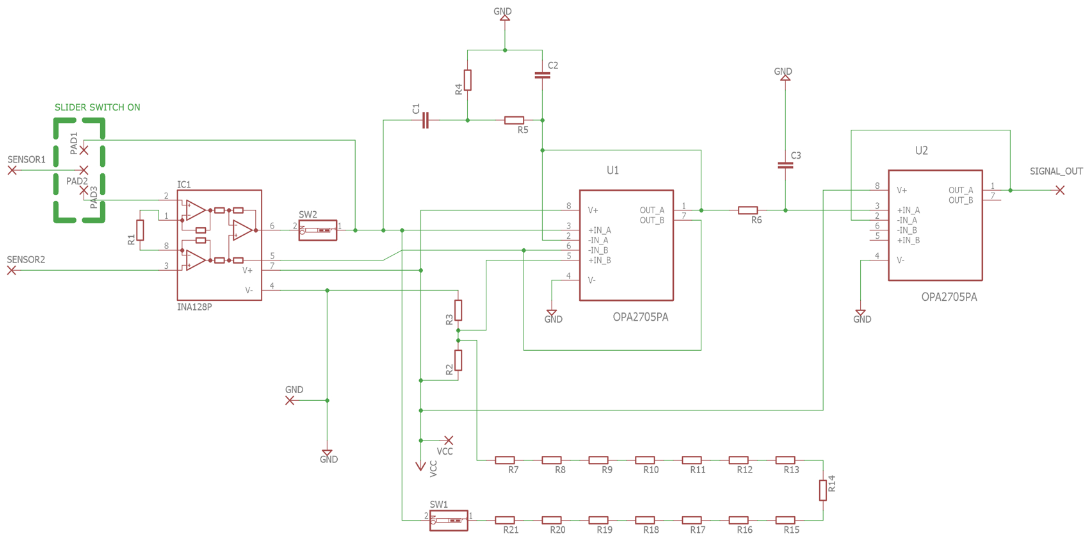
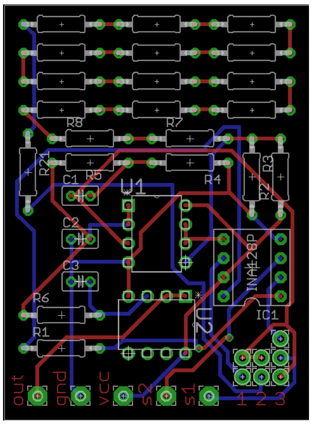



**Figure 11. Schematic of the *EarFS* prototype, supporting both (1) single electrode and (2) differential electrode mode. In single electrode mode, to cover electric field changes of both polarities, a large pull-up/-down resistor is used to elevate the signal level of the earplug-electrode to half the supply voltage. We use fifteen 10 MΩ resistors (R7-21; 10 MΩ resistors are more common than 150 MΩ ones) in series between a simple voltage divider (|R2|=|R3|) and the signal path in order to pull slowly enough for detecting electric field changes. In differential mode, the INA128P instrumentation amplifier filters out environmental noise by common-mode rejection. The difference in voltage between the earplug- (SENSOR1) and earlobe-reference (SENSOR2) electrodes is expected to be rather small, so it is amplified by a factor of 5001 (R1 = 10 Ω), which is well within the gain-range of the INA128P (10k is max). Also the output signal of the INA128P is elevated to half the supply voltage. A band-pass filter (C1 = C2 = 4.7 nF, R4 = 1.8 MΩ, R5 = 390 kΩ) reduces power-hum (50 or 60 Hz) by negatively feeding it back into the signal. Based on application context, C3 & R6 can be used to implement a low-pass filter of choice. Please note: band-pass- & low-pass-filtering are not compulsory.**

when the user walks. An ideal place of the reference electrode would be a relatively stationary position that is far away from the face to get a significantly different electric potential sensing compared to the electrode placed in close proximity to the face. As a matter of fact, the electric field strength declines exponentially with distance, so the reference electrode can also be placed close to the face, such as at the backside of the neck, spine, shoulders, or at the ear lobe. While both electrodes accumulate artificats, the in-ear electrode yields a sufficiently different signal containing facial gestures that remain when subtracting both signals from each other and become visible when amplifying the subtracted signal. To our knowledge, previous work did not use differential amplification in this context before, and we seldom encounter it in HCI applications yet.

#### 3.1.3.5 Implementation

An electric field sensing circuit was designed (*see Figure 12*), which can be used similarly to common EFS sensing circuitry, but also offers signal acquisition by amplifying a differential signal from two separate electrodes. In this mode, the differential instrumentation amplifier reduces and even cancels out most environmental noise.



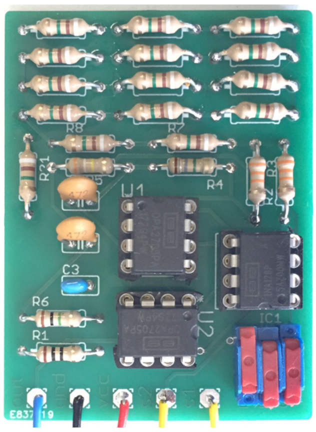



**Figure 12. Left: Eagle PCB layout. U1, U2: OPA2705PA; IC1: INA128P. Right: Final *EarFS* PCB. Switches offer two modes (1) ↑↓↓ single electrode / antenna and (2) ↓↑↑ differential electrode / antenna setup.**

In order to let other researchers replicate our hardware, we additionally provide the schematics of our sensing circuit (*see Figure 11*). Once the hardware is built, one can easily connect the Signal-Out Pin to the Analogue Input Pin of any microcontroller board, such as A0 on an Arduino board. As most microcontroller boards, our sensing device runs with 5V DC.

##### 3.1.3.5.1 Single Electrode Mode and Differential Mode

Three switches have been included in the circuit to allow the user to choose between (1) single-electrode / antenna setup and (2) differential electrode / antenna setup. (1) The slider switch in Figure 11's top left corner connects PAD2 to PAD1, SW2 is off and SW1 is on. (2) All three switches are being reversed – the slider switch connects PAD2 to PAD3. A pull-up/down resistor was included for single-electrode (S1) usage, so that electric field signals will return to the baseline of half $V_{CC}$ when no change in electric fields is present. Thus, only movements that create field changes are perceivable. Concerning the differential configuration, the instrumentation amplifier was biased to half $V_{CC}$, so that electric potential changes of either polarity can be sensed.

## 3.1.4 Study 1: Technology performance

In this section, we evaluate the detection of facial-related gestures by a variety of electric sensing technologies.

### 3.1.4.1 Research Questions

The goal of this study was to gain an insight into the following research questions while trying to keep all variables as constant as possible (e.g., testing all setups by the same user, only testing one session per day):

**Q1**: How does our technology perform compared to other electric sensing technologies?
**Q2**: What would be the best electrode setup providing the highest accuracy rates for each technology?
**Q3**: Which gestures are the top 5 performing ones with the given technology?

In study 1, we were not yet interested in finding out about varying performance levels across users, nor the applicability in mobile scenarios. Therefore, we forfeited on testing all possible setups with multiple users in mobility.

### 3.1.4.2 Task and Procedure

To answer these research questions, we performed an extensive study in which we recorded 14,000 gestures (= 7 ear plugs * 2 un/covered * 25 gestures * 10 repetitions * 4 sensing technologies) from a single user. To avoid fatigue effects, we split the recordings into several sessions, which included 1 technology with all earplugs in sequential order. 25 gestures * 10 reps were recorded with each setup before insulating the earplug or taking the next one. Each gesture was recorded in a time window of 1.25s. To prevent invalid data distortion, the earplug was not rearranged during sessions. When the user was not sure about the correct execution, he was enabled to record an additional repetition. The test subject trained steady gesture execution beforehand and triggered the recording manually after being randomly presented with a gesture left in the pool of 250. A complete session contained 250 * 7 = 1750 gestures.

### 3.1.4.3 Facial Gesture Set

We compiled a set of 25 facial- and head-related gestures (*see Figure 13*) to compare all technologies based on their performance level. The gesture set covers a broad spectrum of which we are aware that not all of them are subtle or socially acceptable. The set was chosen for straightforward repeatability while it includes gestures involving various muscle groups. The contraction of different muscle groups presumably leads to a distinctive signal in order to identify gestures. Apart from typical gestures, such as 'eye-wink', 'smile', and 'protrude-tongue', simple speech was included as well, because speech is performed highly automated due to it being easy to memorize.


**Figure 13. With a set of 25 gestures (including a default gesture) we evaluated four different technologies (EMG, CS, EFS, *EarFS*).**

#### 3.1.4.4 Apparatus: Electrode Ear Plug

We prepared 7 earplugs which are made out of polyurethane foam and go by the name of OHROPAX Color[4] (*see Figure 14*). #1 is a single electrode wrapped around the earplug. #2h - #4h are two to four increasingly smaller electrodes wrapped horizontally around the earplug in a similar fashion. #2v - #4v have electrodes in decreasing sizes, which are vertically placed alongside the earplug. Accordingly, #2v has two electrodes, #3v has three, and #4v has four electrodes mounted on the earplug.

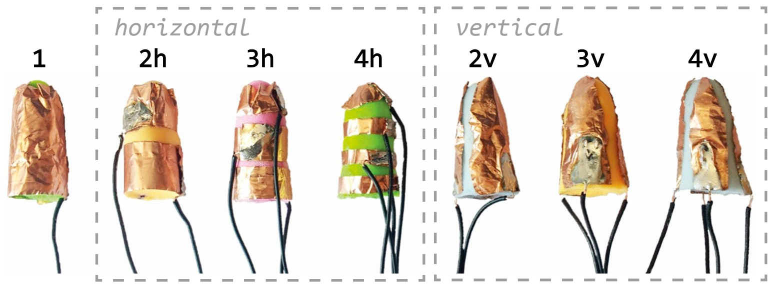



**Figure 14. With 7 different electrode layouts we evaluated each technology. For us, it seemed natural arranging the electrodes lengthwise and widthwise alike with varying partitions while we used them blank (as shown), and covered.**

All electrodes were cut out from copper foil, soldered to the connecting cables, and subsequently glued onto the earplugs with Pattex superglue. All 7 setups have been tested both with blank electrodes and while being covered with the cut-off tip of a common condom. The lubricant was thoroughly washed off beforehand, and remaining moisture left on the latex was dried off before conducting experiments.

[4] OHROPAX Color: *http://www.ohropax.de/produkte/color.html*

#### 3.1.4.5 Apparatus: Electromyography (EMG)

EMG is the most common technology to measure action potentials stemming from muscle activity, which is usually done invasively by needle electrodes. Nonetheless, the superimposed voltage is also detectable on the surface of the skin while it still shows ranges of up to -100mV [Hod51]. In an interaction scenario, surface electrodes on the skin are typically used [STM+09] for measuring electrical potentials through a relatively thick layer of skin and fat. For classifying gestures one can use not only a clean signal, but also noise [MPUZ15] and accumulated movement artifacts [Mat13], which occur in the ear canal when performing gestures.


**Figure 15. Shimmer3 ECG/EMG Bluetooth device, configured in EMG mode.**

In our study, two Shimmer3 EXG units[1] were connected via Bluetooth to a computer (*see Figure 15*). The Shimmer Android/Java API was used to configure the EMG units and to establish communication. A suggested digital filtering (50 Hz noise cancellation and low-pass filtering for signal smoothing) was also implemented. The earplug electrodes were connected to a single channel each in the following way: The earplug-electrode was connected to the positive differential input of the Shimmer3 EMG channel and a clothespin-mounted copper foil reference electrode was clipped to the earlobe of the opposite ear that the earplug was worn in. The reference electrode was connected to the REF input of the up to three Shimmer3 units and connected to all negative differential inputs of active channels.

#### 3.1.4.6 Apparatus: Capacitive Sensing (CS)

Capacitance describes a body's ability to store an electrical charge when a voltage is applied. The higher the electrical charge a body can store, the higher its' capacitance. As a matter of fact, the human body's cells also have the ability to store electrons and thus a negative electrical charge. Depending on the body part, we can speak of an overall capacitance varying between 50 and 150pF [SHHH98]. Excited cells, which accumulate a certain amount of electrons, create the change in capacitance. While this capacitance can be measured invasively, we can also measure it on top of the skin or in distance, such as with an isolated earplug electrode. A typical CS measures the charging time of an electrode. This is also referred to as loading mode [Smi99].

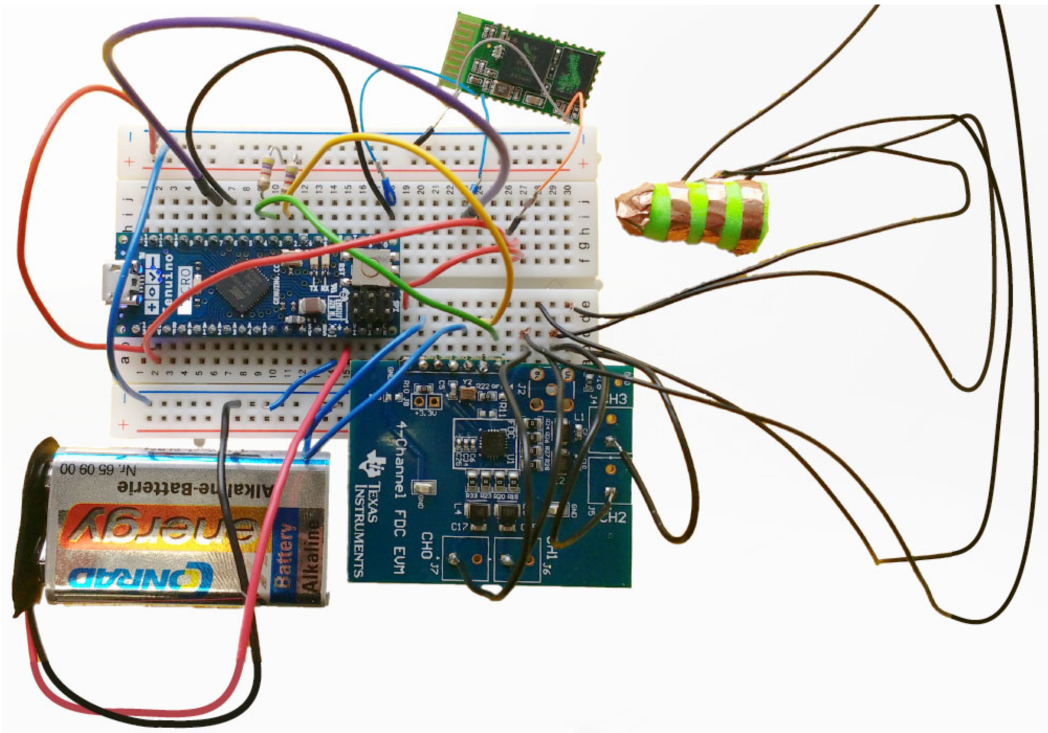



**Figure 16. The Capacitive Sensing shield FDC2214 EVM from Texas Instruments was plugged to an Arduino board transmitting the raw data via a Bluetooth 2.0 modem.**

The FDC2214[2] also uses capacitive sensing in loading mode. We connected it to a Genuino Micro streaming all raw data via an HC05 Bluetooth modem (*see Figure 16*). It is essential to use a battery plus a wireless transmission to avoid irregularities, such as a varying capacitive ground coupling triggered by other hardware components that may also be connected to the computer. To measure each of the four channels in turn, 512 oscillations were used to determine the momentary frequency of the LC oscillator circuit compared to the EVM board's 40 MHz oscillator. After each channel switch, the first 128 oscillations were not considered to allow for the frequency to stabilize.

#### 3.1.4.7 Apparatus: Electrical Field Sensing (EFS)

Electric fields are ubiquitous and exist due to the static electricity of our surroundings. Besides everyday objects, also the human body carries several small electrical fields. Fluctuations in electric fields quickly occur when moving the human body or other charged objects. While we can utilize electrical field changes for a gesture recognition [CGL+12], it is also perfectly suitable for an intended facial expression recognition. However, factors such as ambient noise and baseline drift are the most cumbersome obstacles that gesture recognition and classification endeavours face. Anyhow, all that is needed to implement electric field sensing is basically a "*passive*" electrode (i.e. antenna) with an operational amplifier connected to an analogue-to-digital converter (ADC). To compensate for noise, such as power hum, low-pass filters may apply between op-amp and ADC.

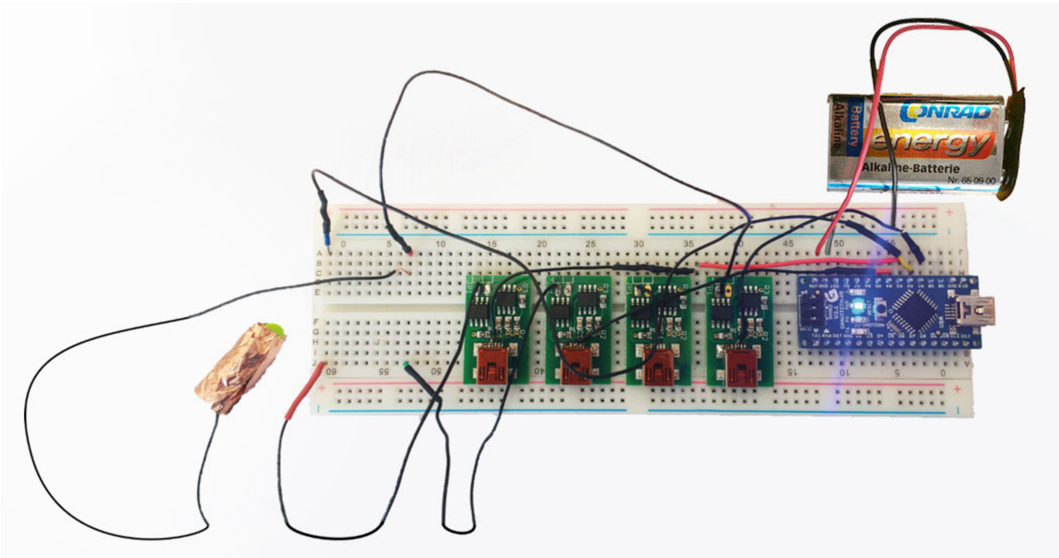



**Figure 17. We "*hacked*" four Loading Mode capacitive sensors from OpenCapSense [GBB+13] to act like an Electric Field Sensor.**

Our EFS setup consists of four "*hacked*" OpenCapSense loading mode sensors, which basically consist of an operational amplifier and an astable Multivibrator that is usually used for a capacitive measurement. However, we only utilize the op-amp whose positive input is connected to the electrode. The op-amp's output is connected to the analogue input of an Arduino Nano (*see Figure 17*), which serves as an ADC and transmits the raw data. It should be particularly noted that here, the op-amps are not connected to an external power source. However, they still output discriminable voltage based on the acquired earplug signal, which also serves as a power supply in a way that the electrode is wired to the op-amp pin right next to the negative supply pin, facilitating a discriminable voltage between the negative and positive op-amp supply pins.

#### 3.1.4.8 Apparatus: *EarFS*

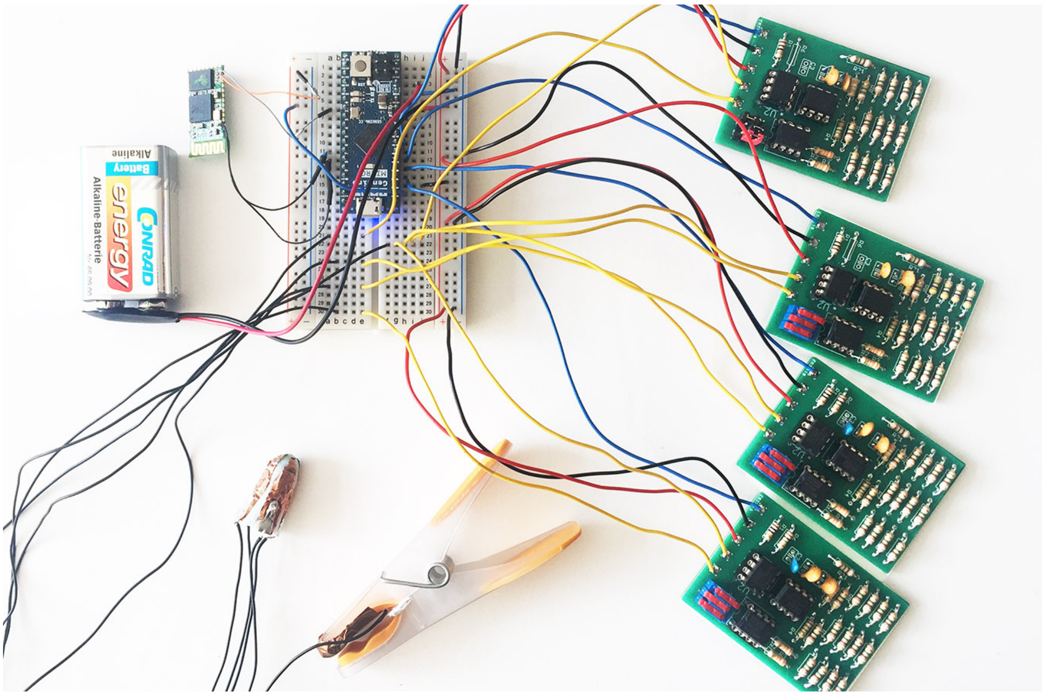


**Figure 18. Four EFS shields are connected to an Arduino in order to use a four-electrode ear plug. The data is being streamed via a Bluetooth 2.0 modem to a computer, while the prototype is powered by a 9V battery.**

Fluctuations in ambient electric fields can originate both from negative and positive charge balance and thus, a standard single supply op-amp design like seen before would be doomed to miss one of the polarities. Therefore, we introduce a second DC-voltage, keeping the antenna voltage at a proportionally steady and elevated level. It is wise to choose a DC-voltage of half the op-amp's supply voltage, since in this way, incoming antenna signals can deviate from the baseline voltage in the direction of both electrical polarities. When no changing electric field is present, a relatively large resistor pulls up/down the antenna voltage to the baseline voltage eventually. It should be noted that larger resistors cause longer latencies. The addition of such a pull up/down resistor with its tendency to pull the antenna voltage back to half the $V_{CC}$ voltage is the reason that only movements and changes are measurable. In addition, we added a reference electrode (*see Figure 18*) to eliminate extrinsic changes in electrical fields with a differential amp.

#### 3.1.4.9 Signal Gathering and Data Processing

The aforementioned electrode-earplugs have been combined with all four technologies while we recorded each gesture with a sample rate of 200 Hz and a window-size of 256. Then, we computed 46 state-of-the-art features found in literature on all raw data recordings. Because we are not aware of any library providing them, we implemented them by hand in Java. For analyzing the data, we use the Weka data mining tool [GOT93] in order to gain an impression on the performance using five state-of-the-art classifiers (*Bayes Net - BN, K-nearest neighbours - Ibk, J48 Decision Tree – J48, Random Forest - RF, Sequential Minimal Optimization - SMO*) while performing a stratified 10-fold-crossvalidation. We have chosen this method, because conducting a manual leave-$k_{instances}$-out method on our huge dataset (14.000 instances) is extremely time consuming and beyond practicality. Nevertheless, we had a quick look ($k$=5) at a single session (*EarFS*, 4-vertical) and could perceive a marginal accuracy drop of $\Delta$=-1.6 %.

#### 3.1.4.10 Results

Before presenting the result, it is important to note that we are talking of a theoretical performance level. To make a sophisticated statement on realistic recognition rates, one should have tested users n>10 in ambiguous environments (including critical environments with high level of electric noise, e.g. a server room). In this research, we decided to keep experiments within reasonable boundaries and share early results of the exact composition with the community.

##### 3.1.4.10.1 Classifier & Feature Selection

In order be able to answer our research questions, we first determined the “*best*” classifier. We compared all five classifiers (*BN, J48, Ibk, SMO, RF*) by means of an *independent samples one-way ANOVA*, but which showed no significant differences for EMG ($F_{4,30}$=1.14; $p$<.357); CS ($F_{4,30}$=0.58; $p$<.680); *EarFS* ($F_{4,30}$=0.06; $p$<.993). Nevertheless, the EFS showed strong significant differences ($F_{4,30}$=17.96; $p$<.0001). Conducting a *Tukey HSD Test* revealed the *J48* ($M$=43.35; $SD$=6.25), *BN* ($M$=43.47; $SD$=5.50), and *RF* ($M$=37.57; $SD$=12.12) to perform better than the *Ibk* ($M$=20.30; $SD$=7.53; $p$<.01). Moreover, the *J48* and *BN* were deemed to significantly perform better than the *SMO* ($M$=31.86; $SD$=8.29; $p$<.05). Beholding the mean performance over all technologies, we can perceive the *J48* and the *RF* to perform quite well. Because the *J48* is most computationally inexpensive and a rather simple classifier, we selected it for further investigations.

Across all best setups, top 5 meaningful features, selected by a *Greedy Stepwise (forwards) algorithm* [CF94], include: *spectralEnergy, spectralFlux, spectralSignalToNoiseRatio, minMaxDifference, and pairDifference*.

##### 3.1.4.10.2 Answering Research Questions

**Q1**: As seen in Table 1, *EarFS* performs similar to other electric sensing technologies, comparing their best setups. A *one-way ANOVA* ($F_{3,27}$=193.91; $p$<.001) showed *EarFS* ($M$=32%) to perform equally to the EMG ($M$=30.8%) and EFS ($M$=52%) equally to CS ($M$=48.4%). Still, a *Tukey HSD Test* ($p$<.01) reveals both EFS and CS to perform significantly better among EMG and *EarFS*.

**Q2**: The electrode setups providing best performance are indicated in Table 1. Generally, we can say that non-insulated, vertically arranged electrodes perform better, because these are more sensitive towards ear canal deformations (changing skin / electrode contact). Since the vertical electrodes are distributed in circular fashion, an increase in their number leads to higher spatial resolution inside the ear canal.

**Q3**: We determined a top 5 gesture set for the best setup of each technology (*see Table 2*). In fact, the recognition rates look quite reasonable and foster curiosity: EMG (*M*=84%), CS (*M*=90%), EFS (*M*=94.5%), and *EarFS* (*M*=90%).

| | | **EMG** (*Shimmer3*) | | | **CS** (*FDC2214 Texas Instruments*) | | | **EFS** (*hacked OpenCapSense*) | | | ***EarFS*** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Electrodes | Average Accuracy (TP) | | | Average Accuracy (TP) | | | Average Accuracy (TP) | | | Average Accuracy (TP) | | |
| *blank* | | all 25 | n≥50% | top 5 | all 25 | n≥50% | top 5 | all 25 | n≥50% | top 5 | all 25 | n≥50% | top 5 |
| | 1 | 19.2% | - | - | 1.6% | - | - | 1.6% | - | - | 3.2% | - | - |
| *horizontal* | 2 | 11.7% | - | - | 16.8% | - | - | 35.1% | - | - | 5.2% | - | - |
| | 3 | 4.8% | - | - | 30.8 | - | - | 40.8% | - | - | 8.8% | - | - |
| | 4 | 12.8% | - | - | 43.2% | - | - | 39.5% | - | - | 13.2% | - | - |
| *vertical* | 2 | **30.8%** | **4** | **84%** | 12% | - | - | 43.6% | - | - | 13.6% | - | - |
| | 3 | 10.4% | - | - | 34.4% | - | - | **52%** | **11** | **94.5%** | 12.4% | - | - |
| | 4 | 19.2% | - | - | **48.4%** | **13** | **90%** | 49% | - | - | **32%** | **5** | **90%** |
| *covered* | | | | | | | | | | | | | |
| | 1 | **11.6%** | **0** | **64.4%** | 9.6% | - | - | 4% | - | - | **5.6%** | **0** | **20%** |
| *horizontal* | 2 | 5.6% | - | - | **38%** | **11** | **84%** | 4.4% | - | - | 2.8% | - | - |
| | 3 | 6.4% | - | - | 35.2% | - | - | 5.2% | - | - | 4% | - | - |
| | 4 | 6.8% | - | - | 21.6% | - | - | 4.4% | - | - | 4.8% | - | - |
| *vertical* | 2 | 6.2% | - | - | 22.4% | - | - | 3.6% | - | - | 4% | - | - |
| | 3 | 6% | - | - | 29.6% | - | - | **7.6%** | **1** | **20%** | 5.2% | - | - |
| | 4 | 3.2% | - | - | 28% | - | - | 5.6% | - | - | 2.4% | - | - |

**Table 1. Performance levels using a *J48 DT* (*C4.5 algorithm*). For each technology we can find three columns: 1) true-positive (TP) rates of the complete gesture set, 2) number of gestures yielding at least 50% TP, and 3) TP score of a reduced top 5 gesture set.**

| | *EMG (Shimmer3)* | *CS (FDC2214)* | *EFS (OpenCS)* | *EarFS* |
|---|---|---|---|---|
| 1 | eyes-left | head-back | chin-on-chest | eye wink |
| 2 | head-back | open-mouth | eye wink | head-right |
| 3 | head-left | protrude-tongue | say-u | open-mouth |
| 4 | say-e | eye-brows together | eyes-down | say-sh |
| 5 | smile | say-a | head-right | smile |

**Table 2. Top 5 gestures for the best technology setup. We chose to select the number of 5 gestures, because the ability to remember shortcuts, such as gestures, dramatically decreases with larger numbers than 7 in a real scenario. Following cognitive engineering, 5 is also a suggested maximum.**

#### 3.1.4.10.3 Summary

The analysis revealed all technologies to be capable of a facial-gesture recognition by measuring them inside the ear canal. In our opinion, the classification accuracy is astonishing considering the broad gesture set of 25 facial expressions. Two characteristic 'clusters' of confusions occurred among the gestures. One cluster can be found around gestures of the Oculi, and the other around the Lingua. Because these gestures are similar in type, the confusion between them is most likely connected to their actual similarity.

### 3.1.5 Study 2: Wearable Performance

Since the first study was performed in a very controlled environment, we thought it may be interesting to see whether our evaluated technologies could be employed as a wearable technology in a mobile context as well.

#### 3.1.5.1 Study Setup

Therefore, we conducted an experiment with 3 participants, aged 26, 29, and 30 years. While each technology was tested with all users, the task was to perform all top 5 gestures of each technology (*see Table 2*) with its' best earplug setup for 10 times in a random order.

There was a marginal training phase in which the user had the chance to perform each gesture once or twice. After the study started, the study leader was shouting each gesture out loud while he was triggering the recording. To test the technologies' limits, we instructed each user to randomly walk around within a spot of 10 x 10 meters in a medium-sized lobby with stone-tiled floor.

In summary, we recorded 600 gestures (3 users * 4 technologies * 5 gestures * 10 repetitions). We again calculated 46 state-of-the-art features from the raw data and used a J48 Decision Tree while performing a stratified 10-fold-crossvalidation.

#### 3.1.5.2 Hypotheses

Since we already know about the theoretical performance in a stationary context, we can establish these hypotheses:

**H1**: *EarFS* will perform equally or better than other technologies, because it works with a differential amplification. Hence, it should be more robust towards influences from external noise in mobility.

**H2**: All other technologies will experience a substantial drop in accuracy, because they are heavily affected by environmental noise occurring while moving.

#### 3.1.5.3 Results

The results confirm our assumption. *EarFS* performs well in context of mobility. Table 3 shows the performance of *EarFS* in a confusion metrics accumulated over all users:

| a | b | c | d | e | <- classified as |
|---|---|---|---|---|---|
| 96.7% | 3.3% | - | - | - | a = eye wink |
| - | 89.7% | 3.4% | - | 6.9% | b = head right |
| 3.3% | - | 80.0% | 16.7% | - | c = open mouth |
| - | - | 13.3% | 80.0% | 6.7% | d = say SH |
| - | 3.3% | 6.7% | 10.0% | 80.0% | e = smile |

**Table 3. Accumulated confusion matrix of all users showing overall performance of the *EarFS* using a *J48 decision tree*.**

#### 3.1.5.3.1 Answering Hypotheses

**H1**: Looking at Table 4, we can see that over all users, *EarFS* (*M*=85.2%) achieves a substantially higher mean accuracy than EMG (*M*=76.7%) and CS (*M*=79.9) when the user walks around randomly. A *one-way ANOVA* ($F_{3,8}$=6.27; $p$<.02) also found statistical differences in terms of performance level. A *Tukey HSD Test* confirmed our technology to significantly outperform EFS (*M*=73.7%). Therefore, we accept this hypothesis: *EarFS* is more robust towards external noise in mobility and yields higher accuracy while it even significantly outperforms EFS.

| EMG (Shimmer3) | CS (FDC2214) | EFS (OpenCS) | EarFS | |
|---|---|---|---|---|
| 84% | 90% | **94.5%** | 90% | sitting |
| 76.7% | 79.9% | 52.8% | **85.2%** | walking |
| 80.4% | 85% | 73.7% | **87.6%** | ∅ |

**Table 4. Overall performance (True-Positive rates) of study 1 (sitting) in comparison to study 2 (walking). The setup: top 5 gestures, preferred electrode setup, *J48* classifier.**

Incidentally, it is even more surprising to see that EFS initially outperformed *EarFS* while sitting. One reason would be because OpenCapSense is a more integrated PCB and does not suffer from small distortions of loose wires like *EarFS*. However, as shown before, it is bound to underperform while walking, since it is not supporting differential measurements.

**H2**: Running a simple *t-Test* confirms $CS_{walking}$ (*M*=79.9%) to be significantly worse than $CS_{sitting}$ (*M*=90%). Also, $EFS_{walking}$ (*M*=52.8%) is performing significantly worse than $EFS_{sitting}$ (*M*=94.5%). We can also see a decrease from $EMG_{sitting}$ (*M*=84%) to $EMG_{walking}$ (*M*=76.7%). However, while EMG is generally performing low, it is not yet statistically different. *EarFS* experiences the lowest accuracy drop (Δ=-4.8%) and does not perform significantly worse. Although CS and EFS significantly dropped in accuracy, we have to dismiss this hypothesis, because EMG did not significantly decrease.

#### 3.1.5.3.2 Summary

The second study shows *EarFS* to not experience a substantial performance drop in mobility while the user is walking. Moreover, the study reveals that EMG is also not heavily affected by walking artifacts due to the nature of its' sensing method. Therefore, the study indicates that electrical field sensing related technologies may not be the perfect choice for a wearable gesture recognition, unless one applies a differential amplification, such as proposed in *EarFS*.

### 3.1.6 Discussion

Considering the rather rudimentary electrode setup and the low-cost sensing device, in our opinion, the achieved classification accuracy above 90% with a gesture set of five is astonishing. This is due to the heterogeneous signal, which is a combination of facial-movement-induced ear canal deformations and biopotential processes. Still, a custom six channel monopolar EMG, using surface electrodes similar to Zhang et al. [ZGTR14] but distributed over the entire face, tends to outperform any in-ear setups. We confirmed this in a pilot study where we attached 7 silver/silver chloride gel electrodes to the face in places right above facial muscles of interest (*see Figure 19*).

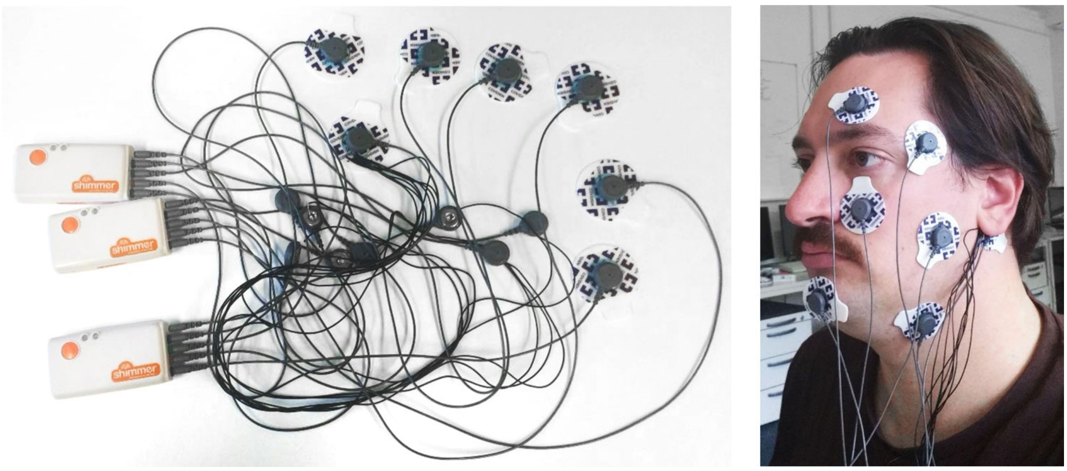


**Figure 19. We utilized 3 Shimmer3 EXG sensor devices with 7 Ag/AgCl gel electrodes (6 channels + 1 common ground placed behind the ear, an area that remains relatively unaffected by muscular movement) to detect same gesture set.**

We again recorded the complete facial gesture set of 25 with a sampling rate of 200Hz and a window size of 256. A total of 346 features (based on 46 state-of-the-art features) have been extracted from the raw data, whereby the most meaningful features included: *maxAmpFrequency, spectralEntropy,* and *logLikelihood*. With this setup, a *RandomForest* classifier performed best while detecting 25 facial gestures with an accuracy of 62%. A reduced set of only 5 facial gestures scored maximum accuracy of 100%.

This pilot clearly highlights the typical trade-off between technology that is obtrusive on the one hand, but on the other hand achieves high accuracy rates. Scoring comparably low precision with an in-ear setup is not surprising, since (1) the maximum number of channels tested with the earplugs was four and (2) sensors cannot directly sense evoking action potentials from the source while resting inside the ear canal. Nevertheless, we expect *EarFS* to technically mature with further iterations (testing different building blocks, EM shielding). However, placing more electrodes inside the ear is not expected to provide significant performance boosts. Instead, a combination of different technologies seems promising and is highly encouraged for further research. While electrodes with direct skin contact could be combined with electrically insulated electrodes, it did not increase performance in our study. In contrast, a future improvement would be to additionally determine the deformations of the ear canal with pressure-activated distance sensors. Another method would be laser-based distance measurements by using modulated laser beams and image-based phase-shift analysis in order to get a distance-to-skin measurement inside the ear canal. Particularly, laser modulation frequencies would have to be very high to cover the sub-millimeter distance range in this approach, and thus suitable hardware would increase the costs of such a sensing device.

### 3.1.7 Summary

In this research project, a novel variant of an electrical field sensing (*EarFS*) has been presented which provides hands-free and partly eyes-free interaction for mobile and *Wearable Computing*. The developed sensing circuit has been introduced in detail so that it can be replicated by any HCI researcher or practitioner. With *EarFS*, an open gap in research has been closed, while it has been shown how to systematically investigate the detection of various facial-related gestures via an electric field sensing inside the ear canal, which has not been done before in this manner. Two studies have been provided that reveal how electric sensing technologies could possibly perform when using an electrode in-ear plug. On top of that, it has show that *EarFS* tends to outperform other electrical sensing approaches when it comes to facial-gesture recognition in mobility while the user is on the go. In mobile scenarios, facial expressions could be used to accomplish quick responses to incoming notifications in manner of a *Reflexive Interaction*. Since facial gestures and expressions cannot typically be "*switched off*" by users, the field of mobile facial expression recognition still yields great potential as far as *Implicit Interaction* is concerned. Based on facial expressions, a future system would be able to know and anticipate the user's intentions before conscious interaction becomes necessary. In terms of apparatus, it is to believe that in-ear devices, such as earbuds, are much more unobtrusive and socially acceptable than other known hands-free and eyes-free technologies. Therefore, similar sensing approaches are envisioned to be integrated into in-ear headsets in the near future. Besides headsets, we also see great potential in *EarFS* to be implemented into various other kinds of wearables, since this sensing approach offers a much wider range of recognition capabilities for gestures and activities in mobility than discussed in this research project.

Illustrating the implementation of a mobile facial and head gesture control system and how to control functions on a smartphone is being presented in the following section.

### 3.1.8 "InEar BioFeedController"

Nowadays the capabilities of smart devices, such as smartphones quickly expand. However, a *Reflexive Interaction* is not supported yet. For instance, the control of a mobile device usually requires rather large procedures including the use of a touch screen by making use of one's hands. However, in everyday life, while being engaged in real world tasks, it is sometimes adequate or even impossible to control a device with by hands. Here, speech control is the most common solution to tackle this problem, but it is still error prone, uncomfortable and works poorly when ambient noise is present. Utilizing Facial and Head gestures in a manner of a *Reflexive Interaction* would enable the user continuing his real world task with no significant interruption, while it would work in everyday surroundings with significant levels of noise, since it doesn't make use of hands. The prototype presented here is an attempt to provide a solution to mobile situations: a headset that enables hands-free and eyes-free interaction for incoming phone calls as well as music player control (*see Figure 20*). It enables safe control of the device in mobile situations as it neither requires the user to come to a standstill, nor does it distract his visual focus.

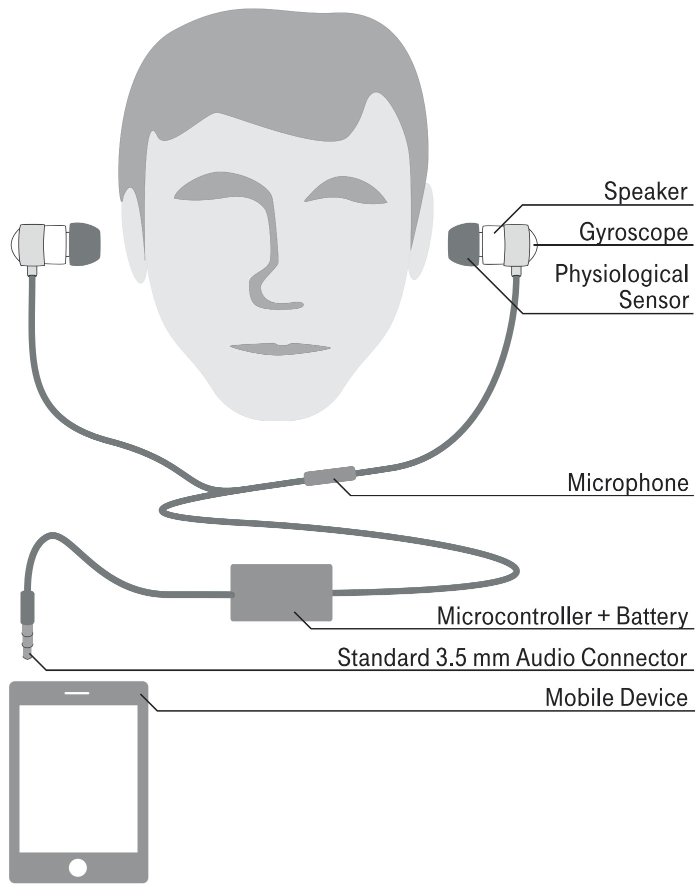



**Figure 20. General construction of the *InEar BioFeedController***

#### 3.1.8.1 Motivation

Technical devices such as mobile computers, tablets, smartphones etc. have thoroughly permeated our everyday lives and are the new mass computational platform [BAU10]. These and many other new technologies have been produced to relieve our brains and simplify everyday tasks, but human-computer interfaces are not always comfortable to use. In many cases they only work well in special situations – when standing still, with finger-touchscreen interaction or by requiring heavy visual focus on the device's display.

Hands-busy and on the road situations are fields of application where control can still be described as a problem that has been explained in the challenges section before. The use of mobile devices such as mobile computers, tablets and smartphones, which are designed to be usable while mobile, is often not feasible in these situations and especially on the road situations, where voice control works poorly or not at all. Alternative control concepts are needed to solve this problem. Regardless of the technology, new solutions for more efficient and easier control of technical devices, which take human factors into consideration, have to be found.

This research aims to contribute to finding a viable alternative control for mobile devices, which matches the requirements of functionality in mobile situations. After giving an overview of previously completed work, this projects introduces a fully functional prototype called the *InEar BioFeedController* (*see Figure 21*), which overcomes the general problem of controlling mobile devices while walking and in hands-busy or hands-lazy situations. Furthermore, it gives an insight into the development of said prototype.

#### 3.1.8.2 Prototype

**Figure 21. The first *InEar BioFeedController* prototype has gold-plated physiological sensors attached to silicon pads. The associated measuring unit is integrated into a black box with a microcontroller and 9V battery. A micro-gyroscope is integrated into one of the in-ear cases.**

Practical and safe control of a mobile device in mobile situations optimally requires a fully eyes-free and hands-free interaction. A theoretical and technically feasible solution to this problem was sought in related work. As the analysis has revealed, "*NeuroPad*" is a prototype that already solves most problems. The interaction concept was adapted, developed further and a new and very specific hardware interface was built, which is tailored exactly to the requirement that it must function well in mobile situations, i.e. on the road and without distracting the user from real world tasks.

### 3.1.8.3 Implementation

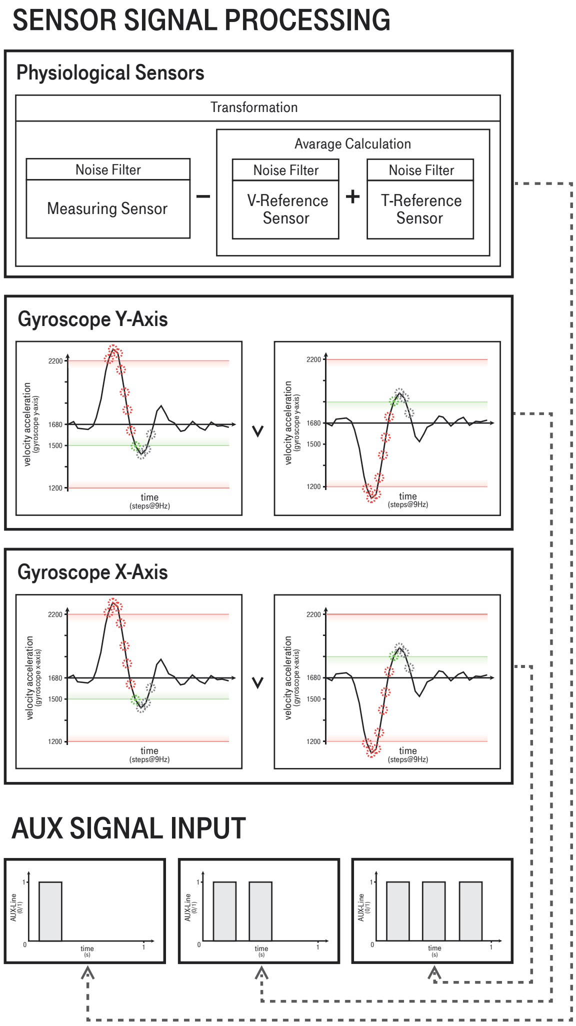



**Figure 22. There are two reference sensors and one measuring unit. The raw signal is already noise filtered and preprocessed. A Fast Fourier Transform (FFT) is used, so "*muscle artifacts*" produced by ear wiggling or eye winking are easily identifiable. The head movement detection is accomplished with a double threshold analysis. If an action is successfully executed, a digital signal is passed through the AUX input to the mobile device (such as an iPhone), which interprets this control signal automatically.**

## 3. Head: Face & Eyes

The building of this prototype presented many different problems; it was a technical challenge combining several different technologies - mobile physiological sensors, a gyroscope sensor - and finding a way to make them functional for mobile devices. Head movement detection is accomplished with the gyroscope sensor, which is integrated into the in-ear headphones. This first prototype uses an SMD4 IC: ENC-03RC. The detection of facial muscle activity is accomplished with a physiological sensor, which is commonly used in biofeedback. To wink one's eyes or wiggle one's ears, facial muscles are activated, which in turn generate an electric current in micro-volt range, measurable in the ear canal. This first prototype uses EEG sensors from "*NeuroSky*"[2], which were originally designed for the measurement of brain waves. Gold-plated electrodes are attached to silicon pads and connected to the associated measuring unit, which is integrated into a black box with an "*Arduino*" microcontroller and a simple 9V battery, which delivers power for an hour. The output command for controlling functions on the mobile device is sent through a standard 3.5mm audio AUX line (*see Figure 22*). This enables control of the music player and incoming phone calls by head gestures and facial expressions on any mobile device. The decision was made use intuitive head gestures like nodding for "*YES*" and head shaking for "*NO*" (*see Figure 23*). To avoid misinterpretation of normal movements, both gestures have to be executed in an exaggerated manner - with a weaker follow-up movement in the opposite direction. Rapid head shaking or nodding within a half-second and excessively slow movements over two seconds are ignored. Wiggling ears or winking eyes, allows users to "*SKIP*" queries.

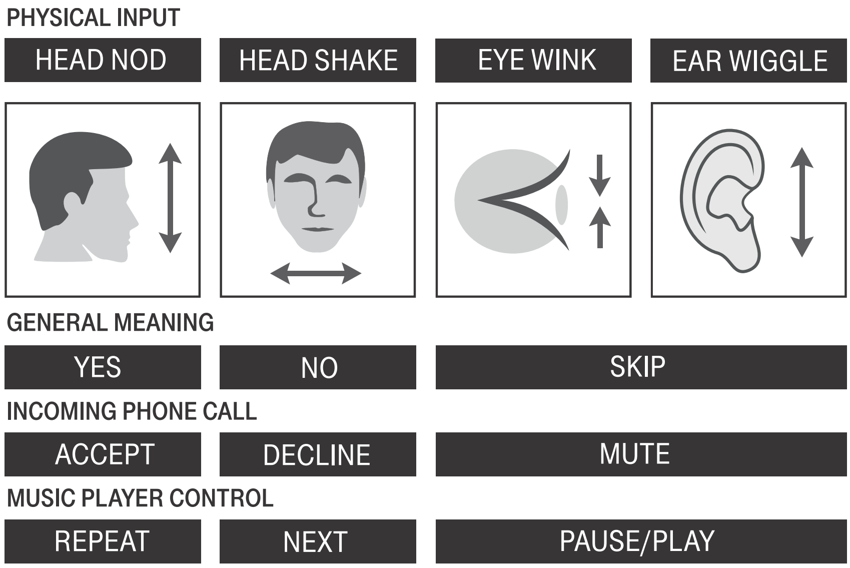



**Figure 23. Function assignment: controllable functionalities include switching music (*on/off / next / previous*) and answering incoming phone calls (*accept / decline / mute*).**

### 3.1.9 Conclusion

Mobile devices have become an integral part of everyday life as they represent a great benefit to people; however, as mentioned, the control in mobile situations can still be described as a problem. The presented prototype demonstrates a possible solution with completely hands-free and eyes-free interaction. For controlling music or incoming phone calls the mobile device does not require physical touch and no visual focus, so the mobile device can stay in the pocket. This prototype allows free movement and comfortable control with natural head gestures and facial expressions rather than artistic performances. The interaction concept makes use of largely unnoticed operation, which does not disturb others. There is no significant maintenance except battery changes. The use of a gyroscope for detecting head movements is considered reliable, after the user learns the exaggerated nodding and shaking. Due to technical limitations rapid head shaking or nodding within a half-second and excessively slow movements over two seconds cannot be detected. Early testing showed that it was possible to identify mouth, nose, eyebrow movements, as well as ear wiggles, and eye winks in the ear canal, which has been demonstrated in *EarFieldSensing*. Because the *InEar BioFeedController* does not use a very sophisticated classification algorithm, only threshold analyses based on the strongest muscle movements are being applied, the prototype only recognizes conscious eye winks and ear wiggles inside the ear canal. Since the sensors rest inside the ear canal, sensor movements are unlikely, which avoid ghost triggers, although sometimes gestures are just not detectable because of the rudimentary recognition method. Moreover, the electrical resistance seems to be different on how deep and closely the sensors are in the ear, which also depends on the shape and width of the user's ear canal. A more dynamic calculation and better sensors would remedy this. Since the prototype is still in its early stages, large numbers of user tests have not yet been conducted to completely assess it. For major field studies an improved prototype with a more reliable physiological sensor, such as an electromyography (EMG) sensor, is needed in order to measure muscle movement more precisely.

While the proposed input interface could be implemented in a future headset, it would enable *Reflexive Interaction* with mobile devices. Although performing facial expressions and head gestures in public may be socially strange at first, it is to assume that it would not be more awkward then seeing people talking to thin air.

## 3.2 [FEEDBACK] Peripheral Visual Perception

The human eye possesses unique properties; in comparison to other senses it can process the highest density of information (up to ~10 million bits/s), it moves quicker than any other organ (up to ~20 ms), and it can perceive information in a wide angle (up to ~160°). While visual attention of a primary task usually demands the eye lens' focus (which is only within ~2°), we can additionally perceive information through our peripheral vision in a wider angle, but which has a substantial lower resolution. However, we can exploit this physiological capability of perceiving feedback in a peripheral way, while providing low-resolution feedback from a secondary task. This would not interrupt the main task and thus favours a *Reflexive Interaction*. How low-complex the presented stimuli has to be, and in which area of our field-of-view we need to display them to enable a *Reflexive Interaction*, is being investigated in this section. Still, before getting there, the term of a "*Peripheral Head-Mounted Display*" (PHMD) is being shaped in the following section.

### 3.2.1 Introduction

Monocular optical see-through head-mounted displays (OST-HMD) comprise of a see-through display positioned in front of one eye. One example in the market recently is the Google Glass. Also known as peripheral HMD [MHAU15], they are particularly useful in providing additional information secondary to the primary task at hand. In mobile scenarios, it is critical that the information on the HMD is easily noticeable without causing too much distraction to the users. Such noticeability-distraction trade-off is an important issue in notification system design [MC03], and display position relative to the user's eye is an important human factor since different display positions necessitate different eye movements that are controlled and influenced by different eye motor and human habits [BTD+74].

In the following sections, the taxonomy for head-mounted displays is being introduced that is based on the property of its functionality and the ability of our human eye to perceive peripheral information, instead of being technology-dependent. The aim of this research project is to help designers to understand the perception of the human eye, as well as to discuss the factors one needs to take into consideration when designing visual interfaces for PHMDs.

### 3.2.2 Related Work

Because the head incorporates all human senses, we can perceive a variety of feedback types – visual perception is one out of five information channels (*see Figure 24*).

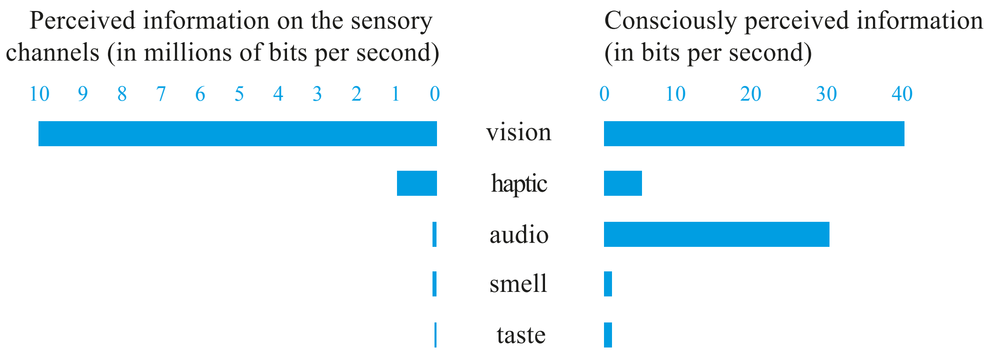



**Figure 24. Actual neuro-chemical perceived information of sensor channels compared to consciously perceived information – based on Nørretranders [Nør98].**

Following visual perception, the sense with the second highest bandwidth is audio. However, in public spaces audio is often not an appropriate channel for interactions, such as for purpose of navigation, since surroundings often create huge amounts of noise and headphones could isolate the user and might cause dangerous situations (e.g. because/when the user is not able to hear a nearing motorcycle). Therefore, most research focuses on utilizing the haptic sensation as an alternative feedback modality.

Sensory cells on our skin interpret mechanical forces such as pressure, touch, vibration and strain into nerve impulses, called mechanoreceptors [CCB01, Züh12]. Also, the ability to perceive temperature changes belongs to the category of haptic sensation. In the following subsection, a quick introduction of alternative sensation is being provided.

#### 3.2.2.1 Acoustic, Thermal, Taste, Smell and Haptic Feedback

Any kinds of sound, such as music or simple tunes, have a substantial impact [Gav93] on our physical condition. Following literature, musical stimuli can have an effect on our subjective perception of pain, on our heart rate, blood pressure, breathing rate, oxygen consumption, metabolism, and brain activity [Sch05]. As we may have experienced on our own: unpleasing noise can also cause adverse mental state changes. Liked music instead can be encouraging, inducing positivity and thus creating relaxation. It has been specifically proved that listening to music can create emotions such as joy and happiness right up to total intoxication [Sch05]. In HCI, auditory interfaces are very common as they can be found everywhere (e.g., ringtone). In Virtual Reality (VR), audio effects also play an important role – such as to improve immersion [DMC07]. Although vibrotactile feedback at the head may be experienced as bothering, it has been used in VR applications. De Jesus et Olivera et al. [dBNM17] attached 7 vibration motors to a HMD in order to convey the position of 3D targets in an immersive virtual reality.

In general, the perception of temperature is an individual phenomenon as the expression of heat and cold thermal receptors is not similar across users. In physiological treatment, heat stimuli are used to ease muscles [Pre82]. In contrast, cold stimuli can be beneficial to treat symptoms of exercise-induced muscle damage [EP99]. In HCI, thermal feedback can be applied in noisy and bumpy environments [WHBH11], however, it is still not broadly being considered. Besides these, we can also find taste interface, but which are not widely spread. While most interfaces are applying chemicals, Ranasinghe et al. [RNNG12] introduced a non-invasive tongue interface based on electrical and thermal stimulation on human tongue. Their results indicate that sour (strong), bitter (mild), and salty(mild) are the main sensation that can be simulated. In terms of smell Henry et al. already demonstrates a nose gesture interface that can simulate a particular smell to increase immersion in VR applications [HHY+91]. Similar to taste interfaces, it has not been explored widely. The most frequently applied alternative feedback sensation is haptic feedback, which can also be applied at the head. However, the head may not be the most suitable position. Own studies have shown vibrotactile feedback to be rather obstructing and uncomfortable to the user [KMM16].

#### 3.2.2.2 Visual Perception

Visual Perception is obviously based on emitted and perceived light. As we know from fundamental medical investigations certain light waves can affect the health of our bodies in a positive way. For instance, bright light potentially improves vitality and alleviates distress [PL00]. Moreover, it is known that adjusting these individually to the user's rhythm yields the power for aiding the body. For example, orange light can be described as visually bright, as it is considered to be warm, activating and moving. As a matter of fact, dark orange light with a wavelength of 628 nm is generally perceived as comfortable. Also, pulsating light causes a quiet heartbeat and affects the brain wave activity and thus the state of consciousness. Furthermore, the brain is able to adjust itself to some external pulse frequencies [Pho15]. In HCI, light has been used to create awareness while allowing to visualize binary information such as an ongoing energy consumption [TSS15] or ambient information [MKP+13]. However, it remains unclear how we can incorporate an ambient light in wearables to convey information in a peripheral manner.

Visual peripheral perception is basically depending on the positioning of the visual stimuli. Putting a visual stimulus far away from the visual focal point (which is only within ~ 2°) would enable the user to still focus on real world task and enable a peripheral perception. For example, attaching an LED at a glass frame would do already the trick while creating a wearable ambient light [CIP+06]. Instead using a single colour LED, which bounds us to a low-resolution information interface, we can also make use of a very tiny screen, such as an optical see-through head-mounted display (OST-HMD). However, as just said before, the position is crucial on order to not distract the user and to enable a peripheral visual perception of information.

While there is more research on monocular OST-HMD recently due to the popularity of Google Glass (e.g., on Parkinson [MVR+14], colour-blind [THK+14], learning and disabilities [BN15, DA15, GZA15, MF15, Sot15]), few studied the effect of display positions on the performance and usability in dual-task scenario. One such research studied the effect of display position on an object tracking primary task while tracking a horizontally moving object within two vertical lines on a miniature cathode ray tube (CRT) display [KMR89]. They found that tracking performances on both primary and secondary tasks decrease as the CRT's azimuth (horizontal) and elevation (vertical) angle increases, and looking upward is slower than downward. This is contrary to the default display position of Google Glass (*see Figure 25-a*), and it raises the question of whether it is optimal for processing secondary info while engaging in a primary task.

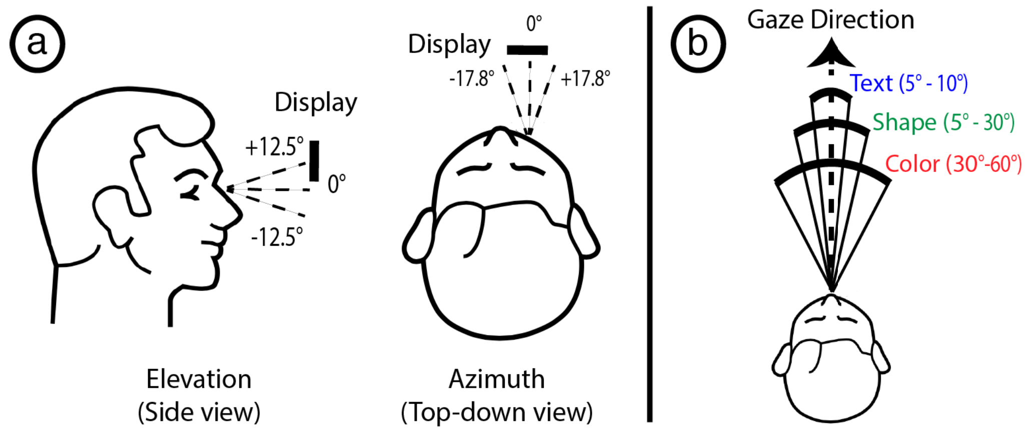



**Figure 25. (a) Illustration of the three elevation and azimuth angles on one eye. (b) Perceivable visual angles for colour, shapes, and text (data derived from [HUG+10]).**

While their findings were useful, their present-day applicability is limited (the study was done in year 1989) as their experiment setup did not reflect the characteristics of most modern mobile use-cases. Moreover, the study did not investigate usability aspects of the display positions extensively. A few more recent studies have looked into display-related issues of OST-HMD, but none of them were studying the positions of the display in relative to our eye with different types of visual stimuli [HUG+10, OKT14].

Therefore, a renew study is necessary and timely. These three major adjustments are suggested: (1) replacing the CRT with a monocular OST-HMD (2) choosing a primary task, such as simulated driving and reacting to mobile notifications as the primary and secondary tasks as both tasks are more modern and reflective of mobile use-cases; (3) studying azimuth angles in both directions (left and right) from the center while previous study only investigated azimuth to the right. Conducting such a study would possibly reveal best positions for suitable for peripheral visual perception with OST-HMD's and would probably also discover limitations for a *Reflexive Interaction*.

### 3.2.3 "Peripheral Head-Mounted Display"

Nowadays, it is designers who create purposes and needs for our daily usage of computers as they also create their own language and definitions (e.g. smartphone, which is a multi-sensory touchscreen mobile phone). Before introducing another new term for Head Mounted Displays (HMD), we look into the various technologies they are based on. There are two commonly used techniques: (1) optical lens projection, which projects an image onto our eye by using a mirror-lens system and LCD, LCos, OLED or CRT technology and (2) retinal projection (RP) also called virtual retina display (VRD), which projects a picture directly onto the user's retina of the eye [GS10]. Because the actual built-in technology of HMDs is often unknown to the user, it is hard to classify them correctly after this scheme. Another way to differentiate HMD's can also be determined whether the image is being displayed in either monocular (to one eye) or binocular (to both eyes) fashion. Additionally, the display can also be transparent (ST-HMD), which is usually achieved optically, with a transparent mirror-projection (OHMD), or by showing the image recorded with a video camera in front (VHMD), as shown in Figure 26.

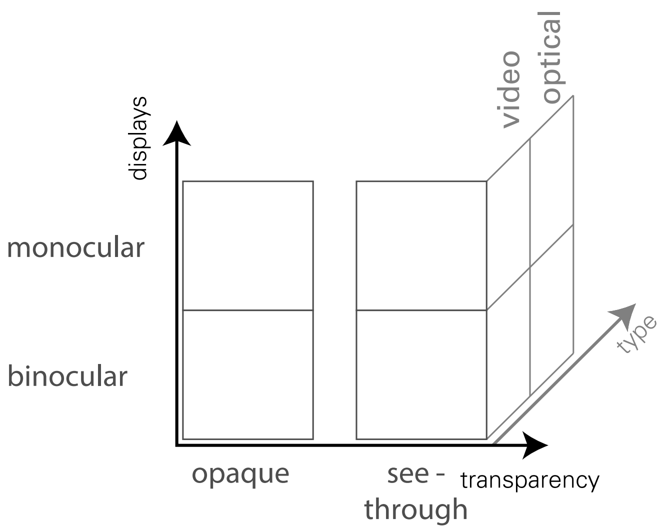



**Figure 26. Current classification based on physical and technology aspects [Jäc13]**

Since the number of HMDs is increasing and yet the classification is still not so clear for designers, it is justifiable to reclassify them. This taxonomy for head-mounted displays is based on the property of its functionality and the ability of the human eye to perceive peripheral information, instead of being technology-dependent. In this sections Human Factors for visual perception are being summarized, which are important to be taken into consideration when designing visual interfaces for PHMDs. We think that a PHMD would belong to a new sub-category of HMD, which is based on their functionality, such as the smartphone is a sub-category of mobile phone.

The term PHMD includes devices such as Google Glass, which are often missclassified as a Head-up display (HUD) [Sta13] if following the original definition by NASA. While NASA defined this term over centuries of space flight research [PR04], it actually describes a display that addresses the eyes-free problem, by absolving the user from the need to angle down their head. Furthermore, it provides augmented information in the user's forward Field-of-View (FOV), which is commonly projected on a windshield. In contrast, the Head-Down Display (HDD) is located at the instrument control panel [PR04]. Also, a HUD is mainly used to augment additional information into reality, which is technically not feasible yet for products such as Google Glass (lens focus on the display causes a blurred environment – *see Figure 28*).

#### 3.2.3.1 Definition: PHMD

A *Peripheral Head-Mounted Display* (PHMD) describes a visual display (monocular or binocular) mounted to the user's head that is in the peripheral of the user's Field-of-View (FOV) / Peripheral Vision. Whereby the actual position of the mounting (as the display technology) is considered to be irrelevant as long as it does not cover the entire FOV. While a PHMD provide an additional, always-available visual output channel, it does not limit the user performing real world tasks.

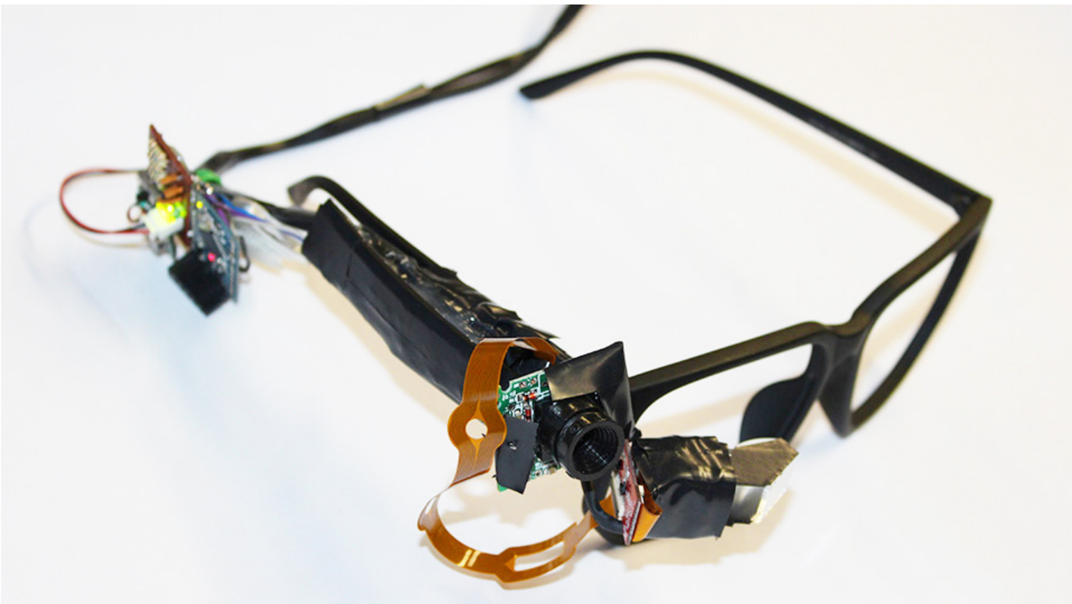


**Figure 27. Do-It-Yourself *Peripheral Head-Mounted Display*: Besides the Optical Display this prototype incorporates a Camera, Capacitive Touch Sensitive Field, Microcontroller.**

While there is an increasing variety of PHMDs reaching the market, Google stopped the delivery of their Glass product. However, we can also build our own device (*see Figure 27*), which we used for several other studies (*see 4.1.7. Botential Field Study*).

#### 3.2.3.2 Characteristics

The most important uniqueness is that the user's FOV is not being fully covered, allowing the user to perform real world tasks without limitations, while not having the pretension to raise or create immersion, such as HMDs often aim for. For current display technologies, while projecting image onto the eye, the screen needs to be focused by the pupil to enable a clear reading of the screen, thus the environment becomes blurred and out-of-focus. So a PHMD such as Google Glass is capable of displaying detailed information, when the pupil is focusing the display itself, as it also allows for peripheral information when the eye focuses on the real world. Still, simple information such as notifications are perceivable when focusing on the real world instead of the display.

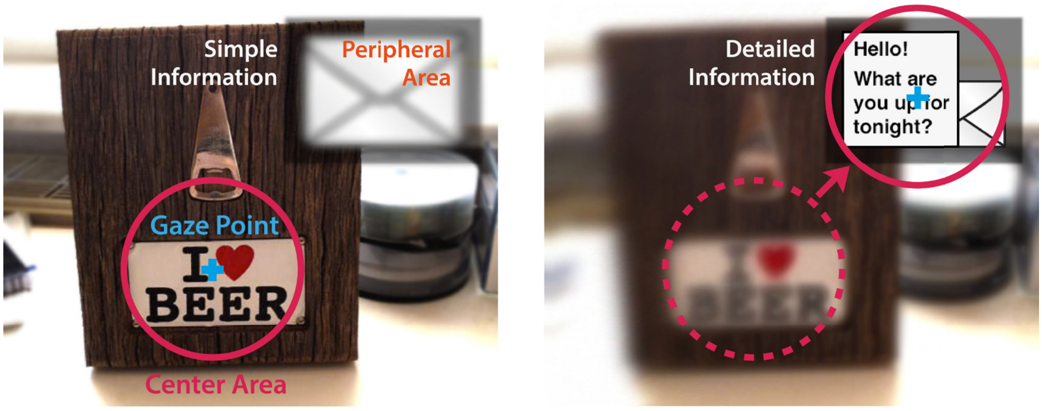



**Figure 28. Difference between detailed and peripheral information (see also [IR11])**

#### 3.2.3.3 Peripheral Interaction

Since the PHMD is resting in the peripheral of the user's FOV, it has a high availability and can be quickly demanded by focusing it. Furthermore, significant changes - depending on the stimuli - of the screen content is still perceivable without focusing the display [CIP+06]. We envision this effect to be used to design peripheral information (e.g. such as visual notifications for incoming emails, approaching appointments, warnings). An efficient response to such perceived information could be accomplished in quick peripheral input described by Hausen [Hau14] - *Peripheral Interaction*. This way, the user is not being greatly interrupted while completing real world tasks. Notwithstanding, suitable input modalities for PHMDs that are not socially awkward remain to be discovered. Negative or positive social effects by wearing a PHMD and devoting attention on the screen while taking part in a conversation might be present, but are not proven yet. In addition, taking part in traffic while focusing on a visual input modality can lead to a considerable decrease of attention to the road. However, compared to smartphone interaction, a quick switch to real world tasks is attainable, because there is no need for getting the device out of a pocket or bag. Furthermore, a PHMD does not need to be held by the user's hands, which offers a fully hands-free interaction. Since it is always available, it can provide peripheral visual information at any time, whereas peripheral information on smartphone in a pocket is not at all or barely perceivable (e.g., while walking).

### 3.2.4 Designing Peripheral Information

Research shows that designing an optimal visual output for Head-Mounted Displays is a complex issue, since there are several human factors that significantly impact users' perception [LW02]. The following effects are known in research:

#### 3.2.4.1 Human Factors

**Depth of Focus / Field:** switches permanently by refocusing on objects, which is different in distances to the user. A display mounted somehow to user's eye has fixed focal distance. Focusing information such as presented on a screen leads to a change in the depth of focus. This causes blurring of information presented at other layers, which especially degrades the perception of high spatial frequency information such as text.

**Eye-Movements:** are actually done at a specific angle of 10°. To focus an object out of this angle, head movements are used automatically for support. However, when wearing an HMD with eye-movements that exceed this angle, since head movements do not have any effect on the interface, a drop in comfort might occur due to tired eye muscle.

**Field-Of-View:** describes the viewing angle of the user. The User's eye has a viewing angle of 94° from the center and 62° on the nose side [IR11]. The vertical angle is about 60° upwards and 75° downwards. HMDs often do not cover the whole FOV, which is also a reason for increased cybersickness.

**Binocular Rivalry:** describes the phenomenon, which occurs when dissimilar images are presented to the human eye [AB99, CB74]. As the two images captured by each eye is incompatible for stereo processing, they fight for visual dominance over the other eye's side view, resulting in alternating views from the two eyes, where the non-dominant view is almost unseen. This effect often occurs when wearing a monocular HMD. In this setup, researchers [Pel99] also observed objects that completely vanish for several seconds from user's attention.

**Visual Interference**: describes the phenomenon when both eyes perceive different images that are overlapping, but the brain is not able to distinguish between those. This phenomenon is also known as the inability for visual separation.

**Phoria:** describes a muscle state of the eye, when the eyes are not focusing on a specific point. There are three different states, which can be distinguished: Esophoria, Exophoria, Orthophoria. While one eye is closed or being obstructed by a display, phoria can occur, which has the potential to cause vertigo and nausea as well[5].

**Eye-Dominance:** Although the user has two eyes, one eye is predominantly used. The other eye is used to make corrections and provide additional spatial information. It is recommended to wear a monocular HMD over the dominant eye [LW02].

[5] Z-Health Performance Solutions: *http://www.zhealth.net/articles/the-eyes-have-it*

#### 3.2.4.2 Peripheral Perception

While most of these factors mentioned above become problematic when both eyes are covered with displays, a single display resting in the Peripheral Vision can be considered to be unproblematic, since it does not permanently influence the perceived picture of the real world. As mentioned earlier, there are two types of information being perceivable with a peripheral head mounted display: (1) detailed information: when consciously focusing on the display and (2) peripheral information: through the human's visual perception, when focusing at the 'real world' (*see Figure 28*).

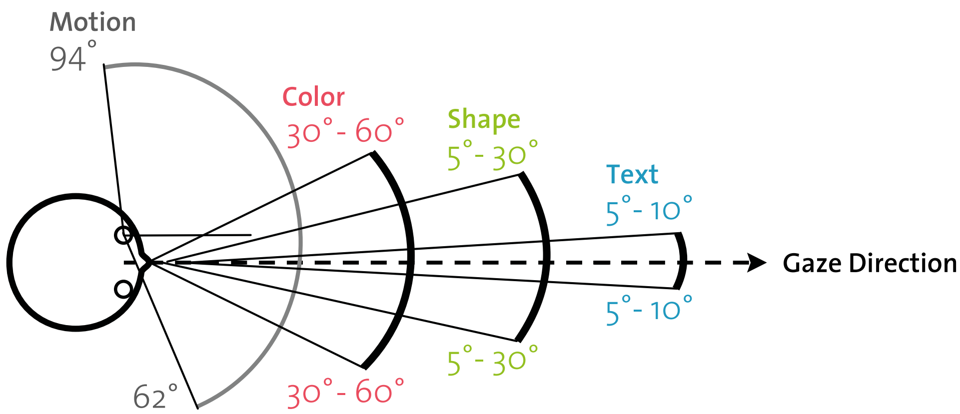



**Figure 29. Differentiable Areas and Angels for Perception of Motion, Colour, Shape & Text (see also [IR11])**

Most obvious changes are "*motion*", which can be perceived over the whole spectrum of the FOV. In a smaller angle, change in colour is also quite well perceivable (*see Figure 29*). In contrast, perceiving shapes and reading text requires very dedicated attention of the pupil. However, when being very focused on a dedicated task, rough changes in shapes are still perceivable in a peripheral way.

Even in the field of Human-Computer Interaction, there have been investigations on this visual "*peripheral channel*", such as peripheral colour perception with eyeglasses [CIP+06]. Furthermore, researchers proposed to additionally utilize an eye tracker for a *Peripheral Head-Mounted Display*, in order to improve user experience [IR11].

While most HMDs suffer badly of the effects of Binocular Rivalry, Depth of Field and Phoria it is different for the PHMD. Since the PHMD is not totally covering the FOV and also not augmenting information on real objects, it is not affected by known problems monocular HMDs usually suffer from, such as the effect of attention switching between reality and projection. Such problems have been figured out over centuries of airspace research and usually occur when trying to augment reality [RVC90]. These potential dangers, when operating in critical situations, such as taking part in traffic, are less pronounced for PHMDs.

### 3.2.5 Study: Positioning Glass

The physical position of the display on a monocular OST-HMD in relative to our eye is an important factor of the performance and usability in dual-task scenarios. We investigated 9 different display positions in a modern dual-task scenario with 27 participants. The experiment-involved participants responding to 3 different types of notifications displayed on the HMD while performing a visually intensive primary task.

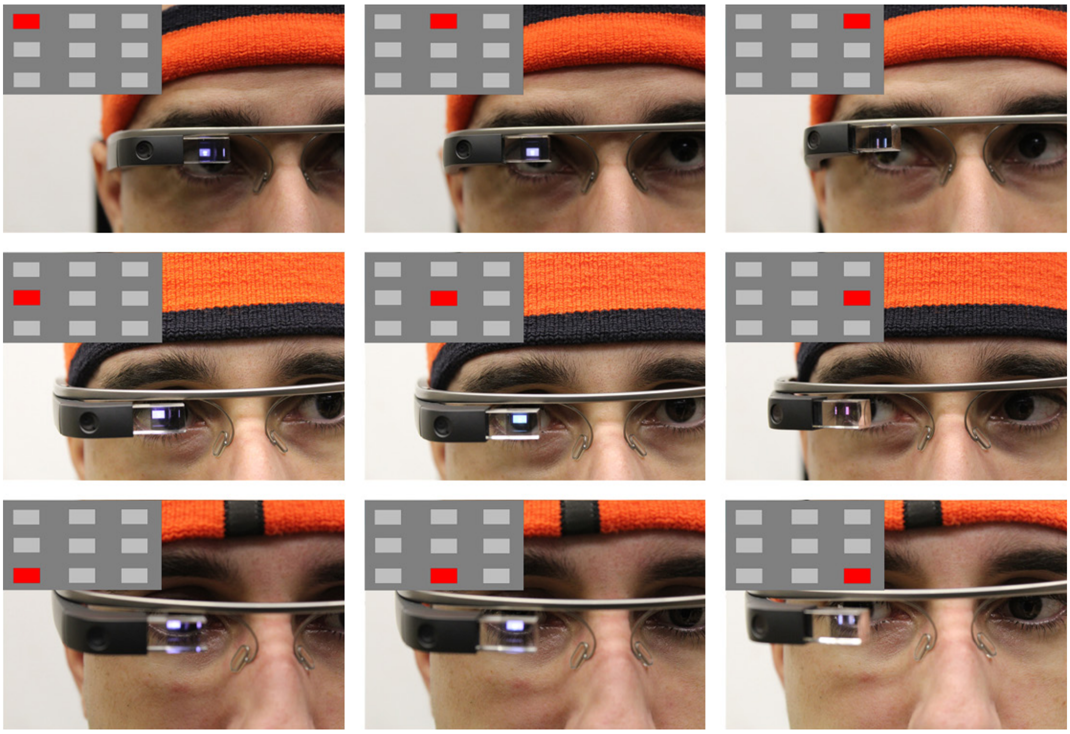


**Figure 30. We investigated nine display positions on a monocular OST-HMD. The red rectangle on the diagrams located at the top left corner of each image indicates the display position from users' point of view.**

In this research project, we study how different display positions of a monocular OST-HMD affect the performance (*noticeability*) and usability (*distraction, comfort*) of the primary and secondary task in a dual-task scenario. While previous studies used object tracking as the primary task [KMR89], we used simulated driving as 1) it has similar characteristics to a decent number of mobile use-cases, 2) it can be conducted in a laboratory controlled setting, 3) it uses the same processing structures (*visual attention*) as a dual-task paradigm with high attention load, making it an often-used primary task in HCI research [Pas94]. Based on our knowledge, our study is the first to investigate this problem in the modern setting. However, our results should not be interpreted as indications of how the display positions would affect driving performance or safety in real life. Our experiment with 27 participants quantified the performance differences between 9 different display (*see Figure 30*) positions and showed that milliseconds differences could be crucial for high vigilance tasks. At the same time, usability and task characteristics can influence users' overall preferences. We discussed this trade-off through the lenses of our qualitative findings and suggested that the middle-right position strikes the best balance for use-cases with characteristics similar to simulated driving. As the trade-offs for different dual-task scenarios are different yet important, we suggested future work to study scenarios with different task characteristics.

## 3.2.6 Experimental Design

### 3.2.6.1 Participants

Twenty-seven participants (11 females) aged 20-27 (*M*=23.4) were recruited from host institution. All participants had at least one year of driving experience and normal or corrected to normal eyesight. Sixteen of them were right-eye dominant (Miles Test), and none had used monocular OST-HMD before the study.

### 3.2.6.2 Apparatus and Software

**Figure 31. Physical setup – the participant's eye is fixed 50 cm away from the screen, providing a ~62° horizontal viewing angle. Driving simulator is controlled with a racing wheel.**

We used Google Glass (Explorer Edition 2.0) as the monocular OST-HMD since it is one of the few with a monocular form factor in the market. The experiment software was developed in Java with the Glass SDK to present stimuli and collect data. For the simulated driving primary task, we used a customized version of OpenDS, a reliable and easy to use open source driving simulator used by a number of HCI researchers [DA15]. Both the experiment software and driving simulator were run on a Windows-based PC (Intel Core i7 3.4GHz) with a 23-inch LCD monitor that provides ~62° horizontal viewing angle from 50cm away. A Thrustmaster Ferrari GT Experience Racing Wheel was used to operate the driving simulator (*see Figure 31*).

#### 3.2.6.3 Display Position and Calibration

We investigated 3 elevation (+12.5°, 0°, -12.5°) and 3 azimuth angles (-17.28°, 0°, +17.28°) to generate 9 display positions (*see Figure 25 -a and -b*). The display was placed in front of the right eye. The maximum elevation (~12.5°) were chosen based on Google Glass's default angle of elevation above a user's straightforward line-of-sight, whereas the azimuth (~17.28°) were chosen based on the maximum outward angle that the display hinge can afford. The angles we studied are similar to previous work [KMR89]. The upward and downward elevation and leftward and rightward azimuths were kept identical to ensure that the velocity and angular distance for each vertical and horizontal saccades were roughly the same [BTD+74].

The depth of view between the primary and secondary display was also kept consistent in the experiment. The monitor presenting the primary task was positioned 50cm away from the users to achieve a depth of view of 1/0.5m = 2 dioptries (DPT), while the Google Glass has a depth of view of 1/2.4m = 0.416 DPT [Goo14]. In our setup, the depth of views between the primary and secondary display exceeds the limit of human eye's depth of view (approximately ± 0.3 DPT). Therefore, a switch of focus is required when subjects shift their attention from the primary to the secondary task, mimicking most real world scenarios where two stimuli of interest are not in focus at the same time [Cam57].

To ensure HMD's display positions were consistent across participants, we performed a calibration procedure with the participants before they started each block. First, we positioned the participants 50cm away from the monitor and affixed their eye-level to the center of the monitor by adjusting their chair height. A red dot was drawn at the monitor's center as the reference point. Then, 9 red dots were shown on the monitor. Each dot represents the center of the HMD's display at the 9 positions we studied, and they were predrawn to the correct elevation and azimuth angles 50cm away from the monitor. Participants were then told to adjust the display position by aligning the respective red dot to the center of their HMD's display while looking straight. The adjustments were achieved by tilting Google Glass's display hinge horizontally (for azimuth angles) and its frame vertically (for elevation angles). After ensuring the red dot was aligned and the four edges of HMD's display were visible and not clipped, we stabilized and affixed the frame adjustments with an elastic headband to finalize the calibration.

#### 3.2.6.4 Tasks and Stimuli

Since monocular OST-HMDs are used in mobile scenarios, we designed a lab-based dual-task experiment that mimics such scenarios, with simulated driving as the primary task and notification responding as the secondary task. We chose simulated driving as the primary task as it demands high visual and attention resources, according to previous work [SMZB07]. However, we do not claim that our findings can be applied directly to or reflective of real life driving. In the driving task, participants drove on a three-lane road consisting of straight paths and curve turns, and they were instructed to keep their car in the center lane as much as possible. At the same time, they were told to pay attention to incoming notifications on the HMD and to respond as fast as possible. To response, participants were told to memorize the information and then pressed the gear shoulder button behind the steering wheel. This paused the simulator and removed the notifications from the HMD, and a post-trial multiple-choice test was given to ask participants to indicate the information they saw (*see Figure 32*).


**Figure 32. Three types of notifications evaluated: (i) colour (ii) application icon with a number and (iii) text.**

The type of multiple-choice questions was different based on the notification types. For colour notifications, participants were asked to identify the colour they saw from a set of 6 colours. For applications, participants responded by selecting the icon that appeared from a set of 6 and identifying the number (randomly assigned between 1 and 12) that was displayed in the upper right hand corner of the icon. For text, participants were asked to indicate either the information or number they saw. The texts were generated from 6 stubs, each with 6 substrings and a number between 1 and 12. The simulator resumed after recording the response and a minimum of 10 seconds was given to the participants to correct their steering to a normal driving state before the next trial began. To balance the difficulty of the primary and secondary task, the notifications were designed to appear just before their car reach the curvy turns. The appearance is randomized so the participants did not know on which turns the notification would appear.

#### 3.2.6.5 Design and Procedure

We designed three types of notifications: colour, application, and text (*see Figure 32*), and each represents visual elements with different perceivable visual angles (*see Figure 29*) and information complexity [IR11]. We measured the lateral deviation from the lane center to determine how the display positions affected the primary task. For the secondary task, we measured their reaction time and error rate in responding to the notifications correctly.

The experiment was a $9 \times 3$ within-subject design with two independent variables: display positions (9 positions) and notification types (colour, app, text). Sequence of the position was counter-balanced using Latin Square while the appearance sequences of the notifications were randomized within each block. A short practice was given before the actual study. The actual study consisted of 9 blocks (9 positions), and each block consisted of 9 trials with 3 repetitions for each of the 3 notification types. Display position calibration was conducted before each block. After each block, participants evaluated the comfort level and preference of the position on a 7-point Likert scale. After the study, we conducted interviews to get their overall evaluation. In total, there were: 27 participants × 9 display positions × 3 notification types × 3 repetitions = 2187 trials.

## 3.2.7 Results

For reaction time, error rate, and lane deviation, we ran *two-way repeated measures ANOVAs* [Gir92] on both factors for general statistical test and pairwise *t-Tests* with *Bonferroni Correction* for post-hoc analysis. For comfort level and preference, we ran Friedman tests and *pairwise Wilcoxon signed-rank tests* with *Bonferroni Correction* for post-hoc analysis. Detailed data from our study is shown in Figure 33. As there is a lack of evidences on eye dominance leading to better visual acuity [Poi07], we did not compare the results of participants with a different dominant eye in our study.

### 3.2.7.1 Reaction Time (RT)

| Display Positions | Reaction Time (s) | | | | Comfort Score (1: not comfortable at all, 7: very comfortable) | Preference Score (1: not preferred at all, 7: most preferred) |
|---|---|---|---|---|---|---|
| | *Color* | *App* | *Text* | *Overall* | | |
| Bottom Left | 1.14 | 1.46 | 2.06 | 1.54 | 3.44* | 3.26‡, † |
| Middle Left | 1.13 | 1.51 | 1.89 | 1.51 | 4.19 | 4.00 |
| Top Left | 1.15 | 1.49 | 2.29* | 1.64* | 3.67‡ | 3.48* |
| Bottom Center | 1.14 | 1.35 | 1.76 | 1.41 | 4.19 | 4.30 |
| Middle Center | 1.12 | 1.21*‡ | 1.63* | 1.32*‡ † | 4.63 | 4.37 |
| Top Center | 1.11 | 1.58‡ | 2.00 | 1.56‡ | 4.70 | 4.67‡ |
| Bottom Right | 1.16 | 1.61 | 1.90 | 1.55 | 4.19 | 4.07 |
| Middle Right | 1.06 | 1.49 | 2.02 | 1.52 | 5.07*‡ | 5.00*, † |
| Top Right | 1.13 | 1.64* | 1.90 | 1.55† | 4.67 | 4.44 |

**Figure 33. Results for reaction time (s) and mean score for comfort and preference in 7-pt Likert Scale. * ‡ † represent significant post-hoc tests (*p*<.05).**

Display position has a significant main effect on RT ($F_{8,208}$=2.42, $p$<.05). While the average RT in responding to notifications was quick (<2.5s), some positions were faster than others (*see Figure 33*). Post-hoc analysis revealed that middle center ($M$=1.32s) was significantly faster than top center ($M$=1.56s, $p$<.05) and top left ($M$=1.64s, $p$<.05).

Notification type has a significant main effect on RT ($F_{2,52}$=79.8, $p$<.001) as well. Post-hoc analysis revealed significant differences between all 3 types (all $p$<.001), with colour ($M$=1.12s) being faster than app ($M$=1.48s) and text ($M$=1.94s) (*see Figure 33*). This is consistent with prior findings on the perceivable angle of different visual stimuli [IR11].

We also found a significant interaction between display position and notification type ($F_{16,416}$=2.41, $p$<.05). While display position did not have an effect on colour, it was significant for app ($F_{8,208}$=2.76, $p$<.05) and text ($F_{8,208}$=3.09, $p$<.05). Post-hoc analysis revealed significant differences (all $p$<.05) between middle center ($M$=1.62s) and top left ($M$=2.29s) for text; and between middle center (1.21s) and both top center ($M$=1.58s) and top right ($M$=1.63s) for app.

#### 3.2.7.2 Error Rate (ER) and Lane Deviation (LD)

| | QUANTITATIVE RESULTS | | | | | | QUALITATIVE RESULTS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | App Reaction Time (s) | | | Text Reaction Time (s) | | | Comfort (1-7 ratings) | | | Preference (1-7 ratings) | | |
| | *Left* | *Center* | *Right* | *Left* | *Center* | *Right* | *Left* | *Center* | *Right* | *Left* | *Center* | *Right* |
| *Top* | 1.49 | 1.58 | 1.64 | 2.29 | 2 | 1.9 | 3.67 | 4.7 | 4.67 | 3.48 | 4.67 | 4.44 |
| *Middle* | 1.51 | 1.21 | 1.49 | 1.89 | 1.63 | 2.02 | 4.19 | 4.63 | 5.07 | 4 | 4.37 | 5 |
| *Bottom* | 1.46 | 1.35 | 1.61 | 2.06 | 1.76 | 1.9 | 3.44 | 4.19 | 4.19 | 3.26 | 4.3 | 4.07 |

**Figure 34. Summary of quantitative and qualitative results in the study. Columns are coded using green, yellow, and red colour scheme to indicate their ranking from best to worst for each metrics.**

Overall, participants were able to perceive notifications accurately (*M*=97%). *ANOVA* revealed a strong main effect of notification type on ER ($F_{2,52}$=10.97, *p*<.001). Post-hoc analysis suggested that colour notifications (*M*=99.5%) have a significantly lower ER than app (*M*=95.5%, *p*<.01) and text (*M*=96.2%, *p*<.01). Meanwhile, LD was affected only by notification type ($F_{2,52}$=11.27, *p*<.001). Post-hoc analysis revealed significant differences between each notification type (all *p*<.05), with a lower LD on colour (*M*=2.4 meters) than on app (*M*=2.6m) and text (*M*=3m). We did not find significant effect of display positions on ER and LD.

#### 3.2.7.3 Comfort Level, Preference and Ranking

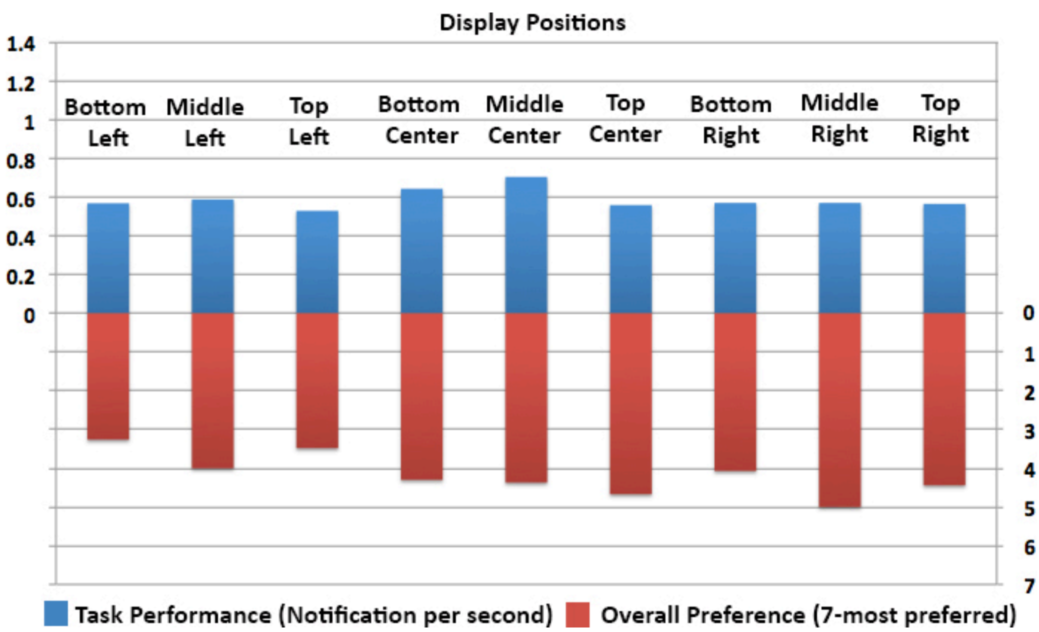



**Figure 35. The tradeoffs between task performance (in notifications per second, blue bars) and overall preferences (in 7-point Likert scale, red bars) for each display position. When considering both time efficiency and user preferences, middle center and middle right positions have the best-combined scores, as shown by the longer bars.**

While noticeability of the display positions was revealed mostly in the quantitative data (RT), the qualitative results elucidated the distraction and comfort level as well as how participants weighted this trade-off with noticeability. We found a significant difference in subjective comfort level depending on display positions ($\chi^2(8)=25.96$, $p=.001$). Post-hoc analysis revealed that middle right was deemed more comfortable than both bottom left and top left (all $p<.05$, *see Figure 33*). Subjective preference scores were also affected by the display position ($\chi^2(8)=29.08$, $p<.001$). Post-hoc analysis indicated that middle right was significantly preferred over bottom left ($p<.01$) and top left ($p<.05$), while top-center was preferred over bottom left ($p<.05$).

### 3.2.8 Discussion

Our findings have highlighted important differences between different display positions in a dual-task scenario from the performance and usability perspective. A summary of our results and the overall ranking of the display positions are shown in Figure 33 & Figure 35.

RT wise, it was not surprising that middle-center position is the fastest in overall, and its difference with the slowest (top-left) position is 320 milliseconds (24.2%) in our study. This gap was higher for more demanding tasks such as reading text-based notifications (660ms, 40.5% difference with top-left, *see Figure 34*). While this difference may seem small, it is significant in the context of tasks that require frequent or rapid eye movement, such as police pursue (*see Figure 36 -c and -d*). Therefore, our study has showcased the need to investigate this further in other scenarios in a more rigorous manner in future.

We also found that the average RT for bottom positions were slightly faster, but not significantly, than the top for app and text, which is consistent with previous finding [KMR89] and research in upward and downward saccadic velocity [BTD+74]. This slight difference can possibly be explained by the fact that most people are more accustomed to looking straight/down than looking up for most of the time [Ack13], as most tasks in daily life, such as walking on the street, involve looking downwards or straight ahead, whereas tasks that involve looking upwards is usually less frequent, such as looking at the clock. On the other hand, our study has also uncovered the need to balance performances with usability measures. In terms of perceived comfort and overall preferences, our data showed that middle-right position is the best, followed by top-center and top-right *(see Figure 34)*. Middle-center, while being the fastest, is not the most comfortable and preferred, as some participants found middle center and all the bottom positions to be too distracting to the primary task. According to post-study interviews, this distraction is caused by the overlays of the HMD's images onto the road ahead. The middle-right and the top positions did not have this problem. Participants also commented that their preferences could be different in other scenarios such as reading, where lower region of their vision is not occupied and not as pivotal as driving. Hence, while our study has revealed users' preferences in dual-task scenarios with task characteristics similar to simulated driving (such as walking, cycling, etc.), more future work is needed in other dual-task scenarios with different task characteristics.

### 3.2.9 Conclusion and Design Recommendations

We investigated 9 displays positions of a monocular OST-HMD and how they affect the performance and usability in a modern dual-task scenario. We supported our investigation with quantitative and qualitative data in a well-controlled laboratory study. We found that even though the middle-center position was the most noticeable, participants most preferred middle-right as it does not occlude and distract the primary task in our experiment. As the characteristics of the primary and secondary task can influence the ideal positions, we suggest future work to investigate this problem in other dual-task scenarios. We plan to carry out some of these studies as future work.

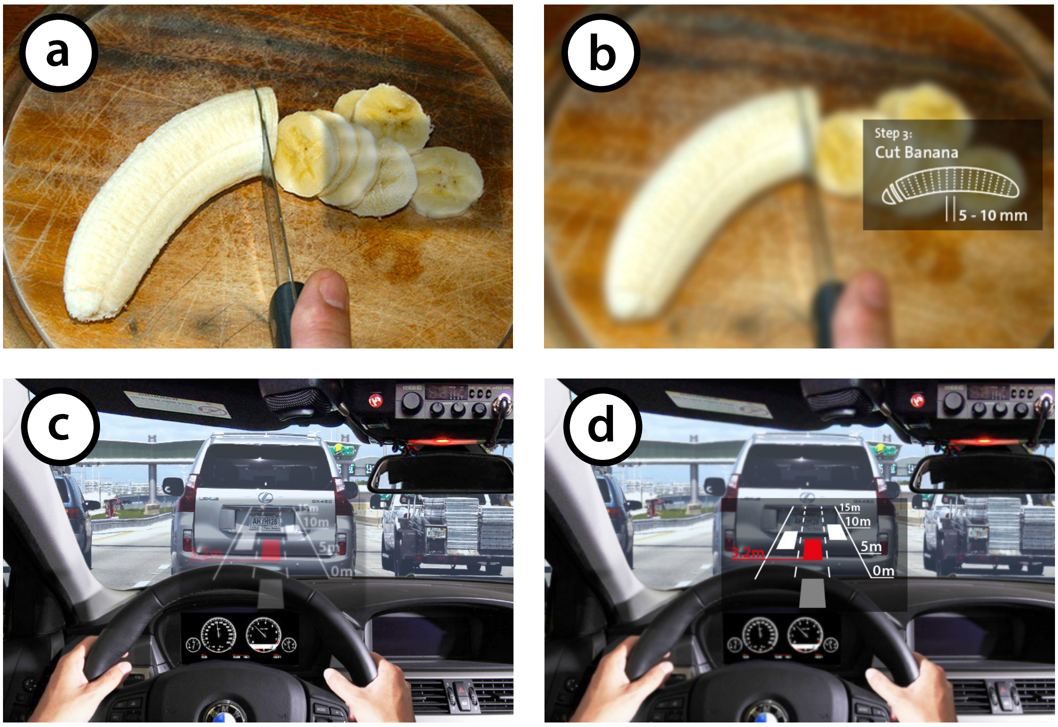



**Figure 36. Illustrations of the cooking scenario (a & b) and the traffic police pursue scenario (c & d) from the first person point of view. In the cooking scenario, putting the display in the middle-right allows the user to see the knife clearly while receiving cooking instructions on the HMD. In the traffic police pursue scenario, putting the display in the middle-center allows the police to track the position of the pursuit vehicle on the HMD without turning the gaze away from the road. The scenarios demonstrate that task requirement is an important factor of the ideal display positions for a specific task.**

Based on our findings, we made the following recommendations on the display positions of monocular OST-HMD. Middle-right, top-center, and top-right are suitable for dual-task scenarios 1) where the HMD has to be used for an extended period of time, 2) when the center of vision is important for the primary task, and 3) while the secondary stimuli is less urgent and important, such as the cooking scenario shown in Figure 36 -a and -b. On the other hand, middle-center and bottom-center positions are suitable for dual task scenarios that require high noticeability on the secondary stimuli, such as the police pursue scenario illustrated in Figure 36 -c and -d.

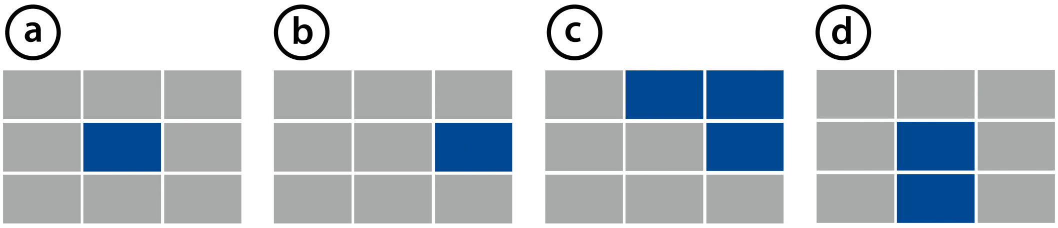



**Figure 37. We investigated 9 displays positions and how they affect the performance and usability in a modern dual-task scenario. Our findings resulted in four design recommendations for the arrangement of information in our field-of-view.**

We conclude with four design recommendations; 1) When willing to design an information presentation system that should yield highest noticeability, such as for extraordinary urgent information, we propose the Middle-Center position for information arrangement (*see Figure 37-a*).

2) When considering the user's subjective felt obtrusiveness, arranging the information on the Middle-Right area of the user's field-of-view should be favoured, since it was most preferred by all participants. This position yields lowest level of occlusion, nor does it distract the primary task (*see Figure 37-b*)

3) When designing information that may coexist to a primary task, we can also suggest Middle-Right, Top-Center, and Top-Right positions to be suitable for a dual-task scenario. (*see Figure 37-c*)

4) When designing an information presentation system suitable for dual task scenarios that require high noticeability, on the secondary stimuli, we suggest Middle-Center and Bottom-Center positions. (*see Figure 37-d*)

When aiming to design a *Reflexive Interaction*, the stimuli is essential. Our experiments show that more complex stimuli, such as text (*see Figure 32 iii*) require significant longer focus, while it also negatively influences the primary task and thus is not suitable for a *Reflexive Interaction*. In contrast, rather low complex stimuli, such as colour changes (*see Figure 32 i*) yield significant lower reaction times and significant lower distraction at the primary task (error rate and lane deviation) and thus is indeed suitable for a *Reflexive Interaction*. Another important factor influencing the success of a *Reflexive Interaction*, is the display position. Even though the Middle-Center and Bottom-Center (*see Figure 37-d*) position provide in combination with a low-complex colour stimuli best reaction times (below a second), it highly occludes the primary task. Only if the stimulus is shown to a very short periode of time, such as a for tiny fraction of a single second, it would still support the concept of a *Reflexive Interaction*. Otherwise, we achieve the opposite effect - a task distraction. Overall, Figure 37-c shows all relevant display positions favouring a *Reflexive Interaction*, provided the stimuli to stay on a low complex level.

# 4. Body: Torso & Limbs

This chapter incorporates two sections investigating novel on-body input and on-body feedback strategies for a future human augmentation that favours *Reflexive Interaction*.

In terms of novel on-body input techniques, "*Botential*" [MPUZ15] is being proposed, which I started to develop at the National University of Singapore as part of my Master's Thesis. The project has been published in collaboration with Simon T. Perrault, Bodo Urban and Shengdong Zhao. While this work has been published as a Full-Paper at *MobileHCI 2017* (Ranking: A2, Acceptance Rate: ~23%), it got also awarded by the Fraunhofer IGD "*Selected Readings in Computer Graphics 2016*" with an Honorable Mention.

The second part of this chapter introduces three wearable prototypes demonstrating mechano-pressure, thermal, and electrical feedback. A proof-of-concept is being presented that enables scalable notifications which adjust the intensity reaching from subtle to ob-trusive and even going beyond that level, while forcing the user to take action. This work is called "*Scaling notifications beyond alerts*" [MDU18] and was carried out in collaboration with Laura Milena Daza Parra. I was mainly driving the ideation, concept, study design and statistical analysis. Mrs. Daza overtook many parts of the implementation, while she independently carried out all studies. This work has been rejected at the *ACM IMWUT* – the ACM Journal on Interactive, Mobile, Wearable and Ubiquitous Technologies, which took over the publication handling from *UbiComp* (Ranking: A1, Former Acceptance Rate: ~23%) due to *«ethical and safety concerns»* following the Primary Associate Editor.

## 4.1 [INPUT] On-Body Gestures

In this section, *Botential* is being presented, which enables for a *Reflexive Interaction*, de-pending on the selected gesture set and the location the wearable input device is attached to, by using a novel on-body interaction method. *Botential* can identify the location of on-body tapping gestures, using the entire human body as an interactive surface to expand the usually limited interaction space in the context of mobility. When the sensor is being touched, *Botential* identifies a body part's unique electric signature, which depends on its physiological and anatomical compositions. This input method exhibits a number of ad-vantages over previous approaches, which include: 1) utilizing the existing signal the hu-man body already emits, to accomplish input with various body parts, 2) the ability to also sense soft and long touches, 3) an increased sensing range that covers the whole body, and 4) the ability to detect taps and hovering through clothes.

### 4.1.1 Introduction

A number of previous research [HBW11, HTM10, OSM+13] have demonstrated the advantages of leveraging our own body as input device for human-computer interaction, which is defined as On-Body Interaction [HRH12]. While mobile devices usually have a very limited interaction space, using our body as an interactive surface has the advantages of being more accessible, offering a relatively larger input footprint (up to two $m^2$ of interaction space [BB95, Ric04]), and the ability to support eyes-free interaction based on proprioception [KHF80], i.e. the sense of our own body's configuration in space. Researchers have proposed a number of approaches to sense on-body inputs from a distance, such as using optical tracking [GBB10, HBW11], or by having the sensing device in direct contact or connection with the body parts, as in ***Skinput*** [HTM10] or Touché [SPH12]. Each of the above approaches has its own advantages but also some constraints. For example, optical tracking is affected by lighting conditions, and acoustic sensing has difficulties in detecting soft and thus silent touches. Capacitive sensing has been used to detect different types of touch events, but not to reliably distinguish the different parts of our body.

In this research, we propose *Botential* (*Body Potential*), a novel interaction technique that senses electrical capacitances and potentials of different body areas when being in touch with the input device. This alternative way of sensing can complement previous approaches and improve mobile interaction. Instead of using the human body as an interrupter [ABW11] or receptor [CMPT12], we treat it as an emitter and enable for the following benefits:

- Identifying the location of taps on the entire body without driving an electrical current through the body.
- The ability to sense soft and long touches and an increased sensing range per sensor unit.
- Supporting a number of techniques for eyes- and hands-free interaction to allow different tapping and hovering gestures even through clothes.

In the following sections we explain the theoretical background of the electrical properties of human cells, methods of measurement, and our developed prototype. To gain insights, on how such system performs in terms of accuracy, we furthermore conducted an evaluation with 10 users. Besides the technical contribution, we envision an interaction concept, conduct a field study, and discuss how this concept could possibly be applied and embedded into wearable devices to enable eyes- & hands-free interaction.

### 4.1.2 Related Work

On-body gestures are a particular form of how we can utilize our body as an interactive surface. It offers novel approach in expanding input space for mobile computing. In the following I introduce some typical on-body input strategies and alternative input strategies ordered by used technologies.

#### 4.1.2.1 On-Body Input Strategies

##### 4.1.2.1.1 Optical Tracking

Optical Tracking is a common way in HCI to convey interaction concepts. In ***OmniTouch*** [HBW11] Harrison et al. demonstrates how to mount a depth camera (Kinect) on the user's shoulder in order to detect an on-body tapping gesture. In ***SenSkin*** [OSM+13], proximity sensors are being attached to the user's lower arm, while continuous control is enables while sliding with the finger on the skin. In practise these setups cannot track the whole body and are affected by unflavoured light issues as it is facing the problem of occlusion.

##### 4.1.2.1.2 Bio Acoustic Sensing

Bio Acoustic Sensing with Piezo Films is presented by ***Skinput*** [HTM10], which allows detection of hitting the forearm or hand based on the produced sound transmitted through bone conduction. Soft or long taps are not feasible to be detected. While the signal attenuates with distance, scaling this to the entire body would require many sensors.

##### 4.1.2.1.3 Resistive Sensing

Resistive Sensing can be utilized to detect mechanical deformations and touch events on the skin with printed tattoos [WBV+12] or an additional artificial skin [WLB+15]. Still, expanding this technology to the whole body might not be realistic, as it can be obtrusive and entails a possibly high acceptance threshold for users.

##### 4.1.2.1.4 Capacitive Sensing

Capacitive Sensing is a reliable way to detect touches on surfaces. Touché [SPH12] presents a method known as Swept Frequency Capacitive Sensing, which measures the impedance with respect to the frequency while driving a high frequency AC signal through the body. Such technique could in theory be expanded to the whole human body. However, A wearable interaction concept and how to reliably identify taps on different body parts is not being demonstrated in Touché but very recently in ***SkinTrack*** [ZZLH16]. Touching a particular part of the ear for control purposes has been as proposed in ***EarPut*** from Lissermann et al. [LHHM13]. Interactive clothing has been proposed and used to detect interaction as in Pinstripe [KWL+11]. In general, this technology consumes little power and allows for fabrication in high density and flexible material. However, expanding this to all clothes requires a big sensor network.

#### 4.1.2.2 Alternative Input Strategies

##### 4.1.2.2.1 Optical Tracking

Optical Tracking is a widely used technology but can be easily undermined by light conditions. *Imaginary Interfaces* [GBB10] uses a small IR camera to detect hand and finger gestures, but it fails under certain light conditions. Depth cameras (Kinect) can be mounted on the human body, such as at the shoe, to detect hand and finger gestures as presented in *ShoeSense* [BMR+12]. In *SixthSense* by Mistry et al. [MM09] RGB cameras are mounted on the chest, body, or head to enable control functions. *SixthSense* additionally combined the use of a projector for augmenting a virtual screen. These input strategies require hand and arm gestures to be performed in front of the body. While these concepts are feasible in virtual environments, gesture recognition is less reliable in common day-to-day situations such as non-ideal lighting or while engaged in other movements. When examined in contrast to these concepts *WristCam* from Vardy at el. [VRC99] enables one-handed control with a wrist-worn camera that recognizes seven different finger gestures.

##### 4.1.2.2.2 Resistive Sensing

Resistive Sensing is one of the oldest but still relevant methods for sensing input. Recently, *WristFlex* [DP14] presented how to incorporate FSRs in a wristband to classify hand and finger gestures. A wristband of another kind, a touch sensitive watch wristband is presented by Perrault et al. [PLEG13] in order to enrich input space.

##### 4.1.2.2.3 Motion Sensors

Accelerometers and Gyroscopes have been used by many researchers such as Aylward and Paradiso [AP07] and Rekimoto [Rek01, Rek96] in order to track in-air gestures. Another one-handed control is demonstrated with *Tickle* from Wolf et al. [WSKR13] who utilize a touchless finger interaction with a finger worn gyroscrope to control a video camera. The drawback is that an algorithm is required to constantly run to distinguish between wanted movement and unconscious movement when performing everyday tasks, which may result in an unwanted control.

##### 4.1.2.2.4 Environmental Electromagnetic Radiation

Still a very uncommon way to detect body gestures is to utilize environmental electromagnetic radiation as demonstrated in *Human Antenna* [CMPT12] or to use *Static Electric Field Sensing* as presented by Cohn et al. [CGL+12].

##### 4.1.2.2.5 Magnetic Field

Measuring a magnetic field would be another method, which has recently been explored for finger gestures. *Nenya* [ABW11] detects the movement of a ring mounted with a magnet around its wearer's finger. The drawback with this technology is that it is limited physically to a specific radius. How to enable a more complex input with this technology in a 3D space is demonstrated in *uTrack* [CLWP13].

#### 4.1.2.2.6 Electromyography

Electromyography (EMG) is a technology that can detect muscle tension through an increase in action potential. Saponas et al. [STM+09] demonstrated its use for detecting finger gestures. In that particular case, many EMG electrodes must be fixed tightly on a certain area, such as around the arm. To measure very clean signals, the electrodes should be invasive. Depending on the number and nature of electrodes, heavy classification algorithms may be required.

As we have seen, researchers have developed various other ways to enable interaction with our own body and to make it suitable for mobile interaction. To better understand the unique properties of each technique, some related work is summarized in Table 5.

| | Technology | Interaction Style | Eyes-Free | Hands - Used |
|---|---|---|---|---|
| *OmniTouch* | Depth Cam. | Contact | N | 1 |
| *Imaginary I.* | IR Camera | In air | N | 2 |
| Cohn et al. | Electric Field | In air | Y | 0 |
| *Skinput* | Projector+Piezo | Contact | Y | 1 |
| *Humantenna* | Electromagnet. | In air | Y | 1 |
| *WristFlex* | FSRs | In air | Y | 1 |
| *Touché* | Capacitive S. | Contact | Y | 1 |
| Saponas et al. | EMG | In air | Y | 1 |
| *ShoeSense* | Depth Camera | In air | Y | 1 |

**Table 5. Brief Overview: Hands-Used is the minimal number of hands needed to interact. A hand is considered not being used if the user can interact while holding an object. Interaction Style: interaction is based on tapping or hovering above a body part or on gestures in air.**

In conclusion, we can see that some alternative interaction concepts already enable eyes-free interaction, which potentially favours multitasking. However, usually at least one hand is occupied, which would always hinder the user to perform two similar tasks, which both demand the same interaction channels. Therefore, we should provide quickly executable interaction being fully hands-free and eyes-free, which favours a *Reflexive Interaction*.

### 4.1.3 "Botential"

*Botential* leverages a unique electrical signature, measured on the bare skin, to provide concrete information on which part of the human body is being touched with the sensor. As a proof of concept, *Botential* is realized using a simple off-the-shelf EMG prototype sensor to measure tiny voltage on the skin caused by the negative potential of cells, which slightly varies across body parts. Due to the prototypical nature of this sensor, we additionally require the support of a capacitive sensor (CS). Frequency based capacitive sensing provide additional information on the virtual capacitance of the skin and the underlying tissues. Nevertheless, with a high quality clinical EMG device there would not be the need for capacitive sensing, as both the resolution and reliability of the system can be significantly enhanced.

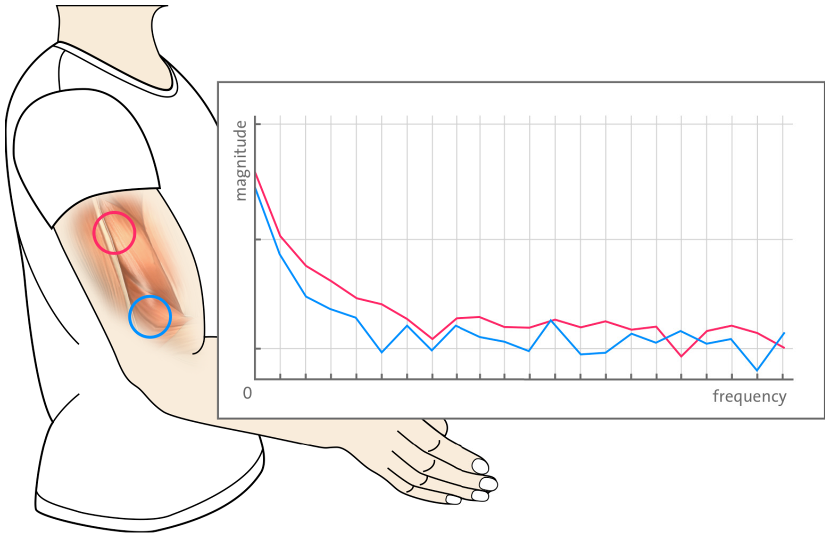



**Figure 38. Illustrating the measured signal spectrum at specific areas. The red/blue lines in the graph represent the signal measured from the red/blue areas.**

#### 4.1.3.1 Background and Theory

In contrast to non-living objects, in living animal and plant cells we can commonly find electric potentials caused by an imbalance of ions between the two sides of a cell membrane [Hod51]. Literature defines two types of electric potentials that can be detected in our body: the relatively static membrane potential called the resting potential (or resting voltage), and the specific dynamic electrochemical phenomena called action potential, which occurs in excitable cells, such as neurons, muscles, and some secretory cells in glands [Fit61]. While action potential occurs when tensing a muscle, the resting potential is always present and can be also found in any other tissue. Furthermore, it has 2 important properties:

1. *Resting potential is different at each part of our body.* For example, the resting membrane potential for skeletal muscle cells is approximately -95 mV and for

smooth muscle cells is -60 mV; our neurons have a resting potential of -60 to -70 mV [Hod51]. The differences in the body's anatomical and physiological structure result in unique resting potentials in almost every part of our body, as illustrated in Figure 38.

2. *The magnitude of resting potential is relatively stable over time and against stimulation, since it is determined by the cells' static properties* [Hod51]. When an excitable cell is activated, e.g. when contracting a muscle, it quickly accumulates a positive action potential. It can increase up to 100 mV, and then discharges in a few milliseconds. This is followed by a very low fluctuation (~1 mV [VD68]) of the resting potential.

#### 4.1.3.2 Sensing Methods

Electromyography (EMG) is a common way to measure such electrical potentials. There are two fundamental measurement techniques: the invasive setup with needle electrodes and the non-invasive setup that directly places the sensors in contact with the bare skin. Particularly when measuring in a non-invasive way on the surface of the skin, the measured signal could contain strong noise accumulated during the propagation of the actual signal through different tissues in the body. The noise received by the EMG sensor can be typically caused by Causative Factors, Intermediate Factors and Deterministic Factors [RHM06]. For us the causative factors are more relevant, because they directly affect the signal, and can be further divided into Extrinsic Factors (e.g. type of contact to the skin, such as through tiny hair/dirt, or the shape, surface, orientation of the electrodes, etc.) and Intrinsic Factors (e.g. anatomical, physiological, and biomechanical factors such as *Microvibrations* [Roh64] or properties of muscle fibers in terms of thickness, type, temperature, etc.) [FCM02].

As mentioned, most of the human body's cells have an excess of electrons and thus a negative electrical potential / charge to the outside. The ability to store this electrical power can be described as a capacitance or as body capacitance when referring to the overall capacitance of the human body. The capacitances vary between 50 – 150 pF depending on the individual body parts [SHHH98]. This capacitance can also be measured invasive or on the skin at different body parts, which is called Capacitive Sensing (CS). In general, we distinguish between three sensor setups for capacitive sensing: Transmit Mode, Loading Mode and Shunt Mode [Smi99], which differ in physical arrangement, number of electrodes, and their function allocation.

Determining action potential of a muscle, usually requires at least two measuring electrodes (e.g. $EMG_{mid}$ and $EMG_{end}$), attached to two different spots over a certain muscle or muscle group. Furthermore, a reference electrode (e.g. $EMG_{ref}$) is required to be attached to a different spot, which should not be affected by any muscle activity. As part of the measurement principle, the sensor always detects the potential difference between the reference electrode and the measuring electrode. The resulting difference between the gathered signals of two measuring electrodes indicates the action potential. This can be used to accomplish a gesture control, such as proposed by Saponas et al. [STM+09] who use the sensor on a fixed muscle group to detect action potential at certain areas around the arm and to thus interpret finger gestures.

Previous research for muscle-computer interaction typically uses EMG to detect action potentials of muscle cells. This technology can also be used to measure resting potential in almost all types of cells, including locations with few muscle cells (e.g. belly). However, pure resting potential of individual body tissue is very difficult to measure without using specialized tools (i.e. Potentiometric Probes [FBL85]) that are intrusive. What can be realistically measured in an interaction setting is a combination of the overall resting potential for all body tissues in a non-intrusive way on the skin at a particular location, plus some noise. While noise is usually undesirable, coloured noise also can provide important information that helps localization, if it is somehow significant across body parts' surfaces.

#### 4.1.3.3 Electrode Arrangement

Compared to the common sensing approaches, we can also re-orient the measuring electrode (facing the air) and make it touchable by any body part. In this arrangement only the reference electrode is still needed to be permanently in contact with the body. Regarding the measuring electrodes, we actually only require one, or arrange both closely next to each other (*see Figure 39*). This way we achieve a contact area, which collects the unique electrical signature of the body part that is touching it.

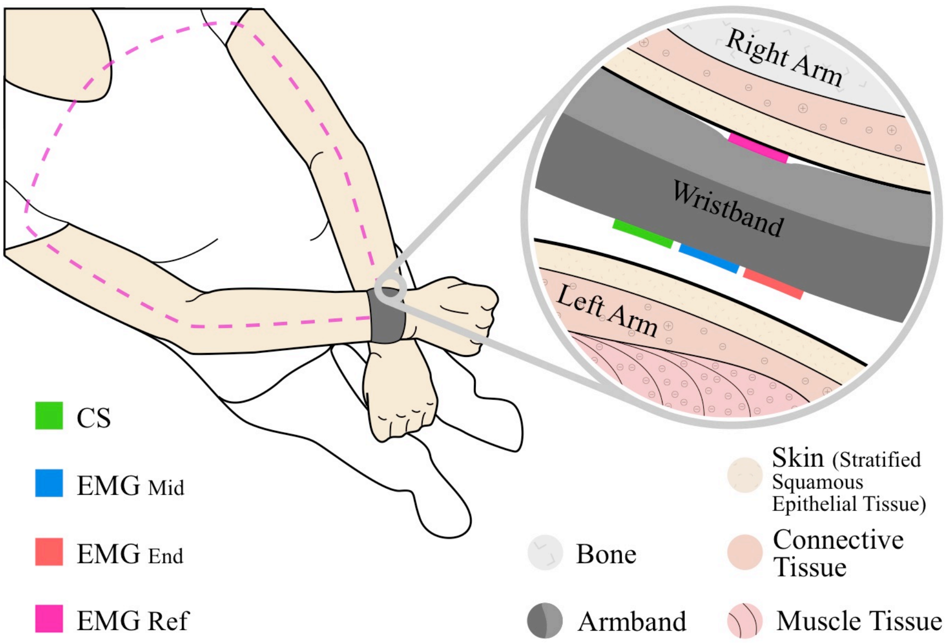



**Figure 39. The setup: the measuring electrodes are re-orientated and act as a touch point.**

### 4.1.4 Implementation

In order to demonstrate the feasibility of our proposed concept, we built a proof-of-concept wearable input device (*see Figure 40*), which we envision to be integrated into everyday wearable accessories as illustrated in Figure 45.

#### 4.1.4.1 Prototype

The prototype basically consists of four components: a portable EMG sensor module (Muscle (EMG) Sensor v2 from Advancer Technologies[6]), a voltage divider circuit (consisting of a 22pF capacitor and a 10MΩ resistor) and an astable multivibrator to enable for a Capacitive Sensing in loading mode, a microcontroller (an Arduino Pro Mini) to pre-process and transform the signal, and a Bluetooth modem (HC-06) to enable wireless communication with a computer, where the data is displayed, processed, and classified. Two conventional 9V batteries and a 3.7V LiPo battery power the prototype. The hardware is mounted on a Velcro tape and thus allows the user to wear the device as a leg, wrist or armband.

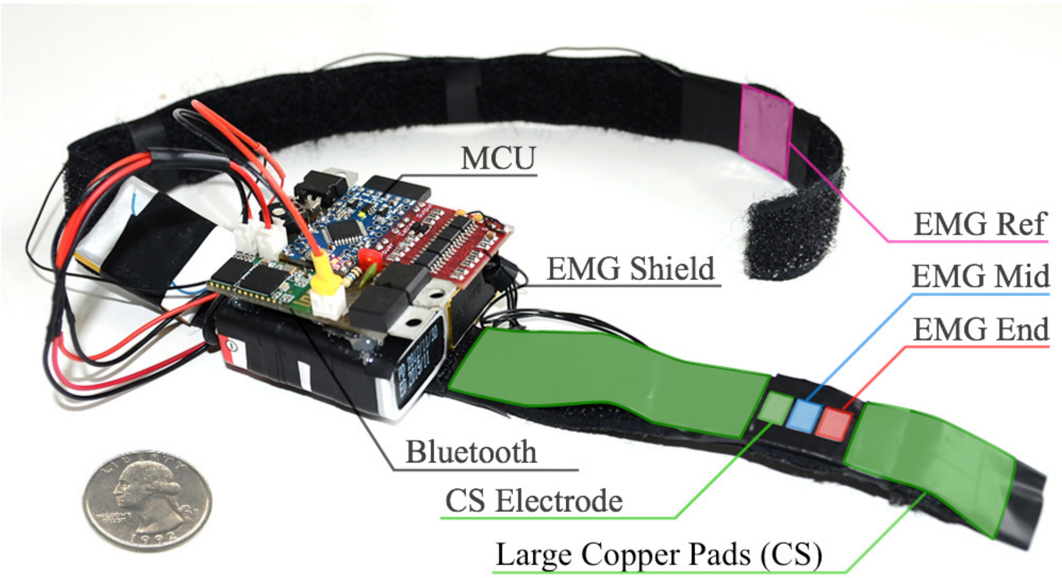



**Figure 40. *Botential* mounted on a band: the EMG mid / end and the CS electrode are surrounded by copper pads which are hidden under black isolation tape and enable hovering.**

The EMG sensor module has three electrodes, from which the reference electrode (REF, size: 20 x 20 mm - mounted on the inside of the band) is always in contact with the skin (e.g. with the exterior side of the hand when worn as a wristband). The other two electrodes (size: 10 x 4 mm each with a distance of 1 mm), which are labeled as MID and END, are integrated on the outside part of the band, to allow for proper contact with a desired body

[6] Advancer Technologies: *http://www.advancertechnologies.com/p/muscle-sensor-v3.html*

part. To gain additional information on which body part is being touched, we put another electrode next to the MID EMG electrode to enable capacitive sensing. These electrodes represent the actual contact area that can be touched with a desired body part. Around the contact area, large copper pads (size: 20 x 35mm + 20 x 70 mm) are embedded to enable the sensing of an approaching body part and touching through clothes.

#### 4.1.4.2 Signal

While a professional needle EMG would be able to provide a frequency-based signal, containing a summation of resting potentials, we are unable to measure such clear signal on the surface of the skin. Instead, we measure a noisy signal, which is a superposition of resting potentials from different fibers plus different noise caused by Extrinsic Factors, which we include as a feature in our electrical signature. These factors are crucial, since the characteristic of the surface that touches the sensor instrumentally determines the measured signal and thus the detected body part.

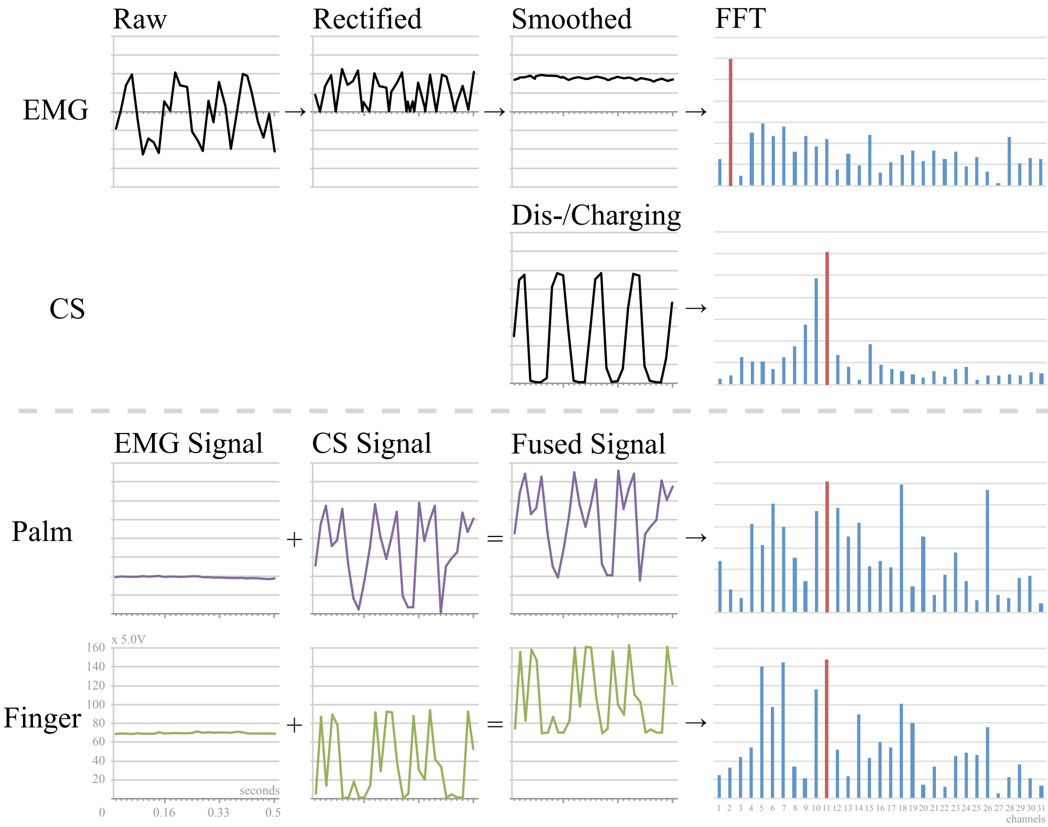



**Figure 41. The gathered raw data of the EMG & CS are being fused and afterwards treaded with an FFT. Features used for touch recognition are extracted from the FFT.**

In contrast to a clinical EMG sensor, the EMG sensor used in our prototype has limited capabilities due to the hardware components, which already rectify, smooth and normalize the gathered signal. This loss in information only enables to behold the amplitude and not the whole frequency spectrum of the actual signal. To compensate that we also use a capacitive sensing in loading mode to enrich the electrical signature with further frequency information and thus extend the set of features. Signals from both EMG and capacitive sensors are then merged together (*see Figure 41*). After this early sensor fusion, we broadcast the computed signal via a serial Bluetooth connection to a computer, where a *Fast Fourier Transformation* (FFT) is applied on the fused signal.

Furthermore, the capacitive sensing (with the integrated copper plates in the armband), also enables a precise detection of a hovering state within the distance of 4 cm, which is achieved by sending electric pulses to the copper plates and measuring the time of charging and discharging.

#### 4.1.4.3 Recognition

Before we can recognize the body part that is being touched with the sensor, we need to first conduct a Training Phase, in which the user is required to record samples of each body part. After completing such process, we can enter the Recognition Phase, in which body parts can be detected based on the known electrical signatures gathered in the previous training phase. The recognition can be performed Online in real-time, which requires a classification to perform quickly with sufficient high recognition rates, since computational resources are limited. Alternatively, we can process the gathered data Offline, which has the advantages of being independent from just-in-time decisions and limited computational or time resources. For evaluation we followed this approach to post process and analyze the data.

*Online*

During the Training Phase, the user needs to use the sensor to touch the desired body parts. Then, the EMG sensor data and the capacitive sensing data are recorded over duration of about 2.5 seconds with a sampling rate of 100 Hz, to create an FFT with [0,127] channels out of one instance with a window size of 256 values. During the Prediction Phase, the live data stream is constantly compared with saved patterns from the training phase while applying a "*Fast Correlation-Based Feature*"-like algorithm [Hal99] to find similarities. While tapping can always be detected immediately, the identification of a body part takes ~500ms but can last up to ~2.5s in this setup. Nevertheless, there is a trade-off between speed and accuracy in recognition.

*Offline*

Based on the experience of our previous test, in the Training Phase we now reduced the window size down to 64 values to create a quicker FFT with [0,31] channels. We recorded each training set (which is a position on a body part) with a sampling rate of 60 Hz over duration of about 11 seconds, to separate 10 instances. Broader window sizes, more instances or higher sampling rates did not provide better results. To not lose information, we waived on applying any filters and then defined 6 features, which provided high separation sharpness on the raw data:

- **Signal Energy**

$$P_{Signal} = \frac{1}{N} \sum_{n=-1}^{n=1} | x_n(f)|^2$$

- **Number of Mean-Crossings**

$$MCR = \frac{1}{T-1} \sum_{t=1}^{T-1} \| \{A_{Window} - A_{Mean}\}$$

- **Summed Second Highest Amplitude**

$$2ndA = \sum_{n=-1}^{n=1} | max_2(A_{Window})|$$

- **Summed Third Highest Amplitude**

$$3rdA = \sum_{n=-1}^{n=1} | max_3(A_{Window})|$$

- **Summed Delta of Highest Frequency in Noise Area**

$$\Delta HighestNoiseAmp = \sum_{n=-1}^{n=1} | \partial_{max\,(A_{Noise})}(f)|$$

- **Signal-to-Noise Ratio**

$$SNR = 10log_{10}\left(\frac{P_{Signal}}{P_{Noise}}\right)$$

The recognition is detailed in the following section.

### 4.1.5 Evaluation

To discover the system's capabilities, we sequentially conducted several tests in which we investigated the cross-user compatibility of the system (**T1**), the distinguishability between 8 different body parts (**T2**), the resolution of each body part in a range of 1.5, 3, 5, 7, 9 cm (**T3**) and the recall accuracy overtime (**T4**).

#### 4.1.5.1 Participants

We recruited 10 participants (1 female) with an age of 24-33 (*M*=27.2). Their height was 1.72-1.98m. All participants were within +/- 10% of their body-mass index and thus optimal for our evaluation to ensure a possibly higher comparability. Among all participants, one participant rejected measurements to be performed on her thigh. **T4** was performed with only one participant.

#### 4.1.5.2 Procedure and Task

For the evaluation, we first marked the recording areas on the user's body parts, as shown in Figure 42. Then, we mounted the contact electrodes on a separate Velcro tape, which was long enough to be fixed tightly to the user's body, to avoid potential irregularities due to the shifting of the sensor. The user was instructed to sit still and not tensing any muscles. Even if some spots are different for each user, such as the finger already ends at 70mm, we decided to still measure the 90mm spot – in this case, on the hand palm. For each user we recorded the raw data in a CSV file and concurrently generated an ARF feature file.

**Figure 42. Tested areas: (1) calf, (2) finger, (3) upper arm, (4) palm, (5) back of the hand, (6) forearm, (7) thigh & (8) belly.**

#### 4.1.5.3 Classification

To determine a classifier, we analysed the feature files with the *Weka data mining tool* v3.7.11 [HFH+09]. For each user we compared all 8 body parts against each other with 5 state-of-the-art classifiers, which we found suitable (*see Figure 43*). To understand the classifiers theoretical performance level, we applied a 10-fold cross validation, but which did not yield any statistical differences as shown by an *ANOVA for correlated samples* ($F_{4,36}$ = 1; $p$=.42). To achieve a more realistic impression on the recall rate, we furthermore applied a leave-one-out method, but which did not show any differences either ($F_{4,36}$ = 1.29; $p$=.29). Also the *Weka's* percentage split of 66% did not yield any significant differences ($F_{4,36}$ = 2.21; $p$=.09). Based on the performances we chose the *Bayes Net* because of its slightly lower standard deviation & comparably high mean.

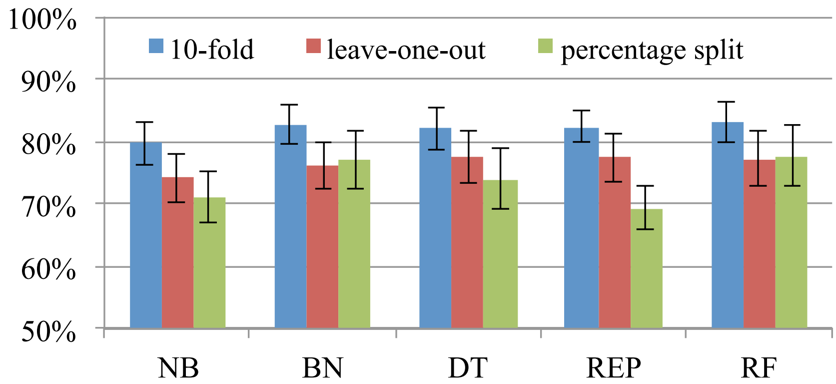



**Figure 43. Classifier performance of *Naïve Bayes (NB)*, *Bayes Net (BN)*, *Decision Table (DT)*, *REP Tree (REP)* and *Random Forrest (RF)*. Error bars are .95 confidence intervals**

#### 4.1.5.4 T1: Cross-User Compatibility

Different users demonstrate different physiological properties, including thick / thin / dry / oily skin, more / less evolved muscles or fat and water sedimentations. Our data also confirmed that it is not possible to train a generic classifier that works for all users. A leave-$k_{User}$-out ($k$=5) cross validation with a *Bayes Net* classifier results in an overall recall rate of 16.1%, due to massive confusions. Therefore, it seems very unlikely that data from one user could be used for another user. It suggests that the system indeed needs to be trained using personal data for each user.

#### 4.1.5.5 T2: Identification of Body Parts

To achieve an overall impression on the recall accuracy of the identification of body parts, we generated a leave-$k_{Instance}$-out ($k$=5) cross validation with the *Bayes Net* classifier for each user, since a cross-user compatibility is not given. The training and test sets have been separated out of the 10 collected instances. The results for all users are summed up together in Table 6.

| a | b | c | d | e | f | g | h | < classified as |
|---|---|---|---|---|---|---|---|---|
| 82% | - | 10% | - | - | - | 1% | 7% | **a** = calf |
| - | 93% | - | 2% | - | 3% | - | - | **b** = finger |
| 9% | - | 69% | 1% | 12% | 3% | 5% | 1% | **c** = upper arm |
| - | 3% | 2% | 82% | - | 5% | 8% | - | **d** = palm |
| 1% | 8% | 9% | 3% | 73% | 4% | - | - | **e** = hand back |
| 1% | - | 5% | 7% | 3% | 80% | - | - | **f** = forearm |
| 10% | 1% | 8% | 14% | - | 6% | 54% | 7% | **g** = thigh |
| 6% | 13% | - | - | - | 4% | 12% | 59% | **h** = belly |

**Table 6. The Confusion Matrix shows all identified instances in percentage (rounded) per body part.**

While the upper arm, belly and the thigh have been confused more often; the finger, palm, calf and the forearm seem to be reliably recognizable. Discarding problematic locations, such as the belly and thigh, would even further improve the overall recognition rates.

### 4.1.5.6 T3: Resolution within Body Parts

To ascertain the resolution of each body part, we assume the ideal case that only 2 spots are being trained. Because we had 5 distances of 15, 30, 50, 70, and 90 mm from our reference point, we had to generate 395 confusion matrices (400-5 on the thigh since one participant did not agree to be measured on her thigh) in which we were comparing a Bayes Net with a percentage split (33%) algorithm to find out about possible confusions. A leave-one-out algorithm would require 3950 matrices that are beyond practicality. The accuracy of each matrix has been summed up below.

When only comparing 2 trained spots at a single body part, the distinguishability is quite clear. In a more realistic context with multiple locations on multiple body parts, the recognition accuracy may not be as high as shown in Table 7, which is a best-case scenario. However, given the relatively heterogeneous structure of our hand, it is still possible to distinguish spots by a distance of only 15 mm on the palm. Although resting potentials, capacitances and the surfaces vary in most parts of our body; they are less differentiable for more homogeneous body parts, such as belly, calf and thigh. Our tests indicate that the distinguishability within a body part is affected by the degree of homogeneity of the underlying body structure.

| 15 | 30 | 50 | 70 | 90 | < distance |
|---|---|---|---|---|---|
| 78.5% | 86.3% | 86.5% | 95.4% | **95.9%** | calf |
| 92.3% | 94% | 99.2% | **100%** | **100%** | finger |
| 91.4% | 96.5% | 95.4% | **99.2%** | 95.7% | upper arm |
| 95.4% | 95.4% | **100%** | 94.9% | 95.7% | palm |
| 96.2% | 96.2% | 93.8% | 97.7% | **100%** | hand back |
| 87.7% | 94.6% | 94.6% | 93.8% | **96.6%** | forearm |
| 77.9% | 83.8% | **96.6%** | 94.9% | 91.5% | thigh |
| 85.6% | **86.5%** | 86.2% | 76.1% | 77.8% | belly |

**Table 7. Resolution of body parts: The percentage values are the probability for our system to distinguish two points for the given distance and body part.**

#### 4.1.5.7 T4: Recall Accuracy Over Time

While performing tests over time, we found out that the electrical signature tends to vary slightly. A complete study on this phenomenon would require more precise apparatus, such as clinical EMGs, and would be very complex in terms of logistics. Nonetheless, to gain an impression on how the system theoretically performs over time, we recorded data of all body parts for one test subject over two days at random time points. For a first analysis (*see Figure 44 – red line*), we took the initial recorded signature as a reference pattern and compared all later recordings with a 10-fold cross validation (Bayes Net classifier) against it.

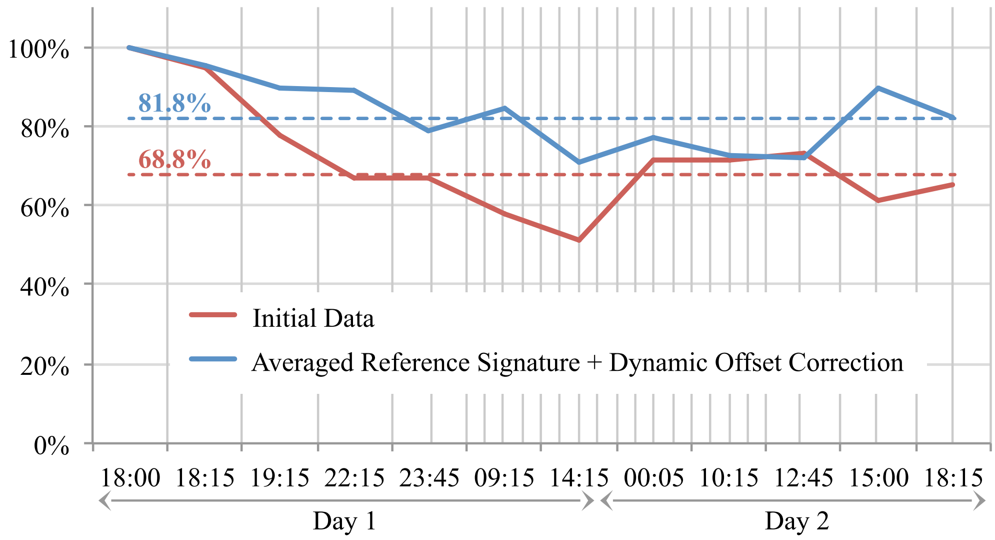



**Figure 44. The curve extending over two days (note: x-Axis is not linear). We conducted a 10-fold cross validation with the *Bayes Net* classifier over the data set. Overall accuracy: initial data (red - 68.8%) and corrected (blue - 81.8%)**

The accuracy (*see Figure 44 – red line*) decreases quickly after a few hours to an average of 68.8%. We suspect that mainly sweating but also *Microvibrations* [Roh64], environmental temperature, and the way the sensor is being placed on the skin have an impact on the measured electrical signature. While we could see some unknown variation to occur, we could also determine an offset change of the signal energy.

To ensure an accurate recognition of all body parts over time, the profiling of a person needs to take multiple references points (e.g. from the morning / lunch / and evening). Furthermore, we can make use of an additional reference sensor, which provides us the current skin resistance, to calculate a dynamic signal offset correction. By applying this last correction, we were able to achieve a recall accuracy of 81.8% (*see Figure 44 – blue line*) for our data, which is a more acceptable accuracy. Another improvement that could be done would be to measure the temperature of the electrode, which has an impact on its current conductivity.

### 4.1.6 Wearable Interaction with Botential

The ability to detect input gestures on various body parts allows *Botential* to support a variety of quick interactions in mobile context, which demand little user attention. These can range from *Microinteractions* [Ash10] to *Reflexive Interactions*, depending on the chosen interaction design. Interacting with *Botential* can be performed eyes-freely or hands-freely due to proprioception. Making use of such technology, users can achieve hands-free interaction either with their forearm or leg if their hands are occupied with activities, such as carrying groceries or riding a bike. Interaction with *Botential* can be performed by either touching the wearable device with various body parts (such as placing the finger, palm, or wrist on a necklace) or moving the wearable device to contact the various body parts (such as moving a ring on the finger to touch the arm, chest, or the leg). Below, we detail how *Botential* can be integrated into five common wearable objects to enhance such mobile interactions (*see Figure 45*).

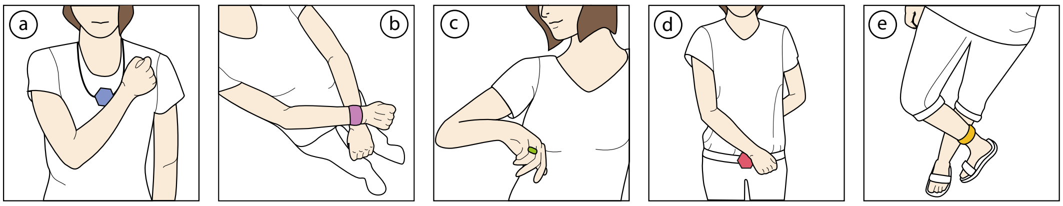



**Figure 45. *Botential* leverages the entire human body as an interactive surface, while enabling the identification of tap gesture locations on different body parts and a hovering through the clothes. It is conceivable to integrate this technology with various wearable objects, such as a) Necklace b) Bracelet c) Ring d) Belt and e) Legband.**

*a) Torso (Necklace): Botential* can be worn as a necklace (*see Figure 45-a*). In this configuration, the wearer can interact by touching the device with the fingers or sliding the palm on its surface. Considering a scenario where the wearer is in a meeting or having dinner, a tap on the necklace with the hand could reject a call, while a sliding with the forearm could send the caller a predefined "*I'm busy*" message.

*b) Wrist (Wristband or Watch):* Integrating a *Botential* unit in a wristband (*see Figure 45-b*) enables two different interaction styles: directly interacting on the wristband with the other arm or tapping, sliding, and hovering above other body parts (e.g., the belly). This method still supports hands-free interaction, which is desirable when holding things in the hands. The user can assign different functions to different body parts. For example, while jogging, the user could invoke the play/pause music command by tapping, or change the volume by sliding on the belly. Since the arm is the most agile part, putting the device on it ensures access to many distinct body parts.

*c) Finger (Ring):* Integrating *Botential* into a ring (*see Figure 45-c*) allows a wide variety of subtle gestures. Since the hand is a highly agile part of the body, it is possible for a user to tap on almost any body part, except the back, which is hard to reach. Since touching body parts with our hands can be performed eyes-freely, this kind of interaction would be very useful in scenarios where visual attention is already committed to real world tasks, but hands are not occupied.

*d) Waist (Belt Buckle or side of the belt):* Attaching the device to a belt (*see Figure 45-d*) enables similar interactions as those on the torso. Mounting the device on the hip also makes it possible to interact with the whole forearm without the need to wear a device on the arm itself. This can be useful in everyday situations when carrying heavy grocery bags, and a binary input, through a tap with the forearm on a belt, is sufficient.

*e) Leg/Foot (Legband or Shoe/Sock):* Attaching the device as a legband at the thigh enables a user to slide or tap with the hand or wrist on the upper leg. Attaching it to the lower leg or to the shoe/sock enables natural leg gestures (*see Figure 45-e*), where the user can slide, hover, or tap using one leg on the other. Leg gestures can be executed in a subtle way and are also useful when both hands are occupied, for example, when holding on to the handgrips in a bus or a train, or when typing on a keyboard. In these situations, it is easy to use tap gestures for discrete commands and to slide one leg on the other.

#### 4.1.6.1 Technological Advantages and Limitations

*Botential* significantly enhances the ability to sense soft, hard and long touches. The pressure applied to the sensor on the skin does not affect the signal, unless it is really squeezed or almost not touching the skin. The system is also robust against commonly environmental influences, such as vibrations while driving or varying lighting conditions. While technology is evolving, such sensor type unit can be easily embedded into a wearable device. When integrated into a wearable object, the system can be used to interact on a large body area, as long as the sensor can reach it. For example, wearing *Botential* on the forearm, wrist, or hand allows interaction with most body parts, except where limited by the user's range of motion (e.g. the ability to reach a certain area on the back). Additionally, the detection of the hovering state enriches the type of interaction one can perform with the body. Although the current implementation only provides information about distance and no indication of the body part being hovered, hovering can be used as an additional design channel to create a buffer state between no action and committed action.

Like any other technology, *Botential* has its own constraints. First, to correctly identify the body part being tapped, the electrodes need to be in direct contact with the skin. Secondly, the measurement on the skin is influenced by intrinsic factors [RHM06], such as blood flow or sweat, which typically affects electrical resistance. However, this can be mitigated with additional sensors that monitor the skin resistance and make appropriate adjustments to the system. External influences, such as electrical surface charging of the skin, such as when being in an electrostatic environment (e.g. server room or fluffy carpet) can affect the signal. Also excessively heavy touches and abrupt movements can make the signal hard to interpret. While variation of the signal over time may seem impractical, we want to emphasize the fact that we still found great similarities in the signal after two days without any recalibrating and a future intelligent system would have the ability to learn and recalibrate itself while being used. Moreover, the accuracy of detection dramatically increases as the number of assigned body locations decreases.

While our study revealed electrical signatures to be user dependent and to slightly vary over time, broader studies with clinical EMG devices and a larger population are required to decrypt the human property of electrical potential and capacitance measurable on the skin. In addition to using an EMG sensor, we may also need to utilize a different sensor. For instance, our prototype also incorporates capacitive sensing to improve recognition and to enable the detection of hovering events, although detecting the exact location of the hovering event is not currently supported.

#### 4.1.6.2 Discussion

Embodied Interaction [Dou04], such as on-body interaction [HRH12] is an interesting approach to meld human and computer together. Leveraging the human skin has several advantages, such as a stretchable, large and heterogeneous surface of about two square meters [BB95, Ric04]. Nevertheless, it is arguable whether interaction on the body is suitable and socially acceptable. Especially when interacting in public with conspicuous gestures, social awkwardness might be pronounced [RB10]. However, this may change as making a call by talking to thin air with a Bluetooth headset also became socially acceptable over the past years. Still, touching different locations on the body has mental associations, which differs by culture backgrounds and disables specific body parts to be used as interaction interfaces, such as the collarbone [PCG+13] or breast.

Multi-user input on the skin of another person is also an interesting scenario to investigate, which conveys rich emotional connections and meanings [HHMK09]. It is to assume, that personal interaction, which is usually accomplished with personal devices (e.g. a smartphones), could be enriched with interaction of one's own skin, rather than using somebody else's skin. Nevertheless, having additional input space available on one's body, might change the perception and probably decrease the aversion of being touched by acquaintances. When offering multi user input, we also have to think on how to design rules to regulate interaction for certain user groups such as strangers.

Thirdly, it is still unclear how *Botential* should be used on the full-body scale, whereby most of the body parts are often occluded with clothes. As already stated, we envisioned *Botential* to be integrated into several everyday wearables. However, we think integrating in a wristband is most beneficial to extend current devices. This would enable the user to interact on each body part reachable with their hand, but especially the forearm and hand, which are the most preferred locations for on-body interaction as found out in a rigorous study by Weigel et al. [WMS14].

### 4.1.7 Botential Field Study

Designing novel interfaces is facing several challenges; an important one is creating interaction concepts that are neither uncomfortable nor socially awkward to the user. Social awkwardness can quickly occur while performing circuitous gestures or touching specific body parts in certain context. Previous research has revealed that tapping on the belt [RB10] or the wrist [PCG+13] tends to be more acceptable than a touch close to the face. To verify *Botential's* ability to complement current input modalities for mobile scenarios, we ran a study to compare two different approaches: using *Botential* to perform on-body gestures vs. the default interaction method of Google Glass, by touching its frame. We recruited 40 participants (14 females, aged 18-52, $M$=27.2). Participants had to wear a Google-Glass-like device running a photo application. To interact with it, 20 participants used the interactive frame and the other 20 used the *Botential* worn on the wrist.

**Figure 46. The first condition requires the user to raise the hand up to the head and touch the frame of the PHMD. The second condition allowed for tapping the wrist at the body, while using an early *Botential* interface.**

We let the participants familiarize with the application and explained to them how to take pictures (by tapping on their body or on the frame), switch to picture display mode (with a long tap), and how to browse through pictures (by sliding on the frame or tapping/double tapping with *Botential*) with the assigned input device. Participants then had to fill out a custom questionnaire, in which we asked them to rate on a Likert Scale from 1 to 5 whether it would make them feel awkward to interact with either the frame or *Botential* (*see Figure 46*).

Because both input interfaces follow a slightly different interaction strategy, it is interesting to find out whether the two groups also perceive the task differently. Therefore, we additionally measured the *NASA Task Load Index* of each participant. The *NASA TLX* [HS88] results did not yield any significant difference between the two input devices for any of the 6 criterions ($p$>.05), thus both groups experienced the performed task quite similar in terms of Mental, Physical and Temporal Demand, Performance, Effort and Level of Frustration, which indicates the comparison to be valid.

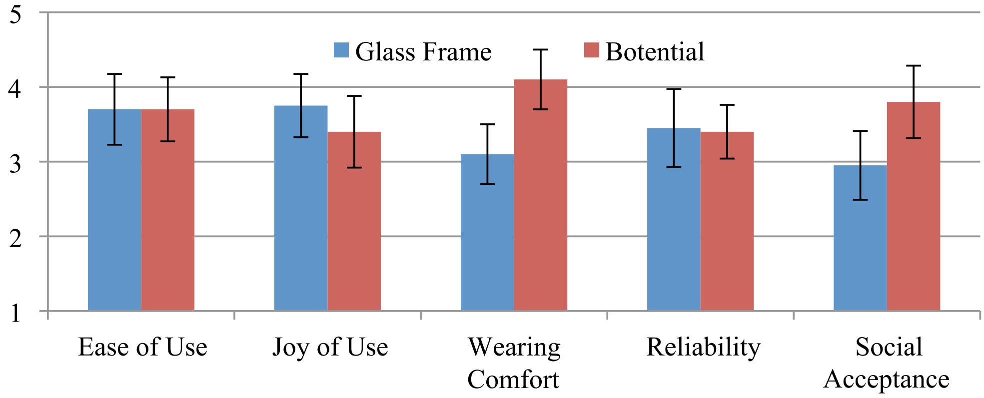



**Figure 47. Results of the Custom Questionnaire. Error bars are .95 confidence intervals**

As seen on Figure 47, our results suggest that users felt interacting with *Botential* ($M_{Botential}$=3.8/5) was significantly more acceptable (confirmed by a Mann Whitney test; $U$=285, $n_1$=$n_2$=20, $p$=.01) than interacting with the frame ($M_{Frame}$=2.95/5). The study confirms that lifting the arm towards the head and exerting pressure on a glass frame is being significantly ($M_{Frame}$=3.1/5, $M_{Botential}$=4.1/5, $U$=309, $n_1$=$n_2$=20, $p$<.001) perceived as more unpleasant than a subtle and natural gesture such as tapping the wrist, belly or touching the side of the leg. Furthermore, participants also suggested these discreet gestures to be suitable to be performed during conversations and other social occasions.

#### 4.1.7.1 Outlook

Wearable devices such as Google Glass are becoming increasingly available to the general public. The major difference between HMDs and current mobile devices is the always-available visual output that allows users to perform quick tasks while on the go. The interaction paradigm on such products usually relies on either speech input, which might not work in noisy areas, or on simple gestures on the device's frame. In scenarios such as important business meetings, voice input or interacting on the glass frame can be less desirable. Alternatively, for these cases, a subtle touch on the side of the leg can be much less obvious and more socially acceptable. We envision *Botential* also to be integrated into smartwatch wristbands, such as from Apple Watch, which would complement these devices with a broader input space and alternative input paradigms.

### 4.1.8 Conclusion

In *Botential*, a novel proof-of-concept is being proposed to enable hands-free and eyes-free mobile input that uses the human body as an extended input space. By sensing electrical signatures on the skin it has shown how to utilize the existing signal the human body already emits, which is different from previous approaches and nicely complements those. While making use of proprioception and our ability to execute movements in our motor periphery in a quick manner, *Botential* enables a *Reflexive Interaction*.

While not just detecting the presence of a touch, but also recognizing a number of locations on the body, designers can assign different meanings to localized areas, which significantly increases the number of commands one can associate with on-body interaction. However, in order to stay within the boundaries of a *Reflexive Interaction*, we would need to stick to a small number of assigned body parts, which can be easily internalized by the users. Furthermore, to increase an intuitive and natural use, our prototype also supports the detection of hovering events, although detecting the exact location of the hovering event is not currently supported.

While our field study demonstrates quick tapping on the body to be a promising *Reflexive Interaction* technique that is also socially acceptable, it remains an open question how many body parts one can assign and still being able to recall them in a fraction of a moment without overthinking. Although a successful *Reflexive Interaction* apparently requires a learning time, it is not very likely the user to be able to recall a two-digit number of on-body tapping gestures.

## 4.2 [FEEDBACK] On-Body Feedback

New computational devices, in particular wearable devices, offer the unique property to be always available and thus to constantly update the user with information, such as by notifications. While research has been done into sophisticated notifications, devices today mainly stick to a binary level of information, while they are either attention drawing or silent. This project, goes a step further and proposes scalable notifications, which adjust the intensity reaching from subtle to obtrusive and even going beyond that level, while forcing the user to take action. Because subtle notifications are aimed to not disturb the user, they favour the concept of a *Reflexive Interaction*, while not disturbing the primary task. To illustrate the technical feasibility and validity of this concept, three prototypes providing mechano-pressure, thermal, and electrical feedback have been developed and evaluated in different lab studies. The first prototype provides subtle poking up to high and frequent pressure at the users' spine, which creates a significantly improved back posture. In a second scenario, the users are enabled to perceive the overuse of a drill by an increased temperature at the palm of a hand until the heat is unbearable and the users are forced to eventually put down the tool. The last project exhibits a speed control at a driving simulation, while electric muscle stimulation at the users' legs conveys information on changing the car's speed by a perceived tingling until the system independently forces the foot to move. Also forcing the user to subconsciously considering a notification, such as by quickly forcing the user's foot to press down the gas pedal is envisioned to support a *Reflexive Interaction*. Although the selected scenarios are far away from being realistic, these lab studies can be seen as a means to validate this proof-of-concept. In conclusion, all studies' findings support the feasibility of the concept of a scalable notification system, including the system to force an intervention. A *Reflexive interaction* relies on subtle feedback that is just on the threshold of recognisability by still not disturbing the user's primary task. Moreover, a future system would automatically scale the feedback to an appropriate level, based on contextual factors and also based on the urgency of information.

### 4.2.1 Introduction

An essential property of ubiquitous computing [Wei91] is the omnipresence of computers that occur in all kinds of shapes, such as wearable computers [Man01]. The high availability of wearables resting at the human body during all day times is unique and allows to constantly convey information. Nowadays, using notifications to keep the user up-to date is an integral part of many wearables, such as smartwatches notifying the user about incoming messages, calls, activity goal, calendar events, alarms, etc. [SHD+14] Many new types of future wearables, for instance smart insoles, may substantially expand the range of features beneficial for users with special needs, such as elderly people or diabetics, while notifying them when entering dangerous grounds [MRKU17], or when dangerous foot postures occur [EFM+11]. While the sensing part is already technical feasible, we need to ask the questions: *How can we convey such information context-appropriate to the user and how can we possibly intervene in an interaction scenario?*

In this project, we sketch possible answers by introducing the concept *Scaling notifications beyond alerts* – a scalable notification system that on the one hand provides very subtle feedback to the user and on the other hand can intervene and force the user to take action. While subtle notifications may be quickly overlooked or intentionally ignored without great effort and disruption, these types of notification are suitable for less important information. However, there may be very urgent notifications, such as important information to keep ourselves healthy. These notifications should be a level beyond obtrusive, in a way that it cannot be overlooked and we are possibly forced to take action.

### 4.2.2 Related Work

As summarized earlier, the human possesses a variety of senses, however, considering this specific area of the body, we can only rely on Tactioception, which is the sense of touch. While Thermo- Mechano- and Nocio- Reception is pronounced at this body zone, we are limited to haptic sensation, but which also incorporates heat, cold, pressure and any other sensation based on touch. The term haptic technology was introduced in the late 1980's to define the aspects of human-machine touch interaction [EOEC11]. Currently, the term has brought together many different disciplines, including biomechanics, psychology, neurophysiology, engineering, and computer science, to refer to the study of human touch and force feedback with the external environment. Haptic interfaces are generally divided into two different classes: tactile and kinaesthetic. The first one provides external stimuli basically on the skin through a device. In contrast, kinaesthetic is related to stimulation of muscles, joints or tendons. Some typical kinaesthetic device configurations are manipulandums, grasps and exoskeletons. This can be demonstrated with electrical muscle stimulation (EMS) such as demonstrated by Lopes et al. [LIM+15]. In terms of haptic sensation, related work demonstrates vibrational (also denoted as vibtrotactile) feedback to be frequently used for providing alternative feedback, because it is highly noticeable, since it yields very unusual sensation [RPZ15]. Having a look at use cases for haptic feedback, we can often find navigation scenarios, in which alternative feedback is being applied. The motivation for this is twofold: on the one hand researchers try to help visually impaired users and on the other hand we believe an eyes-free interaction to be especially beneficial when the user is on the go or occupied with other tasks. Quick eyes-free feedback can especially help when aiming for designing a *Reflexive Interaction*.

#### 4.2.2.1 Vibrotactile Feedback used for the Purpose of Navigation

As stated before, navigation scenarios belong to the most frequently used scenarios in research when dealing with alternative feedback in *Wearable Computing*. Even though verbal cues can provide more accurate commands than vibrotactile feedback for spatial guidance [WSH+11], impaired users like deaf or blind people [BF02] cannot profit from commonly navigation aids. These user groups have an urgent need for assistance when moving in unknown public spaces. Assistive technologies could be wearables such as belts, wristbands, and shoes, which are always available at the user's body anyway.

##### 4.2.2.1.1 Handheld Device

In *I did it my way* from Robinson et al. [RJE+10] or *NaviRadar* from Rümelin et al. [RRH11], the user is required to hold a smartphone or a similar device in their hand to perceive vibration, which conveys the idea of the angle in which the user possibly needs to turn. In *Traxion* [Rek13], Rekimoto proposes a handheld actuator (made of an electro-magnetic coil, a metal weight and a spring) to use a virtual force as a virtual pathfinder. In *Tacticycle* [PPHB12, PPB09], they rely on the fact that certain tasks such as riding a bicycle, in which the user already needs to touch objects or devices, such as the handle bar of a bike. Therefore, vibration motors are attached to both sides of the handle bar, thus enabling navigation assistance. However, we consider hand-held devices as guidance for pedestrians to be highly impractical, since they possibly need to be held in a certain position and therefore hinder the user from accomplishing real world tasks.

##### 4.2.2.1.2 Smartphone in the pocket

While the smartphone is resting in the pocket, it is not obtrusive to the user, but enables the user to understand different vibration patterns on their thigh through worn clothes. Drawbacks are that angle data cannot be transmitted efficiently and users have to learn the specific vibration patterns, which are assigned to actions. This concept has been implemented in *PocketNavigator* [PPB10] and *Navibration* [BKLS13].

##### 4.2.2.1.3 Wristband

Another example of using on-body vibrotactile feedback for navigation, which is hands-free, is using an arm-/wristband as proposed by Kammoun et al. [KJG+12], Brock et al. [BKMJ14] or Panëels et al. [PBS13]. In the wake of the emergence of smartwatches, this position appears to be an area that seems interesting for further investigation. However, it is still an extra accessory which one would have to wear.

##### 4.2.2.1.4 Belt

Compared to related concepts, vibrotactile belts have been very widely explored. In 2004 Tsukada et al. [TY04] proposed *ActiveBelt*, a belt and haptic feedback system with 8 vibration motors attached in a 45° angle, to accomplish a GPS navigation via vibrotactile feedback. Basically, the same setup was presented by Van Erp et al. [VVJD05], which showed promising results for the evaluation of two navigation scenarios on a boat and in a helicopter. A pedestrian navigation of a vibrotactile belt was evaluated by Heuten et al. [HHBP08] and Zöllner et al. [ZHJR11]. Recently, Cosgun [CSC14] additionally utilized a human motion tracking to provide accurate path navigation with a vibrotactile belt. Tactile navigation for cyclists has also been explored recently by Steltenpohl et al. [SB13].

##### 4.2.2.1.5 Jewelry

In 2001, IDEO introduced the concept of a wearable technology in the form of jewelry. In *Technojewelry* [IDE01], a vibrating ring is being proposed to be worn at the user’s finger or toes, which is able to give directions through vibrations via a GPS connection. *Pull-Navi* [KHFK09] describes future earrings, which are able to give directions through haptic force as well. In contrast to the previous project, *Pull-Navi* also presented a working prototype, which was rather cumbersome, but informally tested with about 100 participants. Nevertheless, this technology is still obtrusive due to size factors.

#### 4.2.2.2 Other on-body Feedback used as Assistive Technology

In this section, I introduce recent literature on on-body feedback used as a wearable assistive technology. The projects are separated into two subsections: Limbs and Torso.

##### 4.2.2.2.1 Limbs

In *HaptiColor* [CCP+16] a wristband encodes colour into vibrotactile patterns, and embeds three vibration motors. Colours are encoded using their proximity to the nearest vibration motors. The prototype has been evaluated with six colour-blind participants, while the results show just three motors to ensures an accuracy of up to 95%. Very recently, Chinello et al. [CPTP16] attached four cylindrical servo motors to a bracelet. While the motors experience a rotation movement the skin is being stretched, which provided unique on-body sensation to the user. Also very recently, Huisman et al. [HFvEJH16] attached a vibrotactile array at the inner side of the lower arm that generates gentle stroking touches in order to produce pleasantness responses. The results of their study clearly indicates that the velocity significantly the affects the perceived pleasantness. In addition, it has shown that low intensity stimuli are being perceived more pleasant than high intensity stimuli. Chen et al. [CCCY16] recently built a motion guidance sleeve, which generates subtle pulling motion of the forearm based on stepper motors, which move fishing lines and elastic bands. The sleeve is aimed to imitate a muscle contraction to drive the forearm to rotate. The authors achieve the illusion of an external artificial muscles that pulling the user's arm. Lopes et al. [LIM+15] go even a step further and use electrical muscle stimulation (EMS) in order to stimulate and contract the arm muscles to create a kinaesthetic force feedback. Computer-driven arm movements are the result.

##### 4.2.2.2.2 Torso

Probably the most frequent form factor for vibrotactile feedback at the torso is the belt prototype. It is mostly used for navigation purposes either for pedestrians [TY04] or drivers, such as cyclists [SB13] etc. (*see also previous section*). Another interesting form factor, covering the whole body, is a jacket / vest. A haptic jacket has been proposed by Arafsha et al. [AAE15], which incorporates several actuators, such as motors, heating elements, etc. The developed system is designed for six basic emotions: love, joy, surprise, anger, sadness and fear. It also supports interactions such as hug, poke, tickle or touch all over the body (neck, chest, belly, upper arms). Kon et al. [KNSK16] investigated the *Hanger Reflex* on the waist when walking. The *Hanger Reflex* is a phenomenon that produces a fictitious force and involuntary rotation of the body using skin deformation. This haptic-induced force illusion is previously known to occur at the human head, which rotates unexpectedly when the frontal region and the opposing rear region are pressed using a wearable device. Kon et al. used a u-shaped aluminium-ring, which is moving around the body and subtly making the user to take turns according to the position of the waist ring. Similar concepts, providing subtle notifications favours a *Reflexive Interaction*.

#### 4.2.2.3 Forms and nuances of notifications

Notifications in mobile HCI usually stick to a non-complex level of information, which potentially enable the user to quickly recognize them, which is the key characteristic of a *Reflexive Interaction*. Nevertheless, notifications appear in many forms, while being pronounced in different nuances. When it comes to mobile computing, thinking in particular of smartphones, most common notifications include visual pop-ups and accompanying vibrations. Especially vibrations appear to be highly noticeable [RPZ15] in comparison to alternative feedback types. This may be the reason why vibration is historically grown to be a popular feedback type for mobile and wearable devices. A very common use case in research includes navigation aid for visually impaired users. However, eyes-free interaction can also be beneficial for healthy users such as when being on the go or when being occupied with other real-world tasks. Depending on the design, notifications yield the power to convey binary as well as minor complex information to the user in quick manner, with or without obstructing the user from his primary task.

As demonstrated in Figure 48, notifications can appear in different forms and nuances. While they can be binary, such as an LED being switched on, notifications can become complex, such as when increasing the dimension (e.g., 2D or multi-dimension array of LEDs), when using patterns (e.g., Morse-code blinking LED), and when varying intensity (e.g., brightness or colour of an LED). Combining all those attributes increases complexity of a notification, which on the one hand enables for an increased density of information level, but which on the other hand may be very attention drawing and thus likely to obstruct the user in his primary task, since cognitive load may be high. While this example demonstrates visual feedback, we can also convey this to other feedback channels, such as audio feedback (dimension: channels; pattern: frequency; intensity: amplitude), tactile feedback by vibration motors (dimension: number of motors; pattern: sequences; intensity: power), etc.

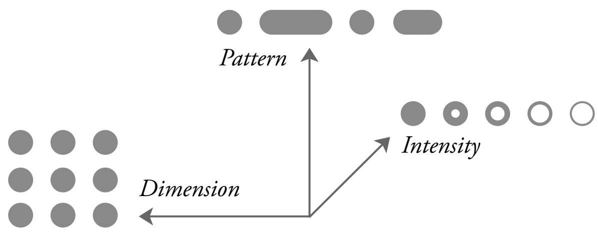



**Figure 48. Illustrating the complexity of notification forms and nuances. Most common variations based on literature rely on dimension, patterns and intensity. Combining the different properties result in more complex notification designs.**

Research presents a great variety of those variations that are based on vibrotactile notifications, which for instance can assist visually impaired people, such as for the use case of pedestrian navigation. In the following, we present examples demonstrating all three directions: dimension, pattern, intensity.

#### 4.2.2.3.1 Dimension

Feedback can be distributed spatially in a single- or multi-dimension. Feedback on a single dimension could be, for instance, a single tone, a single LED, or a single vibration motor. Furthermore, we can increase the quantity of actuators and thus the dimension. In research, we can find various examples for that, such as an array of vibration motors surrounding the user's wrist to provide notifications for spatial guidance [WSH+11], while only one vibration motor is actuated at once. A similar concept is proposed with ***ActiveBelt*** [TY04], a notification belt incorporating 8 vibration motors attached in a 45° angle, to accomplish navigation for pedestrians, when riding a bike [SB13], and when driving a boat and flying a helicopter [VVJD05].

Thus we can say, increasing the dimension, such as spatially distributing actuators, in particular vibrotactile actuators, can be beneficial when conveying binary and low-complex notifications, such as for spatial navigation

#### 4.2.2.3.2 Pattern

Conveying notifications beyond the complexity of binary stages, we can utilize patterns over time. For instance, within a low dimension of a single actuator, such as using the vibration motor of a smartphone. ***PocketNavigator*** [PPB10] and ***Navibration*** [BKLS13] both propose exploiting such one-dimensional vibration patterns for a pedestrian navigation, while the smartphone rests in the user's pocket. Actions, such as directional cues are assigned to very specific vibration patterns, which are required to be learned by the users. Other typical examples include the ***Morse-Alphabet*** [Car86], which is usually transmitted via visual or audio feedback. In contrast, a multi-dimension setup, such as with a two-dimensional array of vibration motors, allow to convey more complex notifications on the one hand. However, arranging actuators in a 2-D space also allows to perceive spatial stroke patterns, which are on the other hand easier to recall by the user. Such spatiotemporal vibrotactile patterns are investigated at different body parts, such as arm, palm, thigh and waist in ***OmniVib*** [AZP+15]. Similar works investigate multi-dimensional vibrotactile patterns on other body parts, such as at the foot [MMUW15, VBV+12].

Although notifications can be conveyed in many other ways, recent literature presents extensive investigations on vibrotactile patterns for notifications

#### 4.2.2.3.3 Intensity

Another possibility to expand the density of information is to adjust intensity of notification. By a change of intensity, we mean sounds to play lauder, LEDs to shine brighter, vibration motors to actuate stronger, etc. For example, changing intensities of vibration motors has been demonstrated in *HaptiColor* [CCP+16], in which a wristband encodes colours into vibrotactile patterns. Other works that exhibit tactile feedback is presented by Huisman et al. [HFvEJH16] who attached a vibrotactile array at the inner side of the lower arm that generates different intensities of stroking touches in order to produce emotional responses. Intensity of sensation especially plays a role when applying thermal feedback, such as at the head [PCM16] and when trying to create emotional feedback, since users demonstrate different threshold of sensibility [AAE15]. Next to haptics, we can of course also vary intensity for other types of feedback, such as taste interfaces [RNNG12].

While the human possesses a variety of senses, which are all set individually by nature, adjusting intensity individually, regardless the type of feedback, may be an important adjustment screw to improve user experience with notifications.

### 4.2.3 "Scaling Notifications Beyond Alerts"

Notifications play a major role in mobile computing, while we can use them to support *Reflexive Interaction*, when they stick to a very low level of complexity.

A unique characteristic of notifications is that they can instantaneously provide us with information at any time. While this is certainly beneficial to the user, there are also drawbacks. One well-known problem is based on the user's attention resources, which are limited, but often demanded when notifications suddenly pop up. At this point an ongoing primary task, such as driving a car, may be interrupted, which yields potential danger. In other situations, a user may perceive notifications to be annoying or highly disturbing, such as when lying down for sleep.

*Considering context.* To reduce interruptions, researchers propose to consider context, such as environmental changes [KS03], the user's emotional state [Liu04], and the user's activity level [HI05]. For instance, Ho and Intille [HI05] conduced a study in which they apply a wireless accelerometer to the user's leg to find out about their current activity. In result the authors propose the strategy to delay incoming notifications until the user initiates a task switch, which is often correlated with physical activity, such as a posture change from as sitting to walking.

*Making it scalable.* Another approach to not constantly overwhelm the user with obtrusive notifications would be to scale notifications in accordance to their importance. A good example for that is demonstrated in *Tactful Calling* [HLWJ09], in which a user is enabled to set the importance of a call by pressing the call-button with varying pressure. Depending on the callers input, the called person receives an either subtle or rather obtrusive call (silent/blinking, vibrating, or a loud audio notification). A similar approach for a scalable notification is demonstrated with audio text messages in *Nomadic Radio* [SS99], in which seven increasing levels of audio feedback (silence, ambient cues, auditory cues, message summary, preview, full body, and foreground rendering) are conveyed via a wearable speaker worn around the neck.

As already pointed out in 1999 by Sawhney and Shmandt [SS99] notifications should be both scalable and contextual. Considering context can be important to coordinate a good point of time for notification, while we can scale the required obtrusiveness of a notification, depending on it's priority and other situational factors.

We want to build on these previous research activities and elevate notifications to a further level, while expanding scalable notification to a new stage that forces the user to take action, in a manner similar to the idea of *forcing feedback*. In this project, we demonstrate our concept with scaling mechano-pressure, thermal, and electrical feedback. To our knowledge, it has not yet demonstrated how to scale these feedback modalities from a subtle notification up to a *forcing feedback*.

Please note: While *forcing feedback* can be described as an interaction concept, it should not be confused with force feedback, which is a certain feedback modality that provides a physical force, such as to a joystick

#### 4.2.3.1 Force feedback and forcing feedback

A few centuries ago, force feedback became very popular in modern aviation, because interfaces, such as the steering joystick, are becoming mechanically detached from the actual control unit. Because of the missing physical connection, information on the wind pressing against the rudder is being represented with simulated forces, which provides resistance to the pushing of a user. While this is a rather rudimentary example, many other types of force feedback have been explored, such as game joysticks and other handheld controllers. However, the most interesting force feedback is demonstrated in research some years ago: Pedro Lopes and his team research force feedback in HCI applications using electrical muscle stimulation (EMS) while stimulating muscles with electrical impulses in order to make the muscles contract, which create a kinaesthetic force feedback. For instance, Lopes et al. [LB13] presents a mobile phone running an airplane videogame, which makes the muscles to contract involuntarily, so the user is made to tilt the device sideways. Trying to resist this triggered motion, the user may feel a paining force in his arm.

In contrast, in research, we can also find a similar feedback, but which is still different and which we could denote as a *forcing feedback*. Instead of just creating a force to resist, we can go a step further and force the users' body parts to move in a certain way or direction. A *forcing feedback* can also be demonstrated by electric muscle stimulation (EMS), such as shown by Lopes et al. [LIM+15] who forces body parts to move, such as hand movements driven by the computer. Hassan et al. [HDW+17] also applies EMS to the calf muscles in order to force a different foot posture, which significantly improves walking performance.

While an EMS system can be considered to provide intrinsic feedback, we can also force the user's limbs to move by external forces. For instance, Chen et al. [CCCY16] presents a motion guidance sleeve, which generates subtle motion of the forearm based on "*eight* *artificial muscles*". Using stepper motors, fishing lines and elastic bands, the sleeve imitates the muscle contraction to drive the forearm to rotate instinctively. The illusion of external artificial muscles creating a pulling force and sensation is being conveyed.

Another kind of a pulling force is demonstrated in *Pull-Navi* [KHFK09], which propose earrings that are able to provide directions through haptic force. The developed prototype is yet cumbersome and incorporates a helmet, two servo-motors, and an external frame reaching to both ears. Pulling an ear forces the user to slightly turn his head to the corresponding direction and thus the user is automatically walks in this direction.

Another phenomenon, called the hanger reflex, that produces a fictitious force and involuntary rotation of the body using skin deformation. This haptic-induced force illusion is previously known to occur at the human head, which rotates unexpectedly when the frontal region and the opposing rear region are pressed using a wearable device. Kon et al. [KNSK16] investigated the hanger reflex on the waist using a u-shaped aluminium-ring, which is moving around the body and subtly forcing the user to take turns according to the position of the waist ring.

Forcing the user to walk in a different direction using shoe interfaces has been introduced by Frey in 2007 [Fre07]. The shoe prototype called *CabBoots* contains electro motors implemented into the thick insoles of the shoes that are able to change the weight distribution within the sole of the shoe. This way the foot is slightly exposed to a subtle pulling force which would automatically drags the user in a predetermined direction.

While rather gross movements can be forced, also tiny reflexes can be triggered as demonstrated by Dementyev and Holz [DH17]. In *DualBlink*, several types of feedback (light flashes, physical taps, and small puffs of air near the eye) are being provided to force the user to blink eyes. Considering the forced effect, we can also denote that as a kind of *forcing feedback*.

In conclusion, force feedback mainly induces a haptic force which follows the aim of drawing the users' attention (e.g., a recoiling joystick to provide information on the windy environment or on the texture of the road) and making the user to resist that force. In contrast, a *forcing feedback* doesn't necessarily rely on a haptic force as it has the aim to (un-)consciously making the user to take action (e.g., making eyes blink, dragging feet to a certain direction for navigation).

### 4.2.4 Concept

To extend related work, we propose scalable notifications that go beyond simply notifying the user, but forcing the user to take action. Providing notifications with different intensities can be useful in several situations, such as when being in a group of people and obtrusive notifications may bother thirds. While subtle notifications can help here, they may also be quickly overlooked or intentionally ignored without great effort and disruption. Therefore, we envision these types of notification to be suitable for less important information. Moreover, there may be very urgent notifications, such as important information to keep ourselves healthy. These notifications should even be a level beyond obtrusive, in a way that they cannot be overlooked and we are possibly forced to take action.

To illustrate the concept of *Scaling notifications beyond alerts*, we have chosen five stages, whereby the silent stage does not provide any feedback and whereby *forcing feedback* provides an extraordinary strong feedback, which may be unpleasant but still not harmful to the user. For instance, providing a high level of heat should be unpleasant, but not create fire blisters. The number of levels between forcing and silent feedback have been evaluated in extensive pilot studies. In result, we found out that with our hand crafted user interfaces, most of the pilot study participants were capable of distinguishing between three different stages. More stages of feedback were substantially worse distinguishable. In order to not unreasonably increase complexity and to still maintain a reasonable difference in perception, we decided for five stages.

| ...feedback | *silent* | *subtle* | *moderate* | *obtrusive* | *forcing* |
|---|---|---|---|---|---|
| pressure force (Nm) | 0 | 0.3 | 0.9 | 1.5 | 1.8 |
| frequency (Hz) | 0 | 2 | 2.5 | 3.3 | 5 |
| thermal temperature (°C) | 24 | 30 | 35 | 43 | 68 |
| electrical current (mA) | 0 | 10 | 12 | 20 | 22 |

**Figure 49. We developed three prototypes providing mechano-pressure, thermal, and electrical feedback. We conducted three studies, in which we tested to distinguish between five stages of notifications. The table reports on overview of all important parameters, to enable replicability of our feedback. Please note: parameters for electrical feedback are user-dependent and need to be set individually. Further information can be found at the according section (Study 1-3).**

With our work, called *Scaling notifications beyond alerts*, we want to extend previous research while combining scalable notifications with *forcing feedback* by mechano-pressure, thermal, and electrical feedback. To underline our concept, we developed three prototypes that demonstrate the feasibility in three different scenarios: *(1) body posture correction, (2) HAV overuse prevention, (3) car speed control*, in which we apply several nuances of tactile notifications, reaching from subtle to obtrusive feedback, plus a silent feedback and a *forcing feedback* (*see Figure 49*). We evaluated a verity of three independent scenarios, in order to illustrate the broad applicability of our proposed concept. Although our selected scenarios are far away from being realistic, we see our lab studies as a means to validate the feasibility of this proof-of-concept.

### 4.2.5 Study 1: Body Posture Correction (Mechano-Pressure Feedback)

In our first study we investigate the concept of *Scaling notifications beyond alerts* for the example scenario of a posture correction at a computer workplace. We evaluated the experience of nuances of mechano-pressure notifications and whether they have an impact on sitting posture.

#### 4.2.5.1 Motivation

Poor back posture while sitting or standing usually results in spine stress and thus in felt pain and discomfort. This can lead to changes of tissue and bone, potentially resulting in spinal musculoskeletal disorders, such as bone spurs and intervertebral disc damage [All00]. Spinal problems usually result in back pain, which often become chronical and thus result in a loss of overall life quality. Especially spinal issues are very costly for the society, since treatment is expensive and lengthy, while the patient is usually disabled to follow a usual workday. Poor posture is very common, as it is estimated that about 80% of all adults suffer back pain at least once in their life time, while 10% will experience a relapse [EFM+11]. Literature has shown that making users continuously aware of poor posture significantly reduces out-of-posture tendencies and encourages healthy spinal habits [WW08]. It is important to increase the patients' awareness of poor postures, so they can correct the spinal curvature using their own back muscles instead of using external support [WW08]. To increase the awareness of poor sitting posture, we want to provide notifications using mechano-pressure feedback.

#### 4.2.5.2 Hypotheses

In order to evaluate the scalability of notifications, we designed a lab study in which we tested whether the users would be able to perceive the nuances in feedback of mechano-pressure feedback and whether different levels yield an impact on the users' sitting posture. We assume the following hypotheses:

- **H1**: A solely mounting of bands, providing constant pressure, has a positive impact on the sitting posture.
- **H2**: Notifications will help the users to improve their back posture.
- **H3**: The intervening notification will force users to significantly correct their posture to an upright position.

#### 4.2.5.3 Apparatus

We developed a haptuator device (*see Figure 50*), working as a back piece that is mounted just at the area of the thoracic vertebrae, which is the middle-upper part of the spine. To keep the device in place, we fixed the device in two ways, using a chest-band and using Velcro-tape, which is wrapped around the shoulders. A solid fixation is crucial in order to enable the best sensation to the user. A very lose mounting would not guarantee the device to stay in place, while notifications may not be distinguishable well enough.

Technology-wise, we used a powerful 12V servo-motor providing a torque of around 160oz-in. The force is being translated via a horizontal gear into a linear force that slides the metal bar from two 5V *Solenoid haptuator coils* (ZHO-0420L) towards the back. There two small metal bars are pushing themselves just next to the vertebrate, the corpus of the spine. Our pilot studies have shown this setup to yield better sensation then pushing directly onto the middle of the vertebrate. We found it necessary to use the *Solenoid haptuators*, since they allow for a poking in higher frequencies than the motor is capable of.

We set up our device to provide four nuances of notifications ranging from subtle feedback (*Servo motor* providing low pressure and the *Solenoid haptuators* poking in a low frequency) to *forcing feedback* (*Servo motor* providing maximum pressure and the *Solenoid haputators* poking in a high frequency) – see also Figure 49. Depending on the anatomic structure of the users' back, especially the nature of the costelas (rips) and scapula (shoulder blades) the device was sometimes slightly less or more tightly attached to the spine, which can hinder the metal bars of the *Solenoid haptuator* to come out entirely.

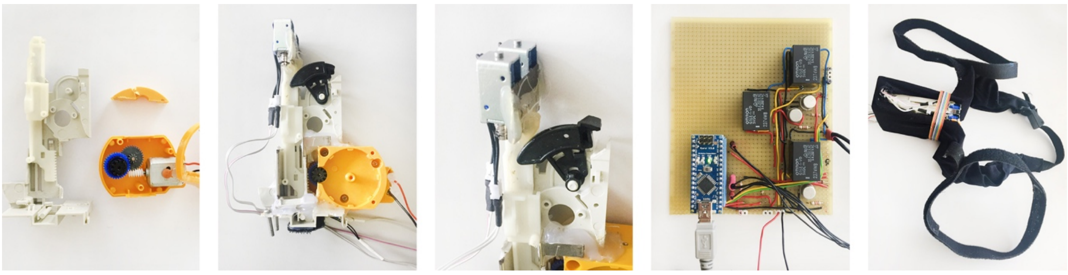


**Figure 50. The left picture shows an early step of the development process. The rotational force of a 12V DC motor is transitioned into a sliding movement, while the motor is driven by a typical Motor Reversing Circuit using two Relays. Two 5V DC poking actuators are attached to the top enable for high frequency actuation, which are driven together by a singe Relay. Since this is a custom hand-crafted prototype, we used hot glue to keep all parts in place. We implemented a capacitive sensor in order to know the position of the slider, while the DC motor as well as the poking actuators are driven by an Arduino Nano through three Relays (G5LE-1-VD). Since the prototype was capable in creating significant forces, we were required to mount the device in a stable manner by using a chest band and two arm/shoulder bands.**

#### 4.2.5.4 Procedure

We instructed the users to sit in an upright position in front of a usual computer workstation. The face was approximately 100cm in distance from the screen, while we made the position and angles of the users' arms to varied from approximately 45° to 130°. We provided all subjects with a brief overview on the upcoming study, while the users were told to perceive tactile feedback at their back, although we did not reveal the actual purpose of the study. The users were asked for their health status, in particular if they were aware of any chronic or acute any spine disabilities. Moreover, all participants hat to sign a letter confirming the *Legal Liability Policy*. To assure safety, we followed general guidelines for studies. After the apparatus was mounted to the users' back, the study leader was sitting down next to the workstation controlling the experiment, while remotely triggering the apparatus to actuate with five notifications (silent-, subtle-, moderate-, obtrusive-, forcing-feedback). Each of the five notification was presented with a temporal displacement of 30s, then the keyboard was moved 10cm away from the subject (which resulted in an angle change of arms and back) and all five notifications were presented again in the same manner. In order to see whether the drift into a bad posture also occurs at different sitting angles, we tested different keyboard distances, while the last distance apparently forced the user to adopt a very poor sitting posture (bending over towards the screen). Since the users' posture worsen over time, we additionally repeated the whole experiment without providing any notifications.

#### 4.2.5.5 Task

The task the users were asked to perform was rather simple, but highly demanding the users' attention and thus very engaging. We occupied the user with playing a computer game called Slither.io, in which one is guiding a worm through a virtual world, by using the keyboard with both hands. Further task specifications have not been made, nor the user had been briefed about the purpose of this study.


**Figure 51. The left pictures show the attached accelerometer and the pressure points our haptuator is targeting after mounting. The right picture shows the study setup: the user playing Slither.io while the study leader is triggering the notifications. A self-build Java/Processing tool communicates with an Arduino Nano, while the user's posture is calculated in degree-angles by the accelerometer and dumped into a csv-file for post processing.**

#### 4.2.5.6 Methodology

Besides being very observant and noting down any qualitative feedback commented by the users, we mainly rely on quantitative data on the current sitting posture. For this, we attached an accelerometer to the users' back and translated the sensor raw data into degree-angles. We recorded the current angle of the spine just before and after providing the notification to the users' spine. We averaged the angle drift across all users to see whether notifications would help the users to correct their posture. The analysis was carried out with statistic methods to see weather the observed effects yield statistical significances.

#### 4.2.5.7 Participants

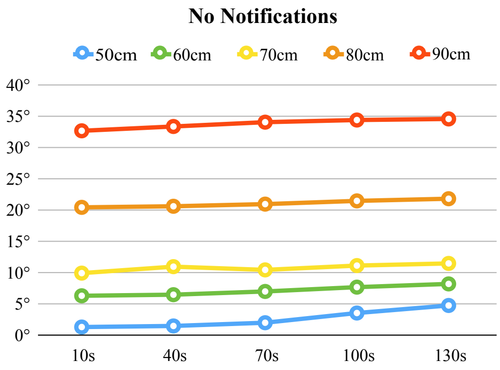
We invited 13 users to take part in our study from which 10 participants were males. All subjects were students, mostly enrolled in computer science, aged from 20yrs to 35yrs ($M$=25yrs; $SD$=4.08yrs). Their body height was ranging from 156cm to 183cm ($M$=175cm; $SD$=9.29cm) and their weight was ranging from 48kg to 85kg ($M$=70.38kg; $SD$=12.74kg). The spectrum of our subjects reflects an average European Citizen, although we dealt with an outlier. The potential minimum outlier; P4 - a female, 20yrs, 48kg, 156cm, however, is within the range of her *Body Mass Index* (BMI) showing normal weight like every other subject except P3. According to the BMI, P3 – a male, 26yrs, 65kg, 183cm, demonstrates to be slightly underweight and could therefore be seen as an outlier in terms of body mass. However, based on the study results, P3 performs similarly to other subjects. Non of the subjects were aware of chronic or acute spine disabilities, while they considered themselves as healthy.

#### 4.2.5.8 Results

Our analysis is based on 975 data points, which represent the angles in degrees of the users' spine posture. At the beginning of our study, we recorded 325 data points = 13 users * 5 postures over time * 5 distances, without providing any notifications in order to see the posture drift occurring over time. (*see Figure 52 – left*). In the second part of our study, we recorded the users' posture change while having our prototype mounted to their back. Here, we recorded 650 data points = 13 users * 5 postures * 2 recordings (before & after triggering the notification) * 5 distances (*see Figure 52 – right*).

Posture change over time (no notifications). Sitting for longer periods of time has a negative influence on our back, since we inevitably change in a comfortable sitting posture that doesn't strain spine muscles, although this is not considered to be very healthy. This change of sitting posture happens unconsciously, while it can already be observed within the very first minutes after sitting down, as we can see in Figure 52 – left.

Just after we made the user to sit down in an upright position (at a keyboard distance of 50cm the angle of the back was something around 90°, depending on the users' spine and sensor position) we set a reference angle to 0°. After 10 seconds the users already lowered their back by ø 1.23°. After 130s the users were already bending over for ø 4.64°. We then moved the keyboard 10cm farther away to a distance of 60cm. Here, we could determine the back posture to obviously worsen, while the back bent even more over to ø 6.21° and which got even worse after a time of 130s: ø 8.16°. We continued the experiment with keyboard distance of 70cm, 80cm and 90cm. As we can clearly see from the Figure 52 – left, the farther the keyboard is away, the crooked the back is.



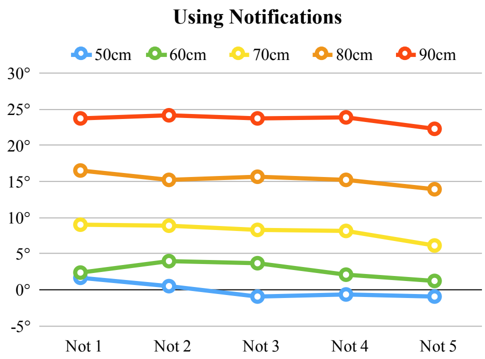




**Figure 52. Both figures show the angle deviation in degree from the initial sitting posture. The left figure displays the time course of the posture change for 5 keyboard distances. The right figure shows current sitting angle after providing the user with notification 1-5. It is to note that notification 1 was silent and thus did not provide any tactile feedback.**

This is also indicated by a *one-way ANOVA for correlated samples* ($F_{4,48}$=68.73; $p$<.0001). A *Tukey HSD Test* could confirm almost all postures to be significantly different from each other and significantly poorer to the initial sitting posture. Furthermore, the postures shown at a keyboard distance of 60cm & 70cm do not seem to be significantly different, which is due to the relatively small sample size of $n$=13.

Next to this obvious fact, we can now underline another finding with numbers: we can see a worsen of spine posture over time, while within 120s the back sinks into itself over all distances by ~2°. Comparing the average drift over time by an *ANOVA* doesn't show any significances ($F_{4,48}$=0.34; $p$=0.85), thus the strength of the drift describing the bending effect over time is not depending on the keyboard distance and will happen for any distance at least for the very first 120s.

*Posture improvement (by mounting bands).* For the actual part of our study we mounted our haptuator prototype (*see Figure 51*) onto the users' back. We can confirm that solely the mounting already creates a positive effect on the sitting posture, which is caused by the pressure created by the arm and chest mounting bands. The assumption, feeling the pressure of the mounting already improves users' posture is confirmed by a *pairwise t-Test (correlated samples)* for each keyboard distance, such as for 50cm ($M_{no\ noti}$=2.5; $M_{noti}$=0.6; $t_5$=-2.91; $p$=.03), 60cm ($M_{no\ noti}$=7.11; $M_{noti}$=3; $t_5$=10.39; $p$<.0001), 70cm ($M_{no\ noti}$=10.65; $M_{noti}$=8.66; $t_5$=6.51; $p$=.0012), 80cm ($M_{no\ noti}$=21.05; $M_{noti}$=16.18; $t_5$=20.1; $p$<.0001), and 90cm ($M_{no\ noti}$=33.73; $M_{noti}$=24.31; $t_5$=39.54; $p$<.0001).

*Posture improvement (by notifications).* Although tightly mounted bands that push the shoulders back significantly improve sitting posture, we can still perceive a negative drift into a poor posture over time, but which is reduced from initially ~2° down to ~0.8° over all distances (within 130s per distance). However, when additionally providing tactile notifications onto the spine, the users' posture apparently improves (*see Figure 53*), which is also confirmed by statistical post hoc analysis.

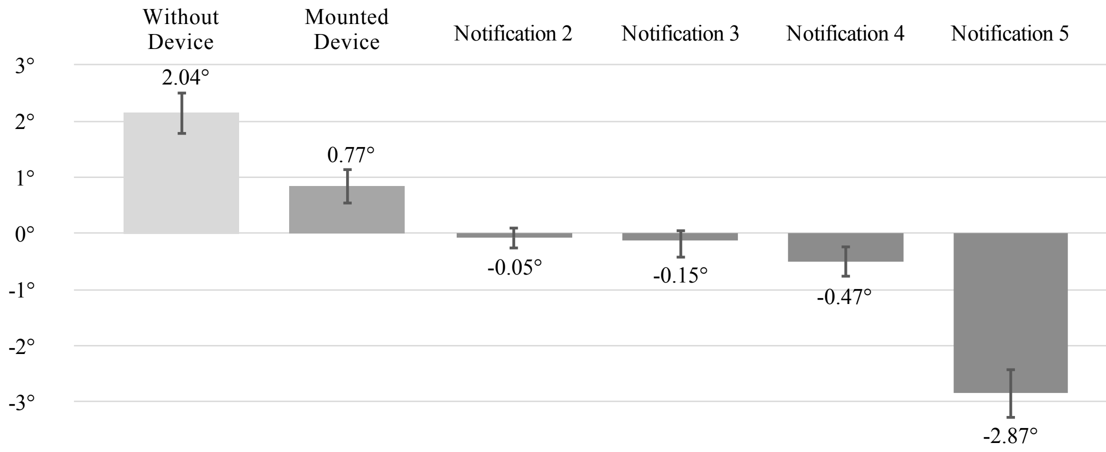



**Figure 53. The diagram summarizes the average drift of the sitting posture the users show when having nothing mounted, having tight bands mounted to the back and shoulders and when additionally using tactile notifications (2-5). It is to note that positive angles represent a drift into a bad posture and negative values represent posture corrections.**

A *one-way ANOVA for correlated samples* ($F_{2,8}$=29.72; $p$<.0002) shows that using notifications to provide a statistical difference. A *Tukey HSD Test* confirms the use of notifications to be strongly different from not apply anything ($M$=2.04°; $SD$=0.8°) as well as being different from mounting bands ($M$=0.77°; $SD$=1.04°). Therefore, we can make the statement, that providing tactile notifications at the spine can significantly encounter the natural drift into a poor sitting posture.

While the average drift, sinking into a poor posture, is around ~2° over 120s, it looks suspicions that applying our haptuator would overcorrect posture, since we measured a correction of -2.87°. Therefore, we take a closer look at the notification stages. Notification 1 – silent feedback / mounting was obviously not providing any tactile feedback, therefore we could see a drift of ~0.8° into a bad posture. Notification 2 was providing a slight tapping on the spine, but so subtle that it just marginally had an effect. While it is significantly different to "*without device*" ($t_4$=5.37; $p$=.006), it is not significantly different to just "*mounted device*" ($t_4$=1.75; $p$=0.08). Although notifications 3-4 provide stronger feedback, which make the user to correct their posture in a greater angle, the statistical outcome is similar to notification 2.

In contrast, notification 5 was significantly outstanding in every way. A *one-way ANOVA for correlated samples samples* ($F_{4,16}$=28.54; $p$<.0001) indicates notification 5 to be significantly different to any other notification, which is evidenced by a *Tukey HSD Test*. Because our haptuator was heavily pushing just left and right next to the spine discs, the users were forced by their natural reflex to straighten their back.

#### 4.2.5.9 Summary

Although this study needs to be seen as a proof of our proposed notification concept, we collected interesting findings concerning the sitting posture in order to answer our hypotheses (*see Hypotheses*).

*Answering assumptions.* We can accept hypothesis 1 (**H1**), a tight arm/shoulder and chest band providing some pressure at the back already reduces that natural drift, although, it doesn't erase it. Still, this may already be a good justification for wearing resistance bands such as proposed by consumer products[7]. Even without instructing the users to straighten their back when receiving feedback (P8: *«I don't get the idea of why it is poking me»*), we found out that providing subtle to obtrusive notifications at the spine to even stop the drift during and shortly after the feedback. This underlines our hypothesis 2 (**H2**), which can be accepted. However, an actual posture change into an upright posture is eventually needed to be performed consciously as also suggested by other consumer products[8,9]. Another way to significantly correct the users' back posture is forcing them by pressing with a greater force next to the spine discs, triggering a natural reflex that straightens the back. Following the data, after triggering notification 5, we are able to force the user to sit upright and to significantly change their back posture. Therefore, we would like to also accept hypothesis 3 (**H3**), although we could perceive two participants to remain unimpressed by *forcing feedback*. We assume this to occurred due to the users' individual perception. Another reason could be a suboptimal mounting of our prototype.

*The individual factor.* Because of the nature of the costelas (rips), scapula (shoulder blades), and the subjective perception on tactile sensitivity and pain threshold, users perceived the feedback in a weaker or stronger way. For example: some users enjoyed the *forcing feedback*: *«It felt a bit like a short back massage [...] the poking could be even harder»* (P2), while others immediately got in an upright position, pulling their shoulders back. P3 eventually started screaming: *«Stop stop stop! Please, I am sitting straight again!»*. In general, the study experiences varied very much across users. One user (P6) was very much engaged into the game and stated: *«The noise produced by the motor and the relays are distracting me playing this game»*, while another user (P2) was bored by the game. However, the initial purpose of the game, which was in diverting the users' attention to something else then on the haptuator, was served. Although the users' perception is very individual, we could show that our notification concept provides significant different nuances perceivable across all users.

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[7] THE ERGO Posture Transformer: *https://www.kickstarter.com/projects/708946960/the-ergo-posture-transformer-perfect-posture-insta*

[8] UPRIGHT GO: *https://www.kickstarter.com/projects/upright-go/upright-go-fix-your-screen-slouch-correct-your-pos*

[9] Backbone: *https://www.kickstarter.com/projects/gobackbone/backbone-the-smart-easy-way-to-a-healthy-back*

### 4.2.6 Study 2: HAV Overdose Prevention (Thermal Feedback)

In this study we investigate our proposed notification concept in the domain of work safety. We evaluated which nuances of notifications using thermal feedback would actually be recognizable at the palm of the hand when being exposed to hand-arm vibration

#### 4.2.6.1 Motivation

A lot of tools used by handcrafters or heavy workers emit considerable vibrations, which spread throughout the entire body. Due to the long-lasting and mostly intense vibration received by the hands and arms, irreparable damage may be caused to the sensorineural [BTL87] and muscular [BZFB91] system. These diseases are well known and denoted as *HAV- / Raynaud- / White Finger- Syndrome*. In order to protect the workers, there are regulations, which demand an evaluation vibration exposure and to assess potential risks. For instance: The *German Vibration Occupational Safety and Health Regulation* [Lä07], which is similar to the European regulations [Don08], obliges the employer to abide with the limit of the daily dosage of $A(8) = 5\ m/s^2$ and to establish certain vibration reduction programs when exceeding a daily dose of $A(8) = 2.5\ m/s^2$. Newer professional tools emitting considerable vibration already track the HAV exposure durations. Older tools can be instrumented with certain sensor-kits[10], which are also commercially available. Alternatively, a manual evaluation has to be done, but which is obtrusive, interrupting the workflow and obviously in accurate. While in research, we can find several other prototypical solutions [LYX+15, WLTS06], HAV exposure dosage can also be tracked with a commercial smartwatch [MBK16].

However, all these tracking systems yield the same drawback: they do not inform the user in an adequate way about their current and daily HAV exposure dosage. For example, most devices provide numbers and graphs, which have to be looked up visually, which interrupts workflow. Regardless of their HAV exposure dose, reaching certain limits and even exceeding the daily limit is not communicated in a different way, although it would be important to the worker. We envision a future notification system to unobtrusively provide the users an idea on their current HAV exposure dose. Depending on the received level of vibration, we can provide adequate notifications which allow the user to take breaks on his free will. Moreover, we can even go beyond a simple notification and force the user to take a break through thermal feedback. Also, when transitioning to thermal information instead of requiring the users' visual attention, we gain the advantage of reducing task interruptions.

[10] Castle Vexo H GA2006H Hand Arm Vibration Meter: *https://www.castleshop.co.uk/ga2006h-vexo-hand-arm-vibration-meter.html*

#### 4.2.6.2 Hypotheses

In order to test different nuances of notifications, we designed a lab study in which we tested whether the users would be able to perceive different levels of thermal feedback and whether different levels yield an impact on the task performance. We assume the following hypotheses:

**H4**: Subtle notifications are less recognizable and may be quickly overlooked.

**H5**: The intervening notification will force the user to interrupt the task.

**H6**: Except from intervening notification, all other notifications will not negatively impact the task.

#### 4.2.6.3 Apparatus

According to literature, the most effective way to stimulate mechanoreceptors and chemoreceptors with thermal feedback is applying heat directly onto the skin. Since we are bound to have skin contact, there are limited options in terms of selecting a suitable body spot. We decided to apply different intensities of thermal notifications (see Figure 49) on the palm of the hand for several reasons: *Receptor density*. As a matter of fact, the density of receptive cells is highest at the hand compared to any other spot of the surface of the skin. *Practicability*. Because we apply notifications based on heat, the sensation can quickly become unpleasant when heat exceeds the personal threshold of tolerance. Therefore, we decided to not fix the actuator at the user, but on the device the user holds in his hands.

We selected a drilling machine and mounted a *Peltier Element* (TES1-127025) to it's handle (*see Figure 54*). Additionally, we used modelling clay in order to smooth the sharp edges of the *Peltier Element*. When the device is carried, the *Peltier Element* was in direct contact with the palm. For control, we used an Arduino Nano a with a relay control circuit to drive the *Peltier Element*, since it requires 12V and high electrical power up to 65W.

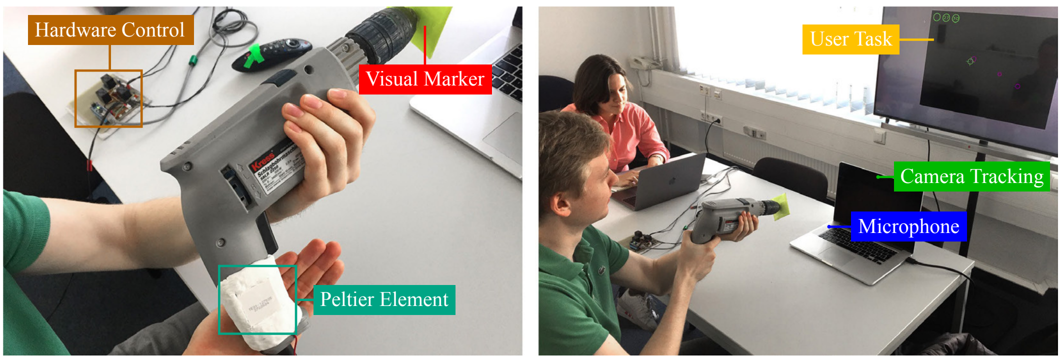


**Figure 54. The left photo shows the prepared drilling machine, which has a *Peltier Element* (TES1-127025) and some modeling clay attached at the handle. The right photo shows the study setup; the subject hat to aim at moving circles and drill them. The position tracking is done with an RGB web cam and the drilling is detected by the microphone.**

In a prototyping manner, a green coloured paper was glued to drill's head (*see Figure 54*). The web camera of a Macbook Pro then tracked the current position of the drill, which was displayed as a crosshair in a Java/Processing application. While purple objects were moving in that application, the user was capable in aiming at them and drilling a hole in the air. The microphone was used in order to automatically recognize whether the user was drilling or pausing.

#### 4.2.6.4 Procedure

We let the participants sit on a desk in front of a *50" LG Smart TV*, which was approximately 1.5 meters away. The study leader was sitting just diagonally across the subjects and controlling the study (*see Figure 54*). After explaining the upcoming task, we again asked the participants to sign the *Legal Liability Policy*, which also protected the study leader. In the unlikely event of physical and mental damage, all legal rights remained with the test subject, which would be needed to be brought against the Fraunhofer Institute. Naturally, the safety of the subjects had always been a priority. All study participants had to explicitly state that they have been briefed, as they voluntarily participate. After explaining the study and the game, the users needed to pick up the drilling machine, while being required holding it in the right hand. Usually the users made use of the left hand in order to support the quite heavy weight of the machine. There were three purple balls floating across the screen, which had to be aimed at and finally drilled. Drilling a hole takes 1.5 seconds, provided the user is within the hit box of the moving target. In order to prevent the user of non-stop-drilling, the drill-ing machine goes in a cool-down mode after a period of 3 seconds, which lasts another 3 seconds. Within that period, holes cannot be drilled.

While the users were playing the game, each of the five notification were presented for 10 seconds three times in a row with a temporal displacement of 20 seconds. The goal of this study design was to see how and when the users are capable of perceiving thermal feed-back at the palm during a drilling task. Apparently, the raised cognitive load and the emit-ted vibration makes perception more difficult.

#### 4.2.6.5 Task

We asked the study subjects to work with the drilling machine, while the actual task was to drill *"holes in the air"*, while the user was aiming the moving targets displayed on a 50" screen. The only goal was to drill as many holes as possible in order to increment the displayed score. Moreover, the user was asked to immediately tell the study leader as soon as he perceives thermal feedback on his palm. Nevertheless, we told the user to be allowed to drop down the tool in case he perceives an unbearable heat at the handle. No further task specifications have been made, nor the user had been briefed about the purpose of this study.

#### 4.2.6.6 Methodology

Also in this study, we mainly rely on quantitative data. For each session, we recorded: (1) the *reaction time* from triggering until recognizing the notification, (2) the *number of holes* having successfully drilled, and (3) the *drilling time*. For the reaction time we rely on the users' oral response or on the physical response, such as laying down the tool. It is important to note that the reaction time is measured from the beginning of triggering the *Peltier Element*, until the user reports to feel it. Therefore, our measured reaction time also includes a small amount of time, which is required to heat up the *Peltier Element*. Besides qualitative data, we also noted down any qualitative feedback commented by the users. The analysis was carried out with statistic methods to see weather the observed effects yield statistical significances.

#### 4.2.6.7 Participants

We invited 15 participants to take part in our study. The age of the participants ranged between 22yrs and 31yrs (*M*=25.5yrs; *SD*=3.11yrs). Their height was ranging from 162cm up to a height of 189cm (*M*=178.73; *SD*=74.5cm), while their weight was ranging between 46kg and 84kg (*M*=69.73; *SD*=11.3). The spectrum of our subjects reflects an average European Citizen, although we dealt with an outlier. The minimum outlier; P13 - a female, 24yrs, 46kg, 162cm, can be considered as underweighted according to the calculation of her body mass index (BMI). However, based on the study results, P13 performs similarly to other subjects. All other participants demonstrate to be within their normal BMI. Non of the participants had known issues, such as a HAV syndrome, while they considered themselves as healthy.

#### 4.2.6.8 Results

Notifications are perceivable in an individual way, such as the intensity and the pleasure or even pain. Because, our notifications range from (silent), subtle, moderate, obtrusive and *forcing feedback*, it may be that some of those notifications may not be recognized. While we evaluated each notification level 3 times, we base the following analysis on 180 data points: 15 participants * 3 trails * (5-1) notifications, since the first nuance of notification was subtle and thus not effecting the user in his performance.

*Recognition.* We ran *a one-way ANOVA for correlated samples* and found strong statistical differences ($F_{3,42}$=74.35; *p*<.0001) while checking which levels of notification have been recognized or missed (*Figure 55 - left*). A *Tukey HSD Test* reveals notification 1 to be significantly less recognized (*M*=0%) than any other notification, which is obvious because our silent notification is not emitting any heat. Notification 2 (subtle feedback) was being perceived just around half of the time within the trails of all participants (*M*=46.6%; *SD*=30.34) and thus was perceived significantly different in comparison to all other notifications (*p*<.01). In terms of recognition, notification 3 (*M*=80%; *SD*=24.56%) and notification 4 (*M*=91.11; *SD*=19.79%) are not significantly different (*p*>.05) to each other. Both notifications, 3 and 4 have been significantly worse recognized then notification 5. In contrast to all other notifications, notification 5, the *forcing feedback* was so alerting, that it could not be missed by any study subject (*M*=100%; *SD*=0%), which is significantly different than all other notifications ($p$<.01).

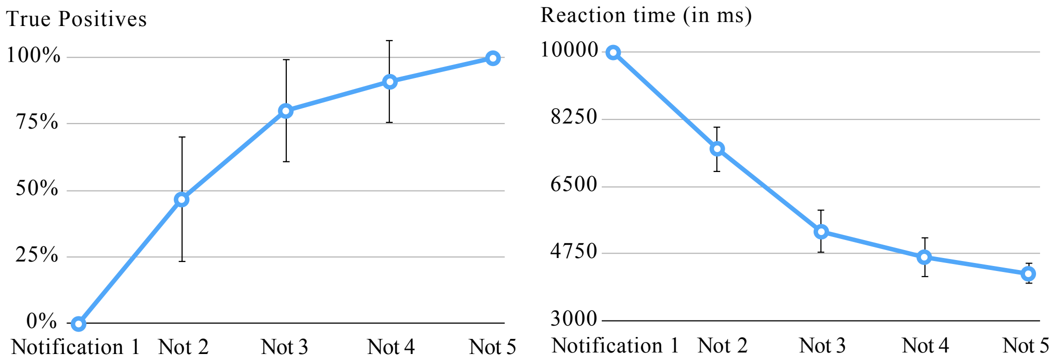


**Figure 55. Left: The quantitative recognition of notifications among all users. Right: Reaction time per level of notification. (Error bars indicate the standard error)**

*Reaction time*. For each level of notification, we had three trails presenting a notification every 20s (10s actuation + 10s pause). When the user was not recognizing the notification, we put a recognition time of 10s. We again, run a *one-way ANOVA for correlated samples* and found strong significant differences ($F_{4,56}$=39.2; $p$<.0001); A *Tukey HSD Test* confirms notification 1 (*M*=1000ms; *SD*=0ms) to be statistically different ($p$<.01) to the other notifications, since notification 1 was silent and thus the user did not respond to it. In contrast, for notification 2 we provided a slight temperature increase up to 30°C, which was perceived in average after ~7s (*M*=7471.2ms; *SD*=2239.4). Notification 3 (*M*=4377.8ms; *SD*=1386.86ms), notification 4 (*M*=4407.27ms; *SD*=1782.87ms), and notification 5 (*M*=4228.13ms; *SD*=1014.17ms) are not statistically different to each other, but have all been recognized significantly faster ($p$<.01) than notifications 1 and 2 (*Figure 55 – right*).

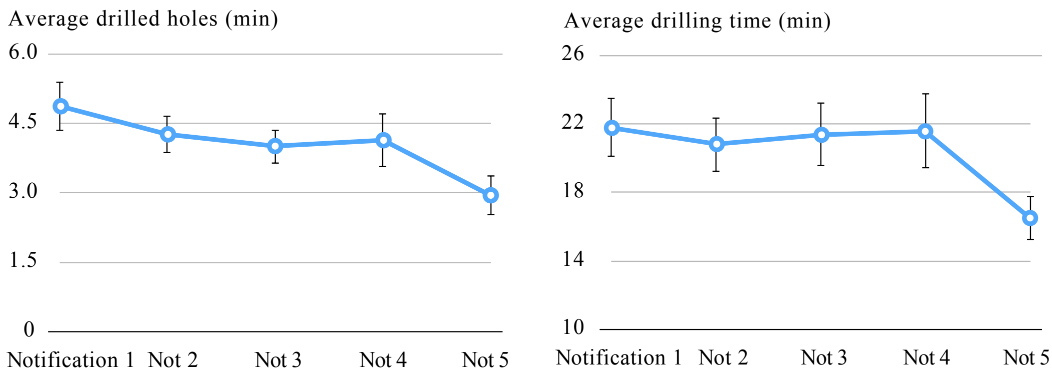


**Figure 56. Left: The average number of holes drilled per minute among all users. Right: The average drilling time per minute among all users (Error bars indicate the standard error)**

*Average number of holes drilled*. While the user is perceiving notifications via the palm of his hand, it may occur that his working performance is negatively effected. A *one-way*

*ANOVA for correlated samples* ($F_{4,56}$=3.62; $p$=0.01) did evidence a significant performance drop. A *Tukey HSD Test* confirms notification 5 (*M*=2.95; *SD*=1.63) to result in a decreased working performance, because the level of feedback was forcing the users to put down the tool, since the heat was not bearable heat. No further differences were found, therefore, other nuances of notifications do not influence the performance negatively for our sample size (*Figure 56 - left*).

*Average drilling time.* We again ran a *one-way ANOVA for correlated samples* ($F_{4,56}$=4.56; $p$=.003) in order to check if the notifications had an impact on the actual period of time the user drilled. A *Tukey HSD Test* revealed no significant differences between notifications 1 – 4. However, notification 5 (*M*=16.5s; *SD*=4.86s) demonstrates a significantly smaller amount of drilling time, which is obvious because the drill was forced to be put down when notification 5 occurred and thus the user was disabled to use the tool. (*Figure 56 - right*)

#### 4.2.6.9 Summary

While we envision *Scaling notifications beyond alerts* to handle the daily HAV doses of the tool, we could not expose the user to considerable vibration for many hours in order to demonstrate such a system. Instead, we designed a lab study in a way that it would answer our hypotheses (*see Hypotheses*).

*Answering assumptions.* Hypothesis 4 (**H4**) can be accepted. The data analysis has shown that subtle notification levels are being significantly less recognized than those being obtrusive. Although, P13 stated notification 2 and 3 to have a similar intensity. In general, qualitative feedback gathered from several subjects, confirmed thermal feedback to be perceivable in a very individual manner. For instance, P8 stated *«Notification 4 is so hot – it is way too intense»*, however, similar to P10 the subjects did not put down the tool at notification 4. Most participants explicitly stated notification 5 to be too hot to touch, which was our goal - P12: *«Sorry, I can't take this»*. Therefore, hypothesis 5 (**H5**) can be accepted. Each of our participants had to remove their right hand from the handle, which interrupted the task, when triggering notification 5. This is also indicated by a significant lower averaged drilling time and by a significantly lower number of drilled holes. However, any other notification (1-4) did not demonstrate any statistical differences in terms of task performance (amount of drilled holes and drilling time). Hence, we can also accept hypothesis 6 (**H6**).

Regarding the drilling task, we had generally positive feedback, while the study was designed to be playful. However, we also gathered a negative comment from a young female - P8 stated: *«It is sometimes just too hard to hit the moving targets. [...] this is really frustrating»*. Another participant (P14), made a very interesting comment: *«Sorry, I was so much concentrated on [recognizing] the heat, maybe I wasn't good at the shooting»*. However, his assumption was contradictory to the collected data, since he was the top scorer amongst all participants in terms of drilling performance, while he recognized all notifications.

### 4.2.7 Study 3: Car Speed Control (Electrical Feedback)

In this last study we apply our proposed notification concept to a more critical domain; multi-tasking in a critical environment in which the user has to control a car while interaction with controls of the car interior at the same time. We evaluated different nuances of notifications and their effect on recognizing a changing speed limits.

#### 4.2.7.1 Motivation

Driving a car is frequently mentioned when talking about dangerous daily tasks. Indeed, according to the U.S. Department of Transportation, motor vehicle crashes are still the leading cause of death for teenagers in the United States. In general, driving yields high risk, also for experienced drivers. Following statistical data, the worst driving hazards caused by the user are the consumption of alcohol (~11,000 fatalities /year), drowsiness (~5,500 fatalities /year) and cell phone use (~1,000 fatalities /year) in the united states[11]. It is apparent that all these hazards are due to an inattention of the user. While driving should be the primary and only task, it occurs to be distracted by several other tasks we perform in parallel. This can be critical when reaching a certain extend, such as when the primary task moves into the background and becomes the secondary task. This can quickly occur when visually focusing interior controls or third party devices, such as an iPod, which significantly effects driving performance such as keeping the speed level [SMZB07] or holding the car in the correct lane when being visually distracted [CPMZ16].

We believe that notifications can help to redraw attention to the driving task, especially when situations on the road change, such as the speed limit. Depending on the level of criticalness, notifications may reach from subtle towards obtrusive or may even force the user to take action immediately. To mimic a mobile scenario in a car, we designed a lab-based dual-task experiment with simulated driving as the primary task and an attention drawing secondary task, in which the user has to control different functions by the car's interior. However, we do not claim our setup to reflect real life driving, rather it is meant to reflect a typical dual task scenario in which the secondary task rivals for the users' attention and thus unintentionally becomes the primary task.

To redraw attention to the driving task, we again provide different stages of notifications. In this third study we utilize an electrical stimulus, which we apply to the users' leg. Due to assurance reasons and safety regulations, we were not allowed to execute the study in a real car on the road. Therefore, we designed a driving simulation in lab study, in which the user needs to control the speed of a car, while being distracted by secondary tasks, such as switching a song on the radio.

[11] Autinsurance.org (Summary on driving hazards): http://www.autoinsurance.org/driving-hazards/

#### 4.2.7.2 Hypotheses

In order to demonstrate the feasibility of our concept *Scaling notifications beyond alerts*, we designed a lab study in which we tested whether the users would be able to perceive different levels of electrical feedback and whether different nuances of notifications have an impact on the task performance. We assume the following hypotheses:

**H7**: Subtle notifications are less recognizable and may be quickly overlooked.

**H8**: The intervening notification will force the car to accelerate significantly faster.

**H9**: Providing notifications with stimuli will improve the users' task performance.

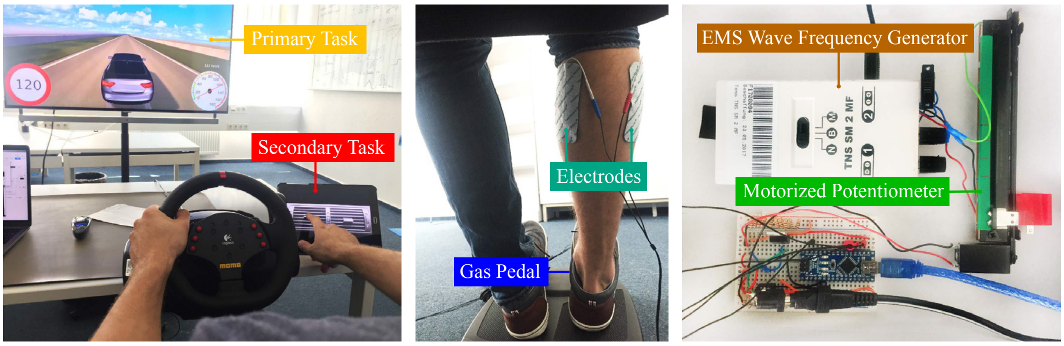


**Figure 57. We designed a driving simulation, which is considered to be the primary task and simulated an interior on a tablet, which asked the user to perform a secondary task. While speeding the car is done by pressing down the gas pedal with the right foot, we applied electrodes to the calf in order to provide notifications and controlling the foot movement. The EMS wave frequency generator was driven by our software using an Arduino Nano, which basically controlled the current knob that we replaced with a motorized potentiometer (10kOhm).**

#### 4.2.7.3 Apparatus

In order to provide automated notifications controlled by a computer application we used an Ardunio Nano and hacked an *EMS Wave Frequency Generator*, also denoted as a nerve stimulator (Pierenkemper TNS SM 2 MF), which is capable in providing frequencies from 0.4Hz-100Hz. Our hack basically consisted of a hardware replacement of a knob by a 10kOhm motorized potentiometer (COM-10976) that could be driven by an Arduino using a *Power MOSFET* circuit (2* IRF640). We used a single channel electrode mode, set a frequency of 80Hz, used a pulse width of 200µs, while we varied the output current from 0-70mA (*see Figure 57*). We designed 5 notifications which needed to be set individually per user. We step by step increased the current and asked when the user would feel a first light tingling. Then we continued increasing the current until the foot moved independently. The other stages between these two had been interpolated. Figure 49 shows the averaged setting of current (in mA) across all users. The driving task was performed on a *50" LG Smart TV*, while using *a Thrustmaster Momo Racing* steering wheel and foot pedals. The secondary task, interacting with car interior controls, was simulated on a *Samsung Galaxy Tablet* SM-T810.

#### 4.2.7.4 Procedure

Before running the study, all participants had to sign a *Legal Liability Policy*, which informed the users about the upcoming study and possible risks. In the unlikely event of physical and mental damage occurring during and after the studies, legal claims could be directed against the Institute. However, user safety was always our primary focus, while we tried our best to improve user experience, such as with setting up a user-dependent threshold for the EMS stimulation. Because the sensation is sometimes perceived unnaturally strange by some users, an uncomfortable feeling may arise at some point. Naturally, all participants had the chance to interrupt or to even abort the study, since they were all taking part voluntarily.

The participants had to sit on a desk in front of a *50" LG Smart TV*, which was approximately 1.5 meters away. A driving simulation is displayed, which was controllable by a steering wheel mounted to the desk and gas pedals, which were placed under the table. A Samsung Tablet was placed on the right, just next to the driving wheel, which displayed different car interiors (*see Figure 58*). The user was instructed to hold the steering wheel with at least one hand. The right hand was used to interact with the tablet, which switched between several interior screens. The users' feet were touching the gas pedal, which allowed to change the speed. EMS skin surface gel electrodes were attached to the users' right calf, which received notifications by electrical stimulation of the *Musculus Gastrocnemius Caput Mediale and Laterale*. A subtle notifica-tion creates an almost unnoticed tickling, the moderate notification creates a tingling of the complete calf, the obtrusive notification would tense the entire calf (feels like some-body clasps the leg tight), and the *forcing feedback* eventually causes the foot to be pressed the pedal down. We chose this gesture, of pressing down the pedal to increase user expe-rience of our study. Moving the foot upwards is technically-wise more complicated since we require more channels, more electrodes, which we would also require to be put under-neath the foot, but which is however, very impractical.

We tested all notifications while the user had the task to keep the car's speed, accelerate and slow down the car. Each notification has been tested 5 times in a row with a time disposal of 20s. The study leader, who was just sitting next to the subject and controlling the study, had the chance to intervene the study, in terms of delaying the notification when the users were not ready or aborting the study when the users didn't feel comforta-ble anymore.


**Figure 58. We built our own driving simulator, which showed the speed limit at the left corner, while a tachometer plus a digital number at the right side showed the current speed. On the tablet we displayed different parts of a BMW interior, while a short request, coloured in yellow, asked the user to perform an action.**

#### 4.2.7.5 Task

The user is occupied with two task: driving a car (continuous speed control by gas pedals), which is supposed to be the primary task and interacting with interior controls displayed on a tablet (discrete input finger control), which is supposed to be the secondary task.

The primary task, was to hold, increase or decrease speed according to the current speed limit traffic sign being displayed at the left corner of the screen. Changing the car's speed is done when pressing down the right gas pedal by the users' right foot. For the start of each round, we always asked the driver to keep a speed of 20kmh. Every 30-40s we started a new round in which the user had to change the speed. In one session, we provided five rounds with a speed change that required the driver to speed up the car by *20→40kmh, 20→60kmh, 20→80kmh, 20→100kmh,* and *20→120kmh*. The given speed changes were provided in a random order.

We conducted 6 sessions (including 5 rounds): while at the first session the driver is not distracted by a secondary task, and thus the users' attention can be fully devoted to the primary task. For the remaining five sessions, the user had to complete an additional secondary task on the tablet. The user was instructed to immediately complete the task appearing on the tablet, which was indicated by a "*dring"-sound*. For instance, the user had to switch on the radio, change the song, lower the temperature of a fan, switching on lights, etc. The task switched in a random order every 10s.

While the users were exposed to a high level of distraction, we provided notifications by EMS to the users' leg as soon as a speed change occurs at the driving task. The users were instructed to immediately adapt to the suggested speed limit as soon as they recognize it. The additional notifications should help the users to recognize changes of the driving task. For each of the remaining 5 sessions, we tested a single nuance of notification.

#### 4.2.7.6 Methodology

In order to investigate the differences of nuances of notifications, we have a look in which way they effect the primary task. Here we measured quantitative data at the driving task, which is: (1) *reaction time*, measured from the beginning of a changed speed limit sign until the user begins to significantly accelerate and (2) *task completion time*, which is the complete period of time needed to reach the new suggested speed limit. Moreover, the study leader needed to be very observant and noted down significant qualitative feedback. This was especially important for this study, because the users may felt quickly uncomfortable due to the very uncommon feedback modality. Because EMS works user-dependent, before starting the study, we evaluated the minimum current required to make the user feel a slight tingling and the maximum current that was required in order to make the foot move. Based on these values, we calculated the users' individual current for each notification. The averaged currents over all users are: $M_{Not2}$=10.7; $SD_{Not2}$=1.3; $M_{Not3}$=12.8; $SD_{Not3}$=1.5; $M_{Not4}$=20.1; $SD_{Not4}$=1.8; $M_{Not5}$=22.4; $SD_{Not5}$=2.1.

#### 4.2.7.7 Participants

For this study, we asked the same participants to join for another session, which already took part in our previous study. Therefore, we had 15 participants aged between 22yrs and 31yrs (*M*=25.5yrs; *SD*=3.11yrs). Their height was ranging from 162cm up to a height of 189cm (*M*=178.73; *SD*=74.5cm), while their weight was ranging between 46kg and 84kg (*M*=69.73; *SD*=11.3). All participants were European Citizens. In terms of *Body Mass Index* (BMI), we had an outlier; P13 - a female, 24yrs, 46kg, 162cm, which can be considered as underweighted according. All other participants demonstrate to be within their normal BMI. Non of the participants had known muscle or nerve damages, such *Carpal Tunnel Syndrome*, while they considered themselves as healthy. Only 11 out of 15 participants completed all tasks. P1, P2, P4, and P8 didn't complete the last notification (*forcing feedback*), while P1 already declined continuing the study during testing notification 4. The data of all completed trails have been included.

#### 4.2.7.8 Results

Having a look at the reaction times (***Figure 59 - left***) the users showed when a change in speed limit occurred, showed significant differences when providing notifications, as evidenced by a ***one-way ANOVA for correlated samples*** ($F_{4,56}$=4.09; *p*=.0056). A ***Tukey HSD Test*** indicates notification 3 (*M*=1671.6ms; *SD*=555.91ms; *p*<.05), 4 (*M*=1600.4ms; *SD*=552.99ms; *p*<.05) and 5 (*M*=1499.47ms; *SD*=305.34ms; *p*<.01) to provide better reaction times than using no feedback - notification 1 (*M*=2302.2ms; *SD*=977.78ms). Due to the rather small sample size, we cannot find a significant difference between notification 2 (*M*=1741.67ms; *SD*=591.62ms) and notification 1. It is to assume that the tasks occupied the users so much, that a subtle feedback was sometimes overlooked.

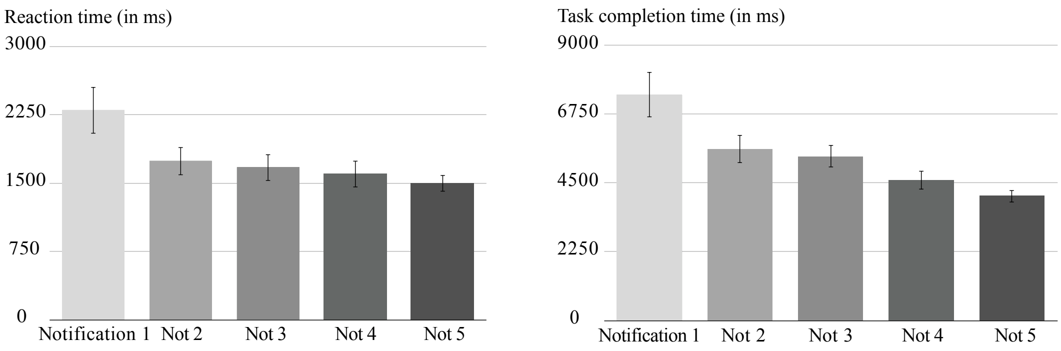


**Figure 59. Left: Average reaction time for each notification. Right: Task completion time for each notification. (Error bars indicate the standard error)**

Comparing the task completion time (*Figure 59 - right*), namely the time the user required to react plus reaching the given speed limit also yields significant differences following a *one-way ANOVA for correlated samples* ($F_{4,56}$=10.89; $p$<.0001). A *Tukey HSD Test* evidences notification 2 ($M$=5610.93ms; $SD$=1731.34ms; $p$<.05), 3 ($M$=5374.47ms; $SD$=1327.67ms; $p$<.01), 4 ($M$=4586.53ms; $SD$=1150.09ms; $p$<.01), and 5 ($M$=4073.27ms; $SD$=676.3ms; $p$<.01), to helping the user to complete the task significantly faster than having no feedback – notification 1 ($M$=7385.47; $SD$=2826.16). No other significances found.

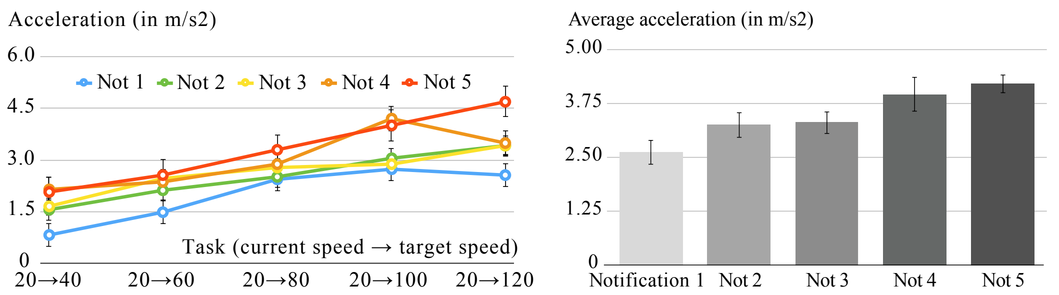


**Figure 60. Left: Average acceleration of each task for each notification level. Right: Averaged acceleration for each notification. (Error bars indicate the standard error)**

We also checked the average acceleration the users showed for each notification. From Figure 60 - left, it becomes visible that a higher speed limit made the user to intuitively accelerate the car in a quicker manner.

However, more interesting is the averaged acceleration occurring for each notification. From Figure 60 – right, we can infer that the user is deemed to accelerate increasingly quicker when receiving an increased feedback. While having a look at the data, a *one-way ANOVA for correlated samples* ($F_{4,56}$=6.53; $p$<.0001) found strong significant differences, which is confirmed by a *Tukey HSD Test*. Increasing the obtrusiveness of notification, such as evidenced by notification 4 ($M$=3.97m/s$^2$; $SD$=1.53m/s$^2$; $p$>.01) and notification 5 ($M$=4.21m/s$^2$; $SD$=1.5m/s$^2$, $p$>.01) coerces the user to accelerate quicker in comparison to not having any feedback – notification 1 ($M$=2.62m/s$^2$; $SD$=1.1m/s$^2$). Further differences could not be found with this comparably marginal sample size.

#### 4.2.7.9 Summary

In this last study, we tried to convey our notification concept to a driving scenario, in which the user is occupied with multiple tasks (controlling the speed of a car and interacting with the interior of the car). We don't claim to mimic a realistic driving experience, instead, we designed the lab study in order to see how if our notification concept works with EMS feedback (*see Hypotheses*).

*Answering assumptions.* Hypothesis 7 (**H7**) needs to be rejected. Although we overloaded the user with multiple tasks, the subtle feedback on his calf has always been recognized. Neither the reaction time, the task response time, nor the acceleration is significantly different when supplying subtle feedback or more obtrusive feedback. Providing notification 5, forces the users' foot to press down the gas pedal immediately until the end. The user was unable to gently accelerate and thus thus the acceleration at the speed changes have been significantly for notification 5 following the data. Therefore, the hypothesis 8 (**H8**) can be accepted, which is by the way also confirmed by the users' statements. P15 stated: *«It is hard to control the speed level with notification 5»*, P12 said *«I must fight to control my foot, because it is just moving»* and P7 explained: *«I wanted to stop at 60, but I couldn't control my foot»*. P7 also suggested this behaviour to make in particular sense when hitting the break instead of the gas pedal. Regarding a task improvement when providing notifications, we could figure out that providing EMS feedback at the users' leg improves the noticeability at the primary task. Providing notifications, enables all users to complete the task significantly faster, while also the reaction time is substantially shorter. Therefore, we can accept hypothesis 9 (**H9**).

*The individual factor.* This study provided us some interesting findings regarding the subjective perception of EMS notifications. Some participants perceived EMS as strong pain (P1), however, some other participants (P3) really enjoyed it. He also suggested notification 5 to act as an emergency stop. While one participant (P10) explicitly stated to be able to consciously perceive all nuances of notifications, we believe that all notifications were perceivable in a different manner. Therefore, we ran a calibration process before running the study. The setup of applying gel electrodes to the calf just before starting the study made some subjects suspicious. Three participant (P8,10,14) were speculating that the electrodes may provide painful electro-shocks when exceeding the giving speed limit.

### 4.2.8 Discussion

The idea of scaling notifications up to an extend that it is not just alerting, but forcing the user to take action is the key aspect of our concept, which favours a *Reflexive Interaction* because a support of *forcing feedback* showed to significantly minimize time required to perform the gesture. Also subtle notifications support favours a *Reflexive Interaction* because they do not disturb the user's main task. To make the perception differences between no notifications, scaled notifications and forcing ones visible, participants had to undergo three studies, in which they were stimulated with different feedback modalities with varying intensities. While our findings confirm perception to be individual, such as subtle feedback was sometimes overlooked, other test subjects demonstrated to be very sensitive. Therefore, in future, it could be a challenge of finding a subtle notification appropriate for a great number of users, based on their individual threshold of perception and based on contextual factors, such as environmental noise. However, we envision a future notification system to also be capable of scaling up feedback based on contextual information (e.g., user's activity level, emotional state, and environmental changes). For instance, being in a meeting room, feedback may be subtle or silent in comparison when being in a cafeteria. If working in a factory, notifications may strongly adapt to the urgency of working task or safety monitoring. One could imagine that a system would notify the user when potential danger occurs, in an obtrusive manner, while transitioning over to a *forcing feedback* to protect the worker.

Also because the threshold of perception is individual, we can clearly see that the transition from commonly used levels of feedback to *forcing feedback* is floating. That is why making a clear cut and denoting *forcing feedback* to not being a type of notification may be questionable from our point of view. We see *forcing feedback* to be an extension of notification, because the user indeed is being made aware of a system's state change, plus an actuation created at the user's side. This mechanism of a *forcing notification* necessarily brings up ethical concerns and discussions on the role of notifications. How far are notifications allowed to direct the user? Should we better create persuasion and incentives before forcing the user to take action? Is there any better way to guide the user to execute the desired action, instead of forcing him? We believe that scaling notifications up to an obtrusive level may be the necessary step to create awareness before taking over control. Moreover, creating persuasion and incentives can be done on a contextual level, such as by making use of gamification elements with scaling notifications before *forcing feedback* becomes necessary. Nevertheless, this is out of the focus of our work, while we aimed to demonstrate the technical feasibility of scalable notifications, which incorporate a *forcing feedback* that we see as the extreme pole of notifications.

In order to underline our theoretical concept, we conducted three lab studies, which on the one hand sketch the potential usefulness, but on the other hand are not representative of real-world scenarios. Due to practicability and mainly safety reasons, we could not go to a real shop floor, nor making the subjects drive a real car. In a controlled environment, occurring effects are better recognizable and measurable, while potentially critical situations, such as when being involved in traffic and the user gets irritated by forced feedback, do not arise. Indeed, there occurred also conflicts with the user's desire, such as to stop speeding up the car, although the foot was still pressing down the gas pedal. This is especial crucial when it comes to a real world scenario. It is questionable when do we really need a forcing level? Who is taking responsibility? What type of scenarios are actually suitable? These and many other questions arise now, but which cannot be answered sufficiently in a project solely demonstrating the technical feasibility based on lab studies. Furthermore, it is evident that results gathered from a lab study may be absolutely not transferable to real world applications. In the real world, we have to fight with environmental noise and with the user's individual level of perception, which slightly varies over the day. Moreover, social acceptance of such interfaces may not be appropriate yet and thus the user may sometimes feel uncomfortable using such system. For instance, only two thirds of our test subjects (8/12 users) stated to be willing to adopt these methods of notification in a future system (choices: yes/no), although, the test subjects rated the perception of our studies to be nor uncomfortable, nor pleasant (3.3/5, based on a 5-pnt Likert-scale). The most preferred scenario was the drilling using the thermal feedback (6 of 12 users) in contrast to the haptuator (3/12) and to the EMS device (3/12). Nevertheless, we believe the general concept to be tremendously relevant in future while being applicable in distinct scenarios, such as for occupational safety applications (e.g., to support the worker and preventing to execute potential dangerous tasks, while avoiding him to touch a certain area) or for games, which usually take place in a static environment, so risks are substantially reduced (e.g., a player interacting in a VR and using multiple modalities to support multi tasking). We clearly see this project as an early impetus for future work, which may focus on applying also seamless scalable levels of notifications in a real world scenario while considering context variables, such as the user's state or environmental influences.

### 4.2.9 Conclusion

In this part of the chapter, the concept of *Scaling notifications beyond alerts* has been introduced, which extends previous work on notifications. It has been demonstrated how to scale a single feedback type until exceeding the threshold of obtrusiveness and thus forcing the user to take action. These short notifications fit well into the frame of *Reflexive Interaction*, because they can be quickly recognized without great cognitive effort. While our lab studies may be far away from being realistic and practical, they could underline our concept to work in a lab environment. Be it mechano-pressure, thermal, or electrical feedback, in each of the studies it was able to present scalable nuances of notifications, which demonstrated different effects on the task. While notifications can be scaled to be subtle, but still recognizable – favouring a *Reflexive Interaction*, it also has been shown how to scale each type of feedback to an extend that it could not be ignored by the users. When forcing the user to execute our desired action, such as sitting upright, pausing the drilling, and pressing down the gas pedal, our experiments showed a *forcing notification* to significantly improve reaction time. This favours a *Reflexive Interaction*, since executing gestures quicker means potentially less attention. Although further studies are required, the proposed notification concept, is envisioned to provide a significant benefit when implemented into real applications. Overall, a *Reflexive Interaction* is more likely to succeed, when making use of scalable notifications and considering context, such as the users' mental state, the environment and temporal variables. Besides that, an intervening notification can provide unique situational benefits, such as avoiding critical events (e.g., touching a hotplate, dangerous limp and spine postures, overregulating a control knob, crossing red lights, ...). No matter the application may look like, in future we need to have an ethical debate between the user freedom to act and the system forced intervention and thus also about possible consequences and responsibilities.

# 5. Foot: Toes & Sole

This chapter divides into two sections. To illustrate enablers for a *Reflexive Interaction*, five applications demonstrate explicit & implicit foot-based input, while five studies investigate the perception of notifications using vibrotactile feedback at the position of the foot.

This section features a variety of publications, such as: *"ShoeSoleSense"* [MMAK13, MMAK14], which has been published with Franz Müller, Christoph Anthes, and Dieter Kranzlmüller as a short paper at the *VRST 2013* (Ranking: B1, Acceptance Rate: ~29%) and as an extended Abstract at *CHI 2014* (Ranking: A1, Acceptance Rate: ~44%), *"CapWalk"* [HMBU15], which was created in a collaboration with Marian Haescher, Gerald Bieber, and Bodo Urban and published as a Full-Paper at *PETRAE 2015* (Ranking: B3, Acceptance Rate: not reported) where it received the Best Technical Paper Award, and *"CapSoles"* [MRKU17], which was published in collaboration with Thijs Roumen, Arjan Kuijper, and Bodo Urban as a Full Paper at the *MobileHCI 2017* (Ranking: A2, Acceptance Rate: ~20%). All in this thesis presented ideas, concepts, studies, and implementations have been done by myself. Except the comparability study presented in *"VR-Stepper"* [MMM+14], which had been designed by me but carried out by Felix M. Manke.

The second section, introduces five studies on the perception of vibrotactile foot feedback [MMUW15] in lab settings and in an in-situ study. This work has been published with Anita Meier, Bodo Urban and Reto Wettach as a Full Paper at the *iWOAR 2015* (Ranking: not reported, Acceptance Rate: ~68%), whereby the prototype and majority of studies have been conducted by Anita Meier. While I repeated a study with additional users, my main part was in analysing data, deriving findings and shaping this work into a publication.

## 5.1 [INPUT] Sensing Foot Input

Utilizing input via the foot yields the potential to enable a *Reflexive Interaction*, since feet are usually not often considered as an interaction channel and thus remain available for quick interactions at a secondary task. In this chapter, a proof of concept, a novel body worn interface, an insole is being introduced that enables location independent hands-free and eyes-free interaction through feet. Forgoing hand or finger interaction is especially beneficial when the user is engaged in real world tasks. However, we can also utilize feet in virtual environments, such as moving through safety training applications, but which is often conducted via finger input that is apparently not very suitable nor immersive. Demonstrated functions of the insole prototype include movement control in a virtual reality installation such as moving straight by walking-in-place, turning by dedicated weight-shifting foot gestures, and jumping. Furthermore, we can utilize dedicated foot gestures to provide explicit input such as for controlling mobile devices. However, utilizing feet, can enable a variety of other applications, which is being introduced in this section. The second section introduces the evaluation of feedback sensation under the foot.

### 5.1.1 Introduction

Interaction concepts almost exclusively make use of hands, fingers and arms. As humans learned to walk upright, former high dexterity organs like feet degenerated. The developed prototype attempts to give the human back the ability to interact once again through their feet. Much like the hand, the foot is still a sensitive organ and should be used as an additional interface to transmit information to computational devices. When in a virtual reality installation such as CAVE-like-installations [CSD+92] (in this work denoted as CAVEs) or wearing Head Mounted Displays (HMDs) like the "*Oculus Rift*" navigation and interaction can be described as a problem as it must be done blindly without visual focus on the input device. Current operating interfaces make use of hands and fingers to navigate in a virtual environment, but which is not the most ideal solution. We can overcome this problem by implementing several capacitive sensors into the insole of a shoe so that walking and jumping, among other movements, can be easily tracked. Turning is also possible by performing a simple foot gesture. By having all sensors attached to the human body the location dependent tracking problem is circumvented so free movements are possible. The proposed prototype is not affected by common tracking issues as occlusion and signal noise (e.g. in difficult lightning conditions). Because the prototype can be easily insert into an ordinary shoe, we can use such an insole interface in everyday situations, which enables for a variety of new features that is being introduced in this section.

### 5.1.2 Related Work

Sensing input through foot gestures has been early demonstrated with sewing machines and cars. Utilizing foot interaction techniques as a computational input has been initially investigated in 1988 by Pearson and Weiser [PW88]. While pressure-based gestures are already sufficient for simple input [PR04], we can also make use of toe-based, heel-rotation-based [SDYT10], and foot-tapping gestures [CBN10]. How these foot gestures can be mapped to real-world applications, has been later investigated by Alexander et al. [AHJ+12]. Other works focus on the idea of combining foot and hand input [JSS+13, LLU13, SS12]. A popular interface to detect foot gestures are pressure floors that can rely on various technologies, such as optical sensing (e.g. via FTIR), as demonstrated in *GravitySpace* [BHH+13] and *Multitoe* [AKM+10], or on piezoelectric sensing as presented in *MagicCarpet* [PAHR97], or through a resistive sensing (e.g. via FSRs) such as demonstrated in Z-Tiles [RLFP04]. However, pressure floors are not mobile and obviously require the user to stay in a specific area. Thus, they limit the user's degrees of freedom dramatically.

While foot interaction is not a new idea, wearable technology meanwhile features insoles, which have been investigated for more than three decades [HCAM82, MI78, MII+86]. Within this period, previous research focused on

(**1**) Analyzing gait to study disabilities [AHAW97, AMC98, BBS+08, KK87, MCPS07] or measure performances [GMP+06, PHH98, QHHG07, SHW+10], (**2**) Providing explicit foot gestures as an alternative control for computers [BRS+03, CPL+05, CR97, FSI15, JSS+13, MMAK14, PR04, PW88, RV05, WWZ14], and

(**3**) Providing feedback underneath the foot to enable alternative interactions that are especially hands-free and eyes-free [MMAK13, MMUW15, RV06, VBM09].

At first we will introduce existing research dealing with sensing foot input via insoles.

#### 5.1.2.1 Smart Insole Research

Over the past three decades, many types of plantar pressure measuring insoles that rely on different technologies [Urr99] (e.g. capacitive sensing [CABL13, IKM+09, MMAK13, MII+86, WQE93], resistive sensing [AHAW97, AMC98, BRS+03, BBS+08, CR97, DMS16, FSI15, Sla14], piezoelectric [GB88, HCAM82, MCPS07, PHH98], strain gauge [KK87, MI78], conductive polymer [BBS+08, WWT92, ZHW+91], air pressure [KKP+11], EFS [BBS+08], EMFI [HSK07], flexible switches [CPL+05], etc.) have been introduced. Historically grown, the main research objective was originally in gait analysis for the purpose of rehabilitation treatment [AHAW97, AMC98, KK87, MCPS07, XHA+12].

#### 5.1.2.2 Foot Input in Virtual Environments

Even if most established input devices for VR Environments usually require use of the hands, Beckhaus et al. [BBH07] believe that hands-free navigation is more beneficial since it can maximize the interactivity in VR environments. Therefore, a chair-based computer interface was developed that enables the user to move in VR environments hands-free. As Pakkanen and Raisamo [PR04] figured out, feet can be used for non-accurate spatial tasks like navigation. This effect is used by LaViola Jr. et al. [LFKZ01] to offload the navigation task to more direct motions of the feet and torso. A World In Miniature (WIM) map is being put under the users feet, to enable the user to reach all areas, with the tap of a foot on the map, in a space limited environment. Additionally, users are able to scale this map. The same approach of using WIM was pursued from Valkov et al. [VSBH10]. A multi-touch projection is used in front of the user for a non-interactive WIM and a Wii-Balance-Board on the ground for navigation tasks. Both of these techniques interrupt workflow. Nevertheless, for an even greater immersive feeling Usoh et al. [UAW+99] evaluated "*real walking*" against "*walking in place*" with the support of simple head tracking, which conveyed the position of the user to the avatar in a virtual world. The obvious limitation is the size of walking space, which restricts the user when being in a CAVE. To overcome this problem, Darken et al. [DCC97] developed the Omni-Directional Treadmill (ODT) – a ground mounted device that allows the user to walk in each direction without leaving the defined area. To track walking in place by foot gestures, Scott et al. [SDYT10] built a system that recognizes and learns foot gestures with the help of the built-in accelerometer via a commodity mobile device. To gain a reliable foot input, Higuchi and Nojima [HN10] proposed a tracking device to be mounted to the shoe sole. This solution is claimed to enable the best capability of performing foot gestures. So Nordahl et al. [NSNT12] developed shoes with integrated vibrotactile haptuators and two pressure sensors. The users wearing a HMD are placed onto a virtual snow ground. Audio feedback of squashed snow and haptic feedback at the feet create a much more immersive impression for this setup. In summary, it can be said that with the rise of virtual environments, researchers proposed a variety of approaches [BRS+03, CR97, MMAK14] to utilize foot gestures, such as walking in place, for locomotion in 3D scenes in order to increase immersion.

While foot gestures have been demonstrated to be used in VR applications, we suggest utilizing them more extensively in real live scenarios for a better multi-tasking without interruption, which enables a *Reflexive Interaction* in the future.

However, new generation pressure-measuring smart insoles yield much more potential, as we can constantly collect user-specific data over a day. This enables to generate a large variety of information (but not limited to) workout activity, a high precision detection of walking speeds [HMBU15], the recognition of dangerous foot poses, unhealthy back postures, and many other features interesting for orthopedic uses. Apparently, an insole yields great potential for healthcare applications [DMS16], but can also be used beyond that. In addition, the foot is a great place to harvest energy based on the exerted pressure while walking [SP01]. Exploring further sensing capabilities of foot is worth prosecuting.

### 5.1.3 "ShoeSoleSense / CapSoles / CapWalk"

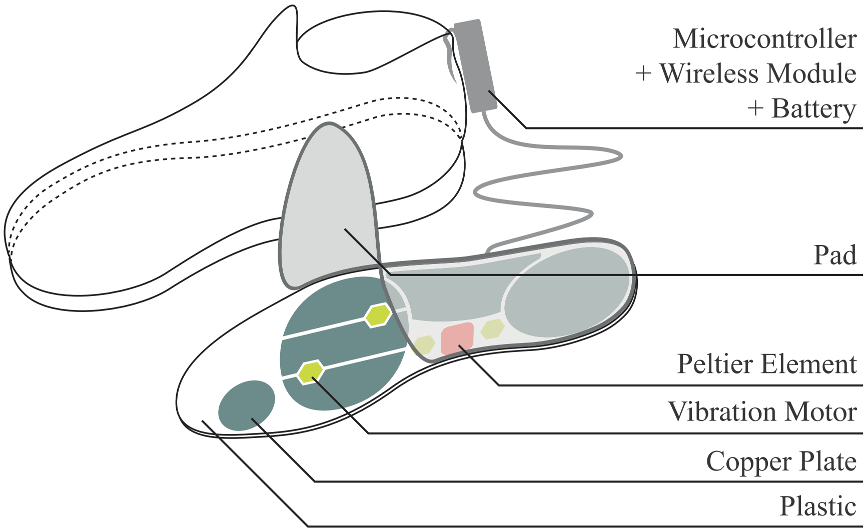


**Figure 61. The design incorporates 6 sensing areas and 3 vibrators and a heating element.**

In this subsection, the design of an insole prototype is being introduced (*see Figure 61*), that is used in several publications [MMAK13, MMAK14, HMBU15, MRKU17]. In contrast to commercially available smart insole-like products, we propose using Capacitive Sensing (CS) because it provides a richer source of data, including a pressure measurement plus a unique capacitive ground coupling effect, which is an extra information helping to detect the surface one is walking on.

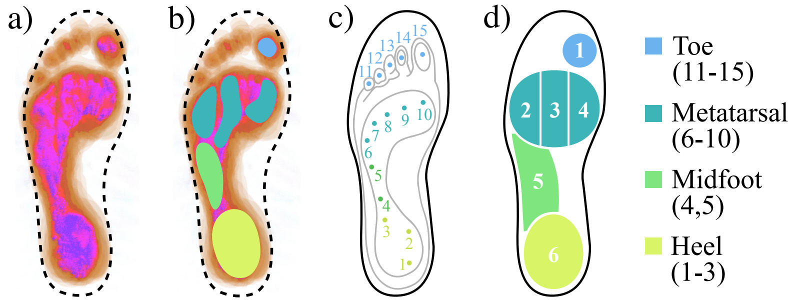


**Figure 62. Study results: a) superimposed plantar pressure pictures of 16 footprints, b) extracted significant areas with a nearest neighbor-like approach, c) in comparison to pressure points from literature by Shu et al. [SHW+10], d) final sensor layout.**

While we aimed to design a general layout compatible across users with foot sizes between 40-47, we took footprints from 16 student volunteers (sizes: 39-47) that enabled me to extract general plantar pressure distribution areas. In accordance with literature [GB88, MCPS07, SHW+10], we can determine four areas (Toes, Metatarsal, Midfoot, and Heel), which provided the basis for the layout (*see Figure 62*). Additionally, we can divide the Metatarsal into 3 sensing areas in order to gain more detailed data on the user's individual gait and to enable foot gestures, (e.g., angling the foot).


**Figure 63. The series of pictures show the assembly process of the prototype. While the final prototype can be wired to any computer, it also works wirelessly with an Android App.**

Electrodes had been cut out of copper tape and attached them to a laser-cut polyacrylate sheet in the shape of an EU size 42/43 insole, which is covered by a buffer layer (white plastic foam). This layer functions as a compressible dielectric between the sensing electrode and the foot. To prevent sweat from touching the electrodes, a black flexible plastic sheath is covering the prototype. At the bottom of the prototype, a silicon insole has been attached in order to keep the prototype in place (*see Figure 63*) after being insert. Inside the Plexiglas base recesses are made where micro vibration motors (ROB-08449) are located, of the same type used by mobile phones. Also a small power saving *Peltier Element* (TEC1-1703) is attached with modeling clay to the surface of the Plexiglas base. These parts are connected with a short cable to a black box that can be clipped onto the shoe.

In order to ensure high replicability for further research, we decided to implement the simplest CS on an Arduino Nano, using the *CapSense library* from Paul Badger[12]. Each electrode is connected to a 10MOhm resistor and a 22pF capacitor (*see Figure 64*). Due to the loading latency from our capacitive sensors, we are only capable of achieving a low sampling rate of 30Hz, but which is still sufficient for any normal walking activities.

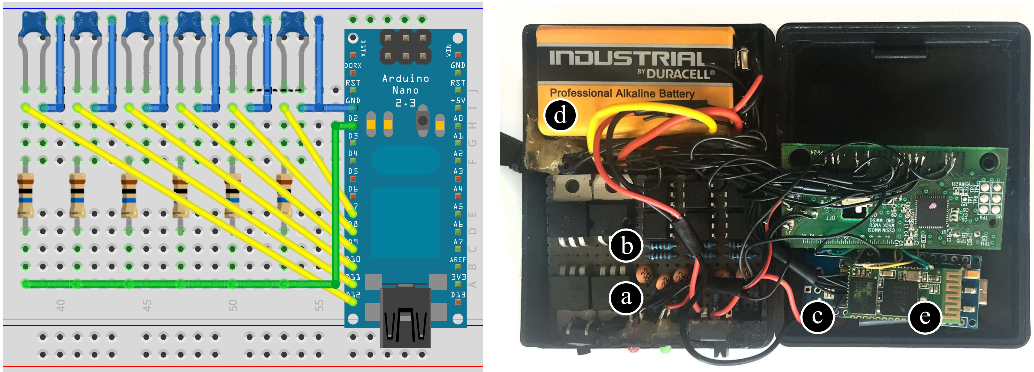


**Figure 64. Left: basic schematics of the CapSense setup. Right: shows the inside of the black box. Besides the (a) Capacitors, (b) Resistors and the (c) Arduino Nano, we can see a (d) Battery, a (e) Bluetooth shield and additional hardware (not labeled here) that enables the insole for several other features, such as the control of a *Peltier Element* and several vibration motors for feedback sensation under the foot.**

### 5.1.3.1 Capacitive Sensing (CS)

CS is a technology-approach used to measure the charging times of an established capacitor (e.g. between an electrode and the human). This sensing approach has several benefits: it is inexpensive, the electrodes can consist of various types of conductive material (e.g. a metal bar, conductive thread etc.), and it yields a high flexibility in shape and stiffness, which allows for a high degree of customization. CS can be operated in three modes (*Transmit Mode*, *Shunt Mode* and *Loading Mode*) based on the electrode arrangement [Smi99].

In order to measure physical pressure with this technology, we require the electrodes to operate in *Loading Mode* [Smi99] and a compressible buffer layer on top to cover the electrodes. For this prototype, we attached six electrodes to a laser-cut Plexiglas blank, which is covered by a 3mm plastic foam buffer pad – keeping a certain distance from the electrode to the foot. While exerting different levels of pressure, this buffer layer is being compressed consequently. Now, when charging/discharging the electrode in a certain frequency, we build up a small electrical field and calculate a capacitance based on the loading time of the electrode. With the aid of this formula of a plate capacitor, we can explain all variables that have an influence on the measured capacitance.

[12] CapSense Arduino Library: *http://playground.arduino.cc/Main/CapacitiveSensor*

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

The capacitance ($C$) between the electrode and nearing objects, such as the feet ($C_f$) and the ground ($C_g$) is determined by the relative static permittivity of the dielectric ($\varepsilon_r$), by the electrical field constant ($\varepsilon_o$), by the size of the surfaces ($A$), and by the distance ($d$) between the electrode and the grounded object.

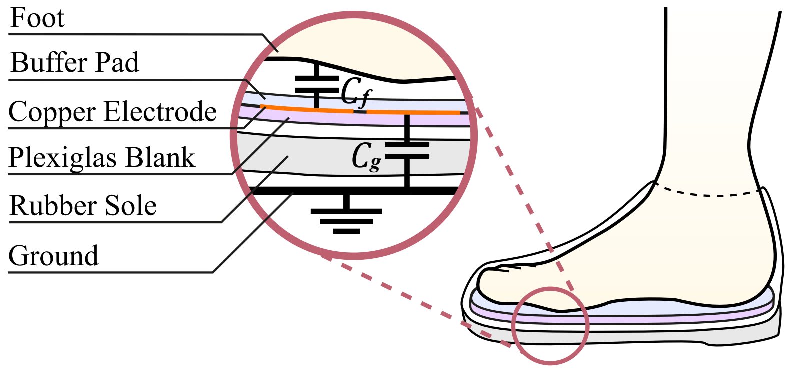


**Figure 65. Having a capacitive insole insert into a shoe, two capacitances can be found: $C_f$, which is mainly determining the measured signal based on the exerted pressure and $C_g$, which carries information on ground coupling.**

While performing a foot gestures of walking activity, the distance ($d$) is changing, which influences the calculated capacitances. Hereby, a small distance ($d$) between the foot and the electrodes results in a quite huge capacitance ($C_f$), which describes a huge force or a heavy weight. We also found out that stepping on different floors, provides a unique offset in signal, which is the ground coupling capacitance ($C_g$) that is varying based on the conductivity of the ground surface (*see Figure 65*).

### 5.1.4 Application 1: Explicit Foot Gestures

The design of the prototype features six different areas being tracked, which enables us to accomplishing input with excreting pressure. Literature demonstrates pressing down the big toe, instead of pushing a button by fingers on a handheld input device [FSI15].

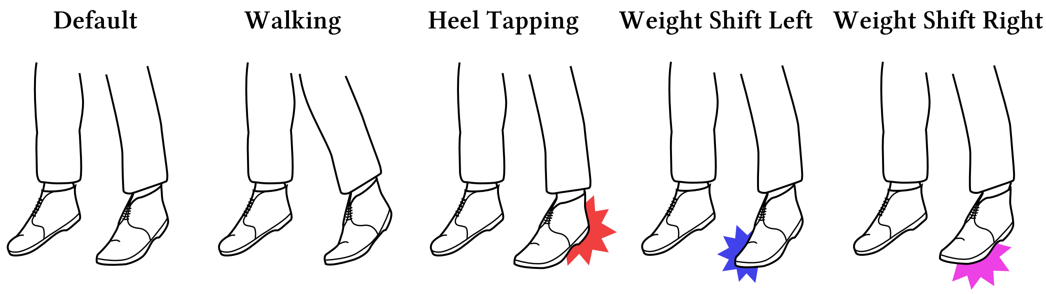


**Figure 66. Several foot gestures are being proposed based on heavy pressure input.**

In contrast, we classified foot gestures based on heavy pressure, such as different types of tapping (*see Figure 66*), which can be assigned to smartphone functionalities (e.g. switching music or responding on phone calls). Subtle foot gestures enable a fully hands-free interaction beyond *Microinteractions* and yield the potential to enable quick input without demanding any attention, which is the basis for a *Reflexive Interaction*.

#### 5.1.4.1 Foot Input in Virtual Environments

While a *Reflexive Interaction* can be enabled by quick foot gestures, such as the control of simple functions on a smartphone, this subsection introduces how feet can be used in a Virtual Environment (VE). User input in a VE is usually accomplished through simple finger interactions, such as walking in a 3D scene by pressing a button. These interactions are not very suitable for movement in VE and can interrupt the user while hindering the user to "*dive into a scene*", which we denote as immersion. Moving through scenes such as a safety training applications by walking-in-place while forgoing hand or finger input for other purposes enables a more realistic feeling, we believe. Already existing solutions, such as multi-directional treadmills, are still expensive and need additional fixation of the body. Others, like using external tracking that are usually accomplished by using statically installed cameras in CAVE-like-installations, also have limitations in terms of occlusion. Being in a virtual environment such as a CAVE-like-installation; the insole prototype enables movement through a scene by simply walking in place. Turning can be managed by executing explicit foot gestures: shifting pressure to the left or right side of the foot. Jumping can also be recognized. An additional input action can be accomplished by tapping on the ground with one's heel. The built insole prototype detects the user's movements and wirelessly forwards that data to the scene manager server.

A study has been designed, which aims to reveal insights on the difference of using commonly hand-controller, alternative input devices and making use of foot movements.

#### 5.1.4.1.1 Hypothesis

The first hypothesis (**H1**) is: moving in a 3D scene by performing leg movements on a Stepper increases immersion. The second hypothesis (**H2**) would be: letting the user involving their whole body - especially the leg movement - leads to a greater joy compared to common devices such as a Wand Joystick. However, due to the faster and more precise actions possible with a Wand Joystick and having tactile feedback when pushing the button, the Wand Joystick might be rated higher in terms of perceived reliability (**H3**).

#### 5.1.4.1.2 Pilot-Study

In a pre-test, we tested the insole prototype vs. a modified Stepper as a locomotion interface for playing Half-Life 2[13] with the *Oculus Rift* in combination the *Razer Hydra*[14]. However, the users quickly found that using such a low resolution HMD is uncomfortable, while a reference point to reality is also missing. Additionally, it was apparent that the stepper is being perceived to be much more immersive, since leg movements are much broader in comparison to just using foot gestures with an insole.

#### 5.1.4.1.3 Study Design

**Figure 67. In a stereoscopic 5-display-wall CAVE at the LRZ Munich, we tested several interfaces, such as the insole prototype, a Stepper, Wii balance board and a hand controller. All devices have been used for locomotion in a VE [MMM+14].**

Based on the results of the pre study, we decided to conduct a broader study in a stereoscopic 5-display-wall CAVE-like installation (*see Figure 67*). To gain knowledge if foot and leg movements have a positive impact when moving in a 3D scene, a within subject study has been conducted with a *VR-Stepper*, *Wii Balance Board*[15] and a *Wand Joystick*[16] in two self-build 3D scenes. The first users' task was it to run as fast as possible through a racing track, which had several hinders, the users had to dodge. The second scene was a wasteland scenario, where the user was enabled for a free walking without any task. Every subject had to go through both scenes by using each interface in a random order.

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[13] Half-Life 2: *http://orange.half-life2.com*

[14] Razer Hydra Gaming Controller *http://www.razerzone.com/gaming-controllers/razer-hydra/*

[15] Wii Balance Board: *http://www.nintendo.com/consumer/downloads/wiiBalanceBoard.pdf*

[16] Flystick 2: *http://www.ar-tracking.com/products/interaction-devices/flystick2/*

After completing all scenes with every interface a questionnaire had to be filled out, which was asking the user to rate the following on a 5-point Likert scale: (1) Ease of Use (2) Joy of Use (3) Feeling of Immersion (4) Impression on Reliability. The system has been evaluated with one group of 10 participants (8 males, 2 females), with an age between 15 and 55.

5.1.4.1.4 Results

*Ease of Use:* A *one-way ANOVA* on the device factor showed a significant difference in terms of ease of use ($F_{2,18}$=5.96; $p$=.01). A *Tukey HSD Test* suggests that the joystick ($M$=3.4) is significantly easier to use than the *VR-Stepper* ($M$=2.2; $p$<.01). No other differences yield. In terms of *Joy of Use*, a *one-way ANOVA* showed no significant difference ($p$>.05) between all devices. However, the *VR-Stepper* ($M$=4) was deemed more joyful than the joystick ($M$= 3.3) and the *Wii Balance Board* ($M$=3.5). The *Feeling of Immersion* was not significantly different following a *one-way ANOVA* ($p$>.05) while all devices resulted an averaging around rating between 2.9 - 3.6. In terms of *Impression of Reliability*, a *one-way ANOVA* found a significant difference in terms of reliability ($F_{2,18}$=22.18; $p$<.0001). A *Tukey HSD Test* determined that the joystick ($M$=3.4) was perceived as more reliable than the *VR-Stepper* ($M$= 2.1; p <.01) and the *Wii Balance Board* ($M$=2.0; $p$<.01).

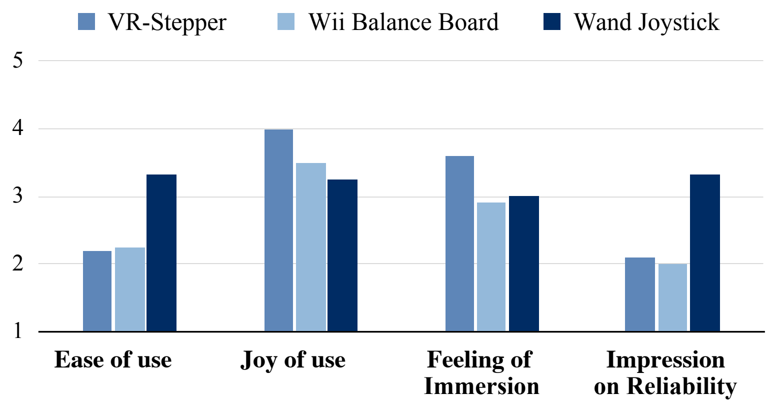



**Figure 68. Summarized quantitative results (mean performance) for each test criteria.**

5.1.4.1.5 Summary

Analyzing the data (*see Figure 68*) showed that using a *Wand Joystick* is significantly easier. Confirming the hypothesis **H3**, the reliability was also significantly rated much higher. Although, the *VR-Stepper* was experienced, in terms of immersion and joy slightly better than the other tested interfaces, we still have to reject hypothesis **H1** and **H2** because the difference was not great enough, yet. Therefore, this short study could not statistically prove that the physical movement of legs results in a raise of immersion. However, a broader study with a doubled sample size and similar feedback would possibly deliver a statistically significant difference for leg movements in terms of immersion. In our application, perceiving a higher immersion is a good indicator for the fact that the user did very much dive into the primary task, while his main attention was drawn there. Therefore, we can only indicate a *Reflexive Interaction* here.

### 5.1.5 Application 2: Recognizing Body Postures

A *Reflexive Interaction* is very much depending on the low complex design of an interaction. Moreover, we can additionally favour a *Reflexive Interaction*, such as by adjusting the output of a system to the user's context. One type of context could be the activity, the user is involved at, or the user's mental and physical state. Using the feet can be used to support in providing this information. While we can recognize whether the user is walking, it is also possible to detect the user's current body posture. For instance, an effective response to a notification in a manner of a *Reflexive Interaction* may not be possible when kneeling or carrying weight.

In addition, the detection of body postures can substantially complement current activity recognition, while it may also be very interesting for future health services, such as when estimating the risk level of falling for elderly people. We tested the insole prototype towards recognizing body postures, including: *standing, sitting, kneeling, lying,* and *carrying a weight of 50kg*. We recorded a small data set containing each posture from three users. When applying a data mining algorithm while using a Random Forest classifier, one can achieve 100% accuracy in separation sharpness.

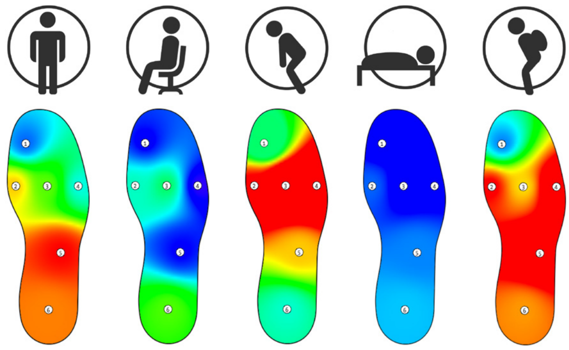


**Figure 69. Heatmap snapshot of planar pressure distribution for 5 postures: standing, sitting, kneeling, lying, and carrying.**

However, based on the visualization (*see Figure 69*) we can see that the difference is already obvious for the human eye and expensive data mining may not be required for a simple posture detection. Therefore, we can calculate a single feature that only relies on two electrodes (the middle front electrode $S_3$ and the heel electrode $S_6$).

$$\textit{Simple Posture Feature} = ((S_3 - S_6)\frac{S_3}{S_6}) + S_6$$

We used 30 samples of each posture and compared their *Simple Posture Feature* using a *one-way ANOVA* ($F_{4,144}$=271.31). It turned out that this single feature is already capable in sufficiently distinguishing all 5 postures with a high significance (*Tukey HSD*, $p$<.0001). Thus, this feature could be easily implemented with two pressure-sensitive sensors of any kind. Because the user's weight and foot shape is individual, we suggest a user-dependent training. Using more than two pressure points yields the potential to enable a detection of unhealthy carrying and lifting.

### 5.1.6 Application 3: Recognizing Walking Styles

As mentioned before, the user's physical activity can have a major influence on success of a *Reflexive Interaction*. Depending on the sensed activity and context, a system must decide what kind of information may be submitted to the user. As a matter of fact, the increasing amount of data and information leads to a higher cognitive load [Duv11] or to distractions, when being involved in real world tasks. Activity recognition systems therefore should not just visualize data the user was not aware of, but also help to adjust the behaviour of devices to the user's current activity state (such as by considering the users walking style). For instance, a system may autonomously decide, based on the user's activity status, to not disturb him with incoming phone calls.

In this subsection we demonstrate what kind of walking-based activities are being recognizable with a capacitive insole (*see Figure 70*). While accelerometry-based walking detections suffer from reduced accuracy at low speeds, the technology of capacitive sensing uses physical distance parameters, which makes it invariant to the duration of step performance. Determining accurate levels of walking activity is a crucial factor for people who perform walking with tiny step lengths such as elderlies or patients with pathologic conditions. In addition, this approach is less affected by external influences such as bad lighting conditions, while it is also invariant to external acceleration artifacts. Moreover, it enables reliable recognition of a very slow walking, in which accelerometer-based implementations can fail or provide high deviations.

We evaluated the recognition of sneaking, normal walking, fast walking, jogging, and walking while carrying weight. This information can additionally be used to assist special user groups such as diabetics, whose optimal insulin dose is depending on bread units and physical activity or elderlies whose personalized dosage of medication can be better determined based on their physical activity. Determining walking activity can also indicate the user's stress level and health status, while we can data mine on anomalies and evaluate workout performance.

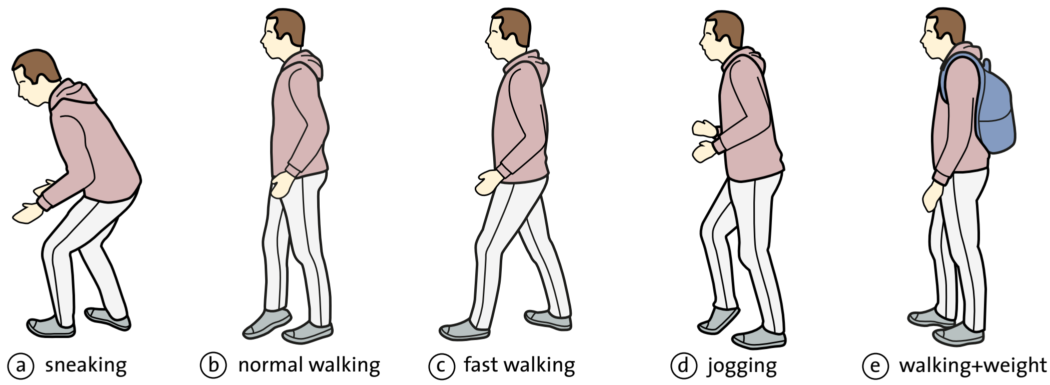



**Figure 70. We evaluated the detection of various walking activities while using three self-built prototypes for the recording process. The walking activities are: a) sneaking - 1km/h, b) normal walking - 2.5 km/h, c) fast walking - 4km/h, d) jogging - 5km/h, e) walking while carrying weight - 2.5 km/h**

#### 5.1.6.1.1 Study Design

To prove feasibility, we conducted a within-subject study while recording sensor raw data according to each walking activity. 13 participants (including 1 female) performed the within-subjects experiment. The participants had an age of 22 - 49 years and weighed between 58 - 93 kg. Their height was 1.72 - 1.92 m. All participants were within +/- 10% of their optimal body mass index. None of them had walking disabilities. In the experiment, the user was instructed to perform different locomotion styles, which had to be executed in the following order: 1. *sneaking* (1 km/h), 2. *normal walking* (2.5 km/h), 3. *fast walking* (4 km/h), 4. *jogging* (5 km/h), and 5. *walking while carrying weight* (2.5 km/h). The different walking styles have been carefully chosen to represent a broad spectrum of walking-based activities, beginning with very slow movements (involves steps with very low impact) and fast movements (includes steps with very inelastic hard impacts). The sneaking task had a unique style of execution (slightly ducked posture) to guarantee an elderly walking style with a very slow movement, low impact and a small amount of steps. All users were asked to perform each action for at least one minute, while the study leader was taking the time and controlling the experiment. A technician was taking care of the prototypes and monitoring the data collection process. During the walking on the treadmill (for the fifth task), the user had to carry a backpack with a weight of 8 kg (~10% of the mean weight of all subjects).

#### 5.1.6.1.2 Feature & Classifier Selection

For the purpose of feature extraction, a window size of 512 samples (approx. 17 seconds) has been chosen. The following features have been extracted: (1) frequency with the highest amplitude, (2) highest significant frequency, (3) spectral centroid and (4) signal energy. The very small feature set was intentionally selected to avoid over-fitting effects. We selected the features in an empirical investigation to describe the main characteristics of the raw data signal (e.g. stride frequency). Moreover, we wanted to avoid using features that are interdependent and or redundant regarding their characteristics. The rather big window size was chosen to enable the recognition of very slow movements, as commonly performed by elderly people. To compute feature vectors for each activity set of 1800 samples, as given by the raw data recording, the features where generated by overlapping windows. Therefore, the window of 512 samples was sliding over the data with an overlap of 87.5%. In conclusion, the window slides in steps of 1/8 of the current window size over the raw data. As a result, 28 instances with feature vectors of four elements are extracted for each activity. Due to technical issues, the number of instances per subject differed slightly for each sensor setup. Based on the generated feature files, a set of classifiers was trained to analyse the recognition performance. The *Weka workbench tool* in version 3.6.11 was utilized for the evaluation. We compared the recall rates for *Naïve Bayes* (*NB*), *Bayes Net* (*BN*), *Nearest Neighbor* (*NN*), *C4.5 decision tree* and a *Random Forest* ensemble decision tree classifier, determined by a leave-one-out cross validation. The results show best recognition rates when applying the *Bayes Net* classifier (*TP*=~86%).

#### 5.1.6.2 Results

To gain a more realistic impression on recognition rates, we applied a leave-one-out cross-validation with unknown data using our selected classifier. Figure 71 shows the overall-performance of the recognition (recall rate) per subject for all prototypes. The blue tinted bars show the recognition results using all 5 classes. The red bars show the “*corrected*” outcome when the activities of *normal walking* and *walking with weight* are being considered as one class. A detailed confusion matrix can be found in Table 8.

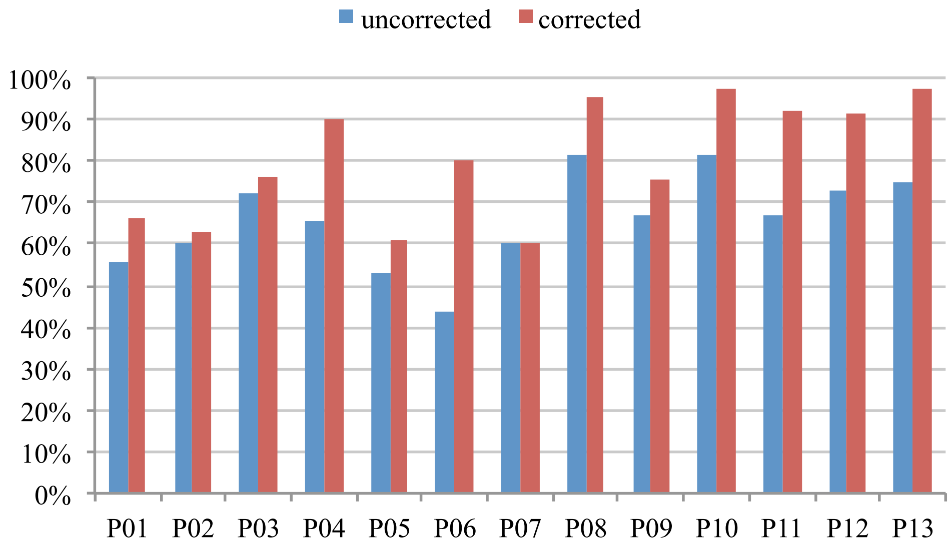



**Figure 71. The overall accuracy of each test subject (determined with a leave-one-out cross-validation by a Bayes Net classifier)**

Apparently, the insole prototype must be able to detect when carrying weight, because of the overall changing in terms of signal intensity due to a higher pressure on the buffering layer. In fact, the data analysis did not yield these results, because of an inevitable signal filtering process (*Offset-*, *High-pass-*, *Median-Filter*), which erased most differences. The filter was applied to overcome a drift effect, caused by the buffering material being squashed between foot and electrode over time.

| a | b | c | d | e | ← classified as |
|---|---|---|---|---|---|
| **301** | 11 | 0 | 3 | 23 | a = sneaking |
| 12 | **194** | 34 | 14 | 72 | b = normal walking |
| 4 | 16 | **250** | 21 | 21 | c = fast walking |
| 15 | 1 | 22 | **286** | 3 | d = jogging |
| 18 | 66 | 45 | 9 | **189** | e = walking + weight |

**Table 8. Accumulated confusion matrix across all users. It is striking that walking with weight has a high confusion with walking, because 1) the load was not very significant and because 2) heaving filtering was applied.**

Understanding the user’s activity level can be crucial for a *Reflexive Interaction*, which is now being enabled by a precise recognition of his walking activity.

### 5.1.7 Application 4: User Identification

In future, we will own numerous types of wearables, implants or body-carried devices that permanently sense various kinds of personal data and communicate with one another in a body sensor network. Thus implicit authentication based on biometric data is expected to become much more relevant. While user habits like users' cognitive resources can both be very individual, knowing about that and identifying the user may also be interesting when adjusting input and feedback modalities to achieve a *Reflexive Interaction*. For instance, gesture sets for picking up a phone call may be set individually per user.

#### 5.1.7.1 Background

Different users demonstrate different physiological and anatomical properties, which on the one hand creates a challenge for HCI designers when designing generalizable interfaces, but which on the other hand provides many indicators for identifying the user. Since the leg length, body weight, roll-over movement, foot shape and size as well as the plantar pressure distribution are all individual, we can already see a lot of user-specific differences. When it comes to walking activities, we can perceive an individual leg/foot movement, and that different users inconsistently perform shorter or longer steps for the same walking speed. Considering these factors, we can account for an individual gait, which we are able to recognize indirectly based on the change of the plantar pressure distribution measured in certain time intervals (*see Figure 72*).

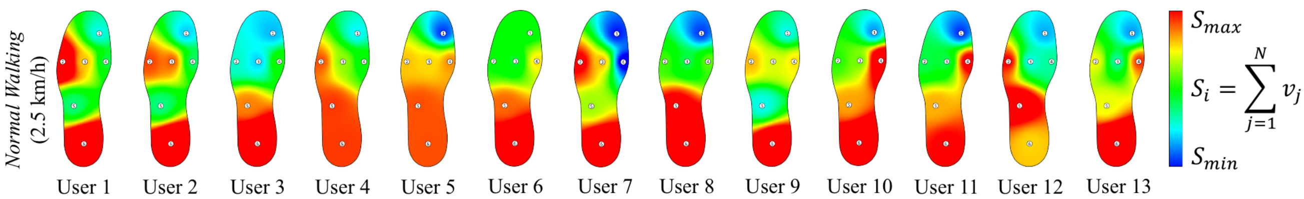



**Figure 72. Plantar pressure distribution over one minute of normal walking (2.5km/h) on a treadmill. ($S_i$ = sum of sensor values; $v_j$ = sensor value; N = 60s*30Hz = samples)**

#### 5.1.7.2 We consider the following research questions:

**Q1**: How accurate is a system in distinguishing different users?

**Q2**: How much time does the system require in order to recognize an individual user?

**Q3**: Is there a difference in recognition rate for other walking activities such as jogging?

#### 5.1.7.3 Study Design

To find answers, we conducted a lab study with 13 participants (including 1 female). The test subjects were from ages 22 - 49 years old and weighed between 58 - 93kg. Their height (1.72 - 1.92m) and shoe size (41 - 46) were in the average range for Central Europeans. In order to establish comparability, all participants had to wear the same shoes (EU size 44) in which we inserted one of our insole prototypes (left side). We avoided using the user's own shoe to prevent possible irregularities based on the structure of the sole. Because of the varying foot sizes, we physically modified our pair of shoes by cutting it open at the front and side to increase wearing comfort. None of our test subjects reported walking disabilities. All users were instructed to perform two walking styles: *normal walking* (2.5km/h) and *slow jogging* (5km/h) on a treadmill so we could control the walking speed (*see Figure 73*). We asked all users to perform each activity for at least one minute.

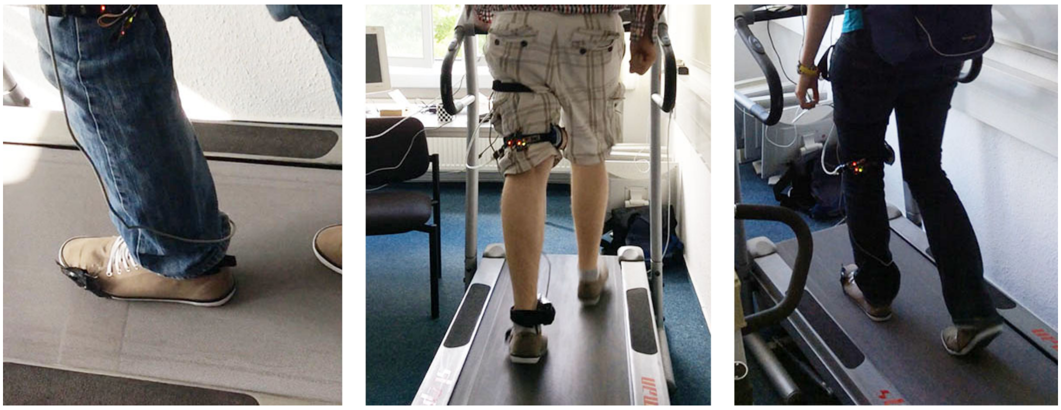


**Figure 73. We ensured comparability with a homogeneous setup across all users (constant speed, same modified shoe, same ground - a laptop with 8735mAh). The type of the treadmill was a Buffalo MTR 818. In addition, we applied a capacitive leg band in order to try identifying the user solely based on stride frequency, but which was not very satisfying.**

### 5.1.7.4 Feature & Classifier Selection

We can calculate 49 features based on the unfiltered raw data of each of the 6 sensor electrodes (providing 14bit), which resulted in a total of 294 features. While the classifiers would automatically select the most meaningful attributes, we still ran a *Greedy Stepwise (forwards)* [Car94] algorithm that determined 27 features to be the most meaningful: *maxAmpFrequency (sensor 1,2,6), spectralFlux (s.2,6), spectralEnergy (s.6), logLikelihood (s.1), averageAbsoluteDifference (s.3,4,6), meanCrossings (s.2,4), geometricMean (s.1), firstQuartile (s.1), interquartileRange (s.4), maxElement (s.1), minMaxDifference (s.1), skewness (s.4,6), kurtosis (s.3), difference (s.1&4, 1&5, 2&6, 3&4, 4&5, 4&6, 5&6).*

In order to find a suitable classifier, we analyzed the generated feature files with the *Weka data mining tool* v3.7.12 [HFH+09] and applied a stratified 10-fold cross validation to determine the theoretical classifier performance. We compared five state-of-the-art classifiers (*Bayes Net - BN*, *Naive Bayes - NB*, *Random Forest - RF*, *Nearest Neighbour – IBK* and *Sequential Minimal Optimization – SMO*) with an *ANOVA for correlated samples*, which yielded significant differences ($F_{4,48}$=5.03; $p$=0.002). A *Tukey HSD Test* suggests that both the *BN* (*TP*=96.7%; *SD*=0.48%) and the *RF* (*TP*=97.8%; *SD*=3.14%) performed significantly better than the *IBK* (*TP*=88.5%; *SD*=2.69%; $p$<.05) and the *SMO* (*TP*=93.4%; *SD*=13.04%; $p$<.05). The *NB* (*TP*=92.9%; *SD*=1.06%) was in midfield and did not significantly perform better. For further investigations, we have chosen the *Random Forest* based on the highest mean performance.

#### 5.1.7.5 Discussion

Our signal gathering process is a straightforward data mining approach. We have 6 planar distributed electrodes providing unfiltered raw data, which we use for calculating 294 (49x6) features. The data implicitly incorporates the user's step length, body weight, foot shape and size, and roll-over movement. While we did not compute each of those parameters separately as additional features, we, however, suggest doing so for future implementations, because it may slightly boost recognition rates further. To avoid redundant data, we have chosen to use a non-overlapping window approach instead of a floating window approach, although this way we must deal with fewer and smaller instances. Due to the nature of our hardware setup, the sensed capacitance of each electrode reflects a mixture of the exerted pressure by the foot plus a ground coupling effect. With a single-layer-electrode setup, decomposing the signal is barely possible. Nonetheless, measuring both, ground-coupling and pressure sensing, separately would require three layers of electrodes; while the bottom electrode would be used to extract ground-coupling, the middle one would be a shielding electrode, and the top electrode would measure plantar pressure exerted by the foot. Although the top electrode layer could be replaced, for example, with a resistive sensor, we do not expect this to be simpler nor cost-effective, since CS already counts to the most flexible and low-cost sensing technologies. On the one hand, CS yields a high versatility in use, while it can measure distances, densities or even pressure. At the same time its very sensitive towards any electrical changes. On the other hand, this can also be disadvantageous, since the system can be interfered when entering electrostatic environments. Another peculiarity one must be aware of is the influence of the system's ground capacitance. In our tests, we usually connected the prototype to the ground of a battery (8735mAh) from a MacBook Pro in order to avoid irregularities of a changing $V_{CC}$. It is to note that operating CS with a Power Supply Unit (PSU) enables for a significant higher sensor range and a higher Signal-to-Noise Ratio (SNR) than operating it by battery. Therefore, recognition rates may further increase when using a PSU. In terms of health safety; CS works with a harmless low voltage. In our setup we even do not expose the user to any voltage, since no body part ever touches a blank electrode.

#### 5.1.7.6 Results

**Q1**: In order to see how the system performs with unknown data, we applied a leave-$k_{Instances}$-out validation, as we split the recordings of all users equally into training and test sets as described before. As seen in Figure 74, the ability to correctly identify users grows with an increasing window size (window size: 4; confidence: 75.76% → window size: 256; confidence: 100%), but causes a longer recognition time (window size: 4; recognition time: 0.13s → window size: 256; recognition time: 8.53s). **Q2**: The time required for identification is mainly constrained by the window size. A quite accurate identification of the user with 94.78% is already being achieved after performing a normal walking activity over 1.07s. Q3: We can perceive that the accuracy drops by ~10% for jogging as compared to walking. The reason for this is twofold: (1) None of our test subjects were familiar with jogging on a treadmill. Therefore, they experienced the walking and running activities as an unnatural movement. This caused a higher variance of execution among many users, which produces a randomness and, in conclusion, inaccuracies. (2) The prototype's sample rate is not optimal for high step frequencies, such as when jogging. Using a more advanced capacitive sensor such as the FDC2214 from Texas Instruments[3] would overcome this issue.

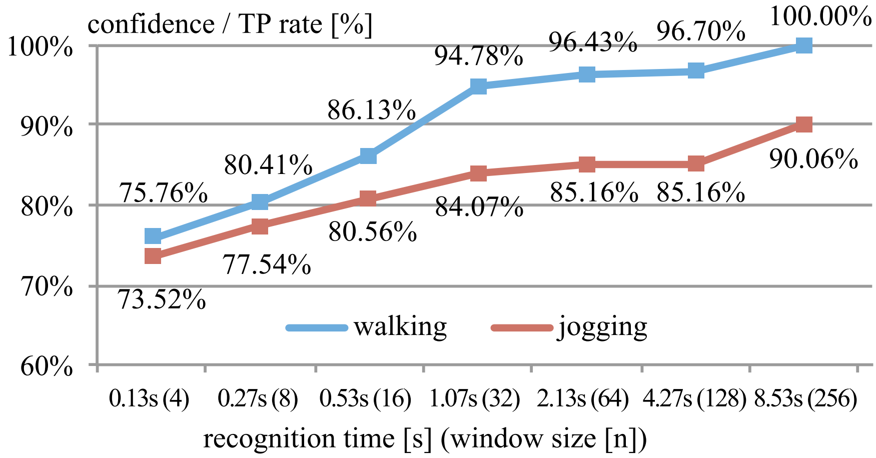



**Figure 74. Smaller window sizes reduce recognition time but decrease the system's confidence for a correct identification**

To create more constant variables, we used the same shoe and preset a speed level in order to compare gaits. However, in reality, users yield their individual walking speed, while they would wear their own shoe, but which would both further improve identification. In contrast to literature, we base our identification on a plantar pressure distribution with an insole. Additionally, we provide insights in theoretical recognition delays, which is usually also not reported in literature. Understandably, one might say that >8s for authentication of a user, based on a pool of 13 users, would be too long – especially when wanting to access a mobile phone. However, in reality the pool would be reduced down to two users (owner and thief), thus recognition delay would substantially decrease. Furthermore, authentication in reality would be possible without any delay while using a generated security token. As mentioned, a recognition delay would only appear right after changing the pair of shoes. Potential impacts of real-world influences, such as temporary gait influences caused by a broken knee, or temporary weight incensements when carrying an object, etc. have not been investigated, but are expected to be problematic.

### 5.1.8 Application 5: Ground Surface Detection

As extensively mentioned before, especially the context plays a major role when implementing a successful *Reflexive Interaction*. Recognizing the type of floor one is walking on can indicate whether the user is in/outside, or even in a dangerous situation (wet and electrified environments). All these factors can now be considered for a system to provide a suitable set of interaction modalities in mobile scenarios.

#### 5.1.8.1 Background

The structure of ground surfaces has a considerable impact on our gait. Floors can demonstrate high variances in structure (e.g. lawn), surfaces can be slippery and smooth (e.g. ice), or very soft and relent (e.g. sand). While measuring plantar pressure distribution, we can perceive noticeable deviations in gait when walking on different types of floors. Since we utilize capacitive sensing, we additionally perceive a unique change in ground coupling for different ground surfaces. Most differences can be found between insulated floors (e.g. dense carpet) and wet or energized surfaces. In this study, we conducted tests to distinguish between walking on sand, lawn, paving stone, tartan, linoleum, and a carpet.

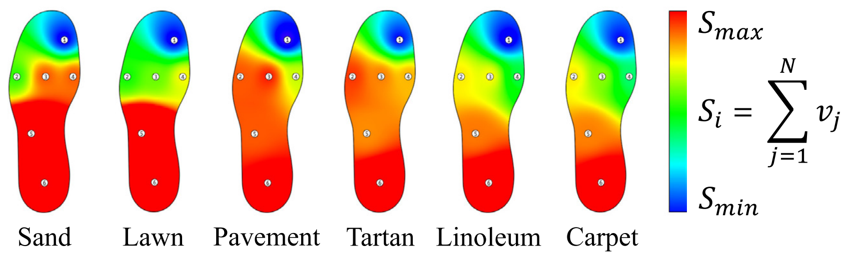



**Figure 75. Plantar pressure distribution over 15s for normal walking (2.5km/h) of a single user. ($S_i$ = sum of sensor values; $v_j$ = sensor value; $N$ = 15s*30Hz = samples)**

Figure 75 indicates the change in gait when walking on soft and relenting surfaces. One may assume that only computing features for the Metatarsal (sensor 2,3,4) is already sufficient for a ground surface detection. However, we consider all sensors, which allows us to see the roll-over movement and the slightly varying offset received from the ground coupling.

#### 5.1.8.2 We consider the following research questions:

**Q4**: How accurate is the system in distinguishing ground surfaces while responding to unknown data?

**Q5**: Which types of ground surfaces are more often confused?

**Q6**: How much time does the system require in order to recognize a different ground surface?

#### 5.1.8.3 Study Design


**Figure 76. All users were instructed to walk 30s straight across six different types of floors, which were: a) Sand, b) Lawn, c) Pavement, d) Tartan, e) Linoleum, and f) Carpet.**

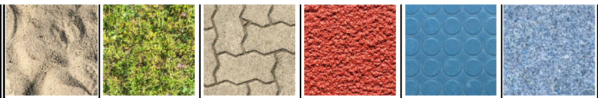
We recruited 11 participants to take part in our second experiment. The test subjects were between 23 – 37 years old (including 1 female). Their shoe size was 40 – 45 (European size), weight 60 – 98kg and their height 1.72 – 1.87m, which is in the average range for a Central European. As previously, all users were wearing the same prepared shoe to avoid the feet sliding in the shoe. All users were instructed to walk on six different ground surfaces (*see Figure 76*) for at least half a minute while following the study leader who was walking in front of the subject with a speed of 2.5km/h. Since we learned from the previous study that our prototype does not provide a good sample rate for fast walking activities, we did not ask the subjects to perform jogging.

#### 5.1.8.4 Results

To prove the feasibility of our idea, we again divided all recordings into two equal sets (training / test) and applied a leave-$k_{Instances}$-out method in order to see how the system performs with unknown data (*Results: see Table 9*).

**Q4**: Distinguishing carpet from other grounds seems to work quite accurately (89.36%). In general, the sharpness of separation between hard and soft floors can be considered as easily distinguishable. **Q5**: Much confusion occurred between the soils of sand and lawn due to the soft surface that caused many random irregularities at the foot roll-over movement, since the feet erratically slipped into the ground. We can also find some confusion between tartan, linoleum and paving stone, because the influence in gait is not substantial and the underlying stone provides a similar ground coupling effect. Still, we can distinguish them with an average accuracy level of 82.46% at a window size of 128. **Q6**: Similar to our first study, the window size affects accuracy and recognition latency accordingly. Thus the chosen setup causes a delay of 4.27s.

**Table 9. Since each user has an individual gait, we generated confusion matrices for each user and accumulated them into one matrix for the window size of 128.**



| classified as > | a | b | c | d | e | f | Recall |
|---|---|---|---|---|---|---|---|
| Sand = **a** | 72.4% | 15.2% | 2.9% | 0% | 2.9% | 6.7% | **72.38%** |
| Lawn = **b** | 9.3% | 86.9% | 1.9% | 1.9% | 0% | 0% | **86.92%** |
| Pavement = **c** | 5.1% | 1% | 84.7% | 4.1% | 3.1% | 2% | **84.69%** |
| Tartan = **d** | 1% | 1% | 10.6% | 78.8% | 6.7% | 1.9% | **78.85%** |
| Linoleum = **e** | 0% | 0% | 5.9% | 7.8% | 83.3% | 2.9% | **83.33%** |
| Carpet = **f** | 3.2% | 3.2% | 1.1% | 2.1% | 1.1% | 89.4% | **89.36%** |
| | | | | | | **Ø** | **82.46%** |

#### 5.1.8.5 The "Blind Test"

Both parameters, the user's individual gait and the ground surface specific deviations, are closely intertwined, because the user's gait is effected by ground specific characteristics. As we saw before, in our first study, knowing about the floor enables us to identify the user quite precisely. At the second study, the system learned the uniqueness of the users' gait, and was then able to infer on the current ground surface. Now, a question is still left: Could a system make sense out of completely unsupervised data and still be capable to correctly identify both, an *unknown user* walking on an *unknown ground surfac*e, at the same time?

We conducted a "*blind test*" in which we performed some more data mining in order to try to identify 11 unknown users walking on 6 unknown floors. Without revealing the ground truth to our classifier, we again trained the system with the first half of our data set and applied a *leave-*$k_{Instances}$*-out method* on the independent test set. We kept a window size of 128 and used a *Random Forest* classifier. Surprisingly, the system was still capable of correctly identifying 75.82% instances. Table 10 summarizes the overall accuracy rates in this subsection for the given setup.

**Table 10. A summary of the recognition rates for the following setup: window size: 128; Recognition latency: 4.27s; normal walking speed 2.5km/h; classifier: *Random Forest*.**

| | **User is *known*** | **User is *unknown*** |
|---|---|---|
| **Floor is *known*** | 100% | 96.70% |
| **Floor is *unknown*** | 82.46% | 75.82% |

In fact, accuracy becomes comparably low, 75.82%, when both types of information are unknown. However, we must acknowledge that these rates represent the accuracy after a very short period of walking (4.27s). As we can see in Figure 75 confidence rises when walking longer periods. Also, we envision a future system to learn the user's gait over time. Furthermore, we believe the implementation of an advanced user-independent ground surface detection in the future would benefit from excerpting and isolating (1) surface specific gait characteristics and (2) the effect of ground coupling.

#### 5.1.8.6 Wet Ground Surfaces

A detection of wet grounds is especially enabled by using capacitive sensing and can enable new applications as sketched earlier. Because liquids, such as water, increase conductivity, wet ground surfaces provide a different ground coupling. We conducted a brief test with three users wearing their own shoe with the inserted prototype, while the insole was wired to a MacBook (powered by 8735mAh battery). We watered 5m of paving stone and instructed the users to walk across both ground surfaces for 30s.

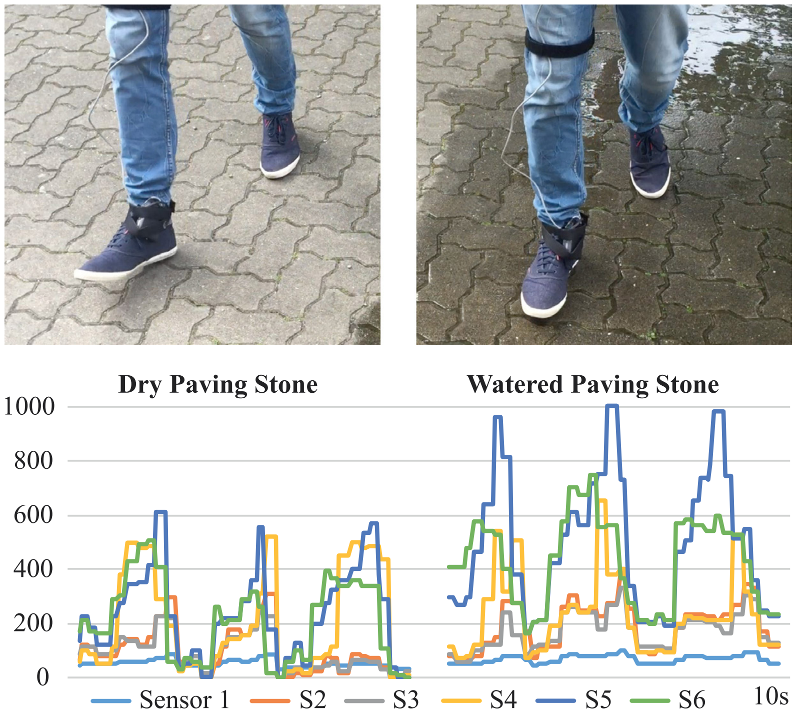



**Figure 77. Showing three steps on dry paving stone (left) and watered paving stone (right). Wet surfaces demonstrate a significantly increased sensor range.**

The results are evident; wet ground yields higher conductivity and enables for a greater sensing range (*see Figure 77*). This is confirmed by a simple ***t-Test*** ($p$=.01) when comparing the overall mean-values of all six sensors between group A: dry paving stone ($M$=143.01) and group B: watered paving stone ($M$=240.86).

#### 5.1.8.7 Electrified Ground Surfaces

Recognizing electrical charged environments may be life-saving. In this subsection, we introduce the behaviour of capacitive insoles when being on electrostatically charged ground surfaces. To demonstrate the effect, we set a metal surface under low voltage. We took measurements from the insole while it was lying naked on the ground and while being inserted into the shoe to show the absorption caused by sole thickness (*see Figure 78*). For both conditions we took 8 measurements (0V, 1.8V, 3V, 4.5V, 6V, 7.5V, 9V, 12V), which we repeated for three times. In contrast to wet surfaces, metal-based surfaces that are set under voltage result in a decrease in sensor range plus an increased offset in sensor data (*see Figure 78*). Comparing the idle *Signal-to-Noise Ratio* (SNR) from the naked insole shows the following significant differences for the SNR idle between 0V ($M=0.5$) and 1.8V ($M=2.57$) confirmed by a pairwise *t-Test* ($p=.045$): The signal range already shows great differences between 0V ($M=138$) and 1.8V ($M=78.3$). For this small sample size, a statistical significance occurs starting from 7.5V ($M=62.7$) following a simple *t-Test* ($p=.024$). A significant difference in terms of received signal offset has been found between 0V ($M=13.3$) and 12V ($M=148$) by a pairwise *t-Test* ($p<.0001$).

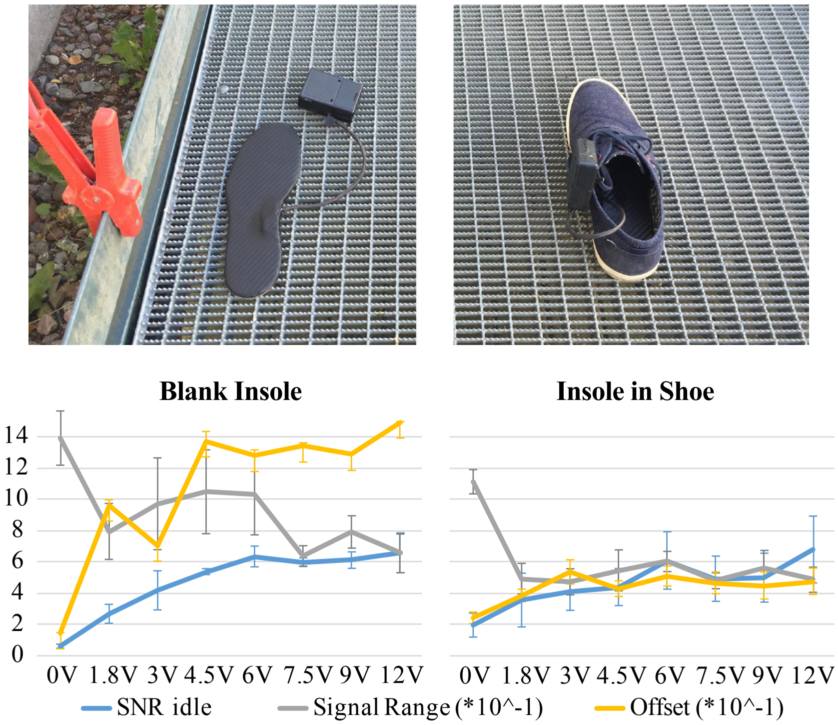



**Figure 78. Shows the difference (SNR, Signal Range, Offset) when standing on an electrified ground surface. Minimizing the thickness of shoe's sole increases the detectability of charged ground surfaces.**

Similar effects can be found when inserting the insole into the shoe. Although the signal range provides statistical differences ($p=.01$) between 0V ($M=109.7$) and 1.8V ($M=47$), we cannot prove any other statistical differences due to the marginal sample size ($n=3$). Greater sample sizes are expected to provide a statistical evidence of this effect. Also to note: as long as the shoe touches the ground, we can sense a difference, but not anymore when lifted in a height of ~10cm while dealing with such small charge up to 12V.

### 5.1.9 Conclusion

In this section, an insole prototype has been introduced that is based on Capacitive Sensing and enables to sense plantar pressure distribution under the foot and an additional ground coupling effect. These technical capabilities enable for a variety of new applications, such as sensing explicit foot gestures for a control. Making use of simple foot gestures (*section 5.1.4*) does not disturb the user's main task and thus abet a *Reflexive Interaction*. While the idea of a *Reflexive Interaction* is to provide the user with suitable input and feedback modalities, in order to not interrupt the primary task, it is apparent that a varying context can influence interaction significantly. For instance, when walking or laying down, a foot tapping gesture is impossible to be performed and thus detecting the users current body posture (*section 5.1.5*) is essential to be considered. Another important information, which should be taken into account, is the current walking activity (*section 5.1.6*). There are unfavourable situations, which may require the system to avoid a disturbance, or to apply a different interaction set to enable a *Reflexive Interaction*. For example, when being in a hurry, such as indicated by a faster walking, or when working out while jogging. In addition, user behaviour may be different, as well as the user's preference of the assigned gesture sets. Therefore, implicitly identifying the user (*section 5.1.7*) in any situation and making this information available for cooperating systems is another importing information to favour a *Reflexive Interaction*. The last context information sourced by feet, is environmental information, such as to detect whether the user is located outside or indoors or in specific areas. In conclusion, the position of foot has been showed to be a suitable position to infer on a verity of context, which is useful information to be considered when designing *Reflexive interactions*.

## 5.2 [FEEDBACK] Vibrotactile Foot Feedback

While accomplishing quick and subtle input via foot gestures, we can also perceive notifications through our feet. Because the foot is not very often considered as an interaction channel, it would not interrupt the user in his primary task and thus favours a *Reflexive Interaction*. In order to find out how a user would perceive feedback under the feet in a mobile scenario, vibrotactile on-body feedback is being evaluated while the user is involved in a typical primary task: navigating as a pedestrian. For this specific task, many researchers already provide different approaches such as vibrating belts, wristbands or shoes. Still, there are questions left that have to be considered, such as: is the position of the foot in comparison to commonly used ones suitable, what kind of vibration patterns are easy to interpret, and how applicable are vibrotactile feedback systems in real scenarios. To find answers, prototypes commonly found in literature have been reconstructed and continued to further evaluate different foot-related designs. The results clearly show that vibrotactile feedback at the foot reduces visual load and thus also potentially reduces stress, while it supports the concept of a *Reflexive Interaction*. Additionally, it turned out that urban space can be very diverse, and ambiguous and therefore a vibrotactile system cannot completely replace common path finding systems for pedestrians.

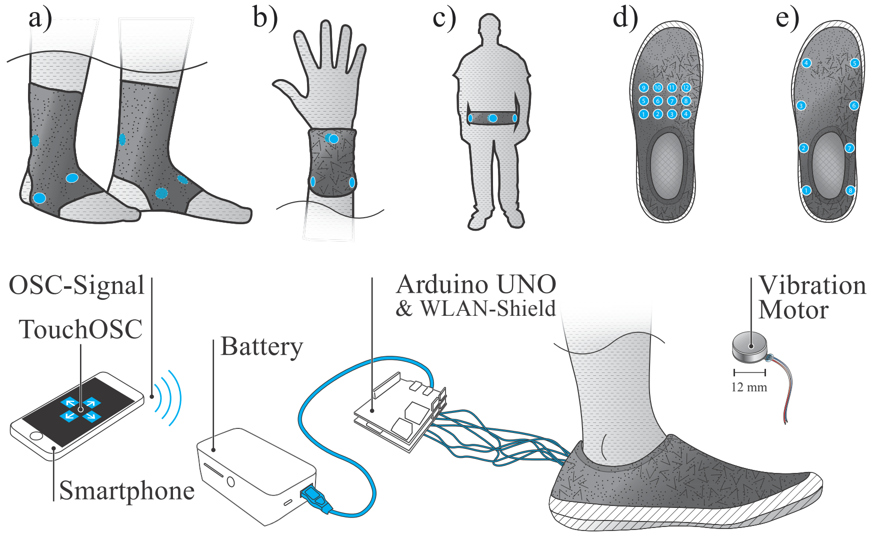



**Figure 79. In this research project vibrotactile on-body feedback has been explored for the purpose of pedestrian navigation. different setups were evaluated: a) sock bandages b) wristband c) belt d) insole matrix layout and d) side wall of the shoe.**

### 5.2.1 Introduction

Many studies show that navigation in unknown environments is traditionally accomplished with visual aids [Mei14]. The majority of people use a smartphone for such a task nowadays. Even though directional feedback (such as "*turn left, right, ...*") is almost binary, using a smartphone many senses are still strained. By using devices such as a smartphone, the visual attention is heavily drawn, which makes navigating potentially dangerous while being involved in traffic, as has been shown in several studies [EAR14, MR10, ZPS+14]. A recent survey [EAR14] reported that 62% of smartphone users below the age of 30 stated to have been at least once involved in a critical traffic situation caused by focusing on their smartphones instead of their surroundings – 43% even stated to be conscious of this potential danger. Especially when being involved in traffic, keeping the visual attention on the road is crucial. Alternative assistance systems can help in this case to decrease a cognitive load, such as demonstrated for the task of driving [Lab90, Liu01, ZPS+14] or pedestrian navigation [PB10, RRH11, ZPS+14]. Like the driver, the pedestrian also perceives his/her environment mostly visually, but also acoustically. However, alternative assistance for pedestrians like acoustic information might not be the best solution, since the level of surrounding noises can be quite high close to roads. Therefore, we agree with Hornecker et al. [HSD11], that this is not an appropriate solution.

The social aspect should also be considered as wearing headphones might be regarded as inadequate [PB10]. Instead, relying on vibrotactile on-body feedback possibly enables eyes- and hands-free interaction, since a smartphone is not needed to be held by the users. Supplying the user with directional aids via tactile on-body feedback will not distract the user from perceiving their surroundings. Another practical advantage of vibration is, that it is perceivable through clothes and can be easily embedded into everyday wearables, such as a belt [CSC14] or an insole [MMAK13].

To evaluate the capabilities of vibrotactile on-body feedback for the purpose of pedestrian navigation, we had to test different body positions and the perception for different designs. Therefore, we built several prototypes, conducted five studies and contributed the following insights:

- Our studies reveal the foot to be capable in perceiving vibrotactile signals quite precisely. In our study, the foot interface performed slightly better than the wristband and the belt. This result is also supported by the fact that the foot has more sensory cells than the human face [Loc84] and yields a higher resolution for haptic perception [DSH05] than other parts, which are commonly used for vibrotactile feedback. In our studies, we could achieve acceptable accuracy rates while walking: ∅ ~86.5% (wristband), ∅ ~87% (shoe), ∅ ~94% (belt), ∅ ~100% (sock bandage)
- With increasing walking speed, the perception of vibrotactile on-body feedback is negatively affected. The accuracy rate at the foot significantly dropped by ∅ ~15% from standing to jogging.
- Our studies and the in-situ field study in particular indicate that vibrotactile on-body feedback does not seem to be capable to be used as a stand-alone technology for pedestrian navigation, since it cannot provide precise enough information for the very diverse environment found in the city. Instead, we believe such feedback systems to be complementary as an assistive technology.

### 5.2.2 Related Work

The foot is a unique spot for many reasons. When thinking back to a time at the beginning of the human's evolution, one can agree that our feet were much more similar to hands. It is an irrefutable fact that meanwhile feet transformed in terms of shape and agility, however, they still possess a similar amount of receptors in comparison to our hands. As a matter of fact, feet are more sensitive than one could image, since they have significantly more sensory cells than the face [Loc84]. Thus feet should be still able to perceive haptic feedback in a precise manner.

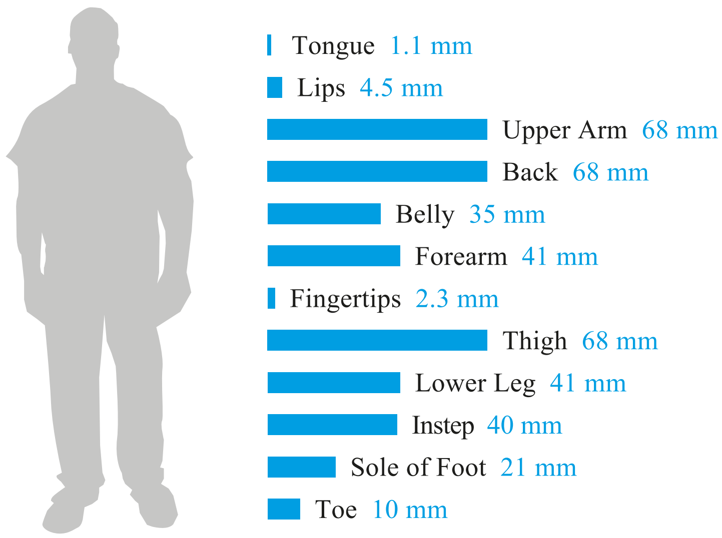



**Figure 80. Resolution of haptic perception on the surface of the human body – based on Deetjen et al. [DSH05]**

In Figure 80, we can see the resolutions of different body parts, in which one point of sensation needs to be apart from another to perceive a difference. As can be seen, the tongue and fingertips provide a very high resolution, but are usually not utilized for conveying haptic feedback since these positions are rather impractical for computational devices yet. Instead, the belly, forearm, hand, and the sole of the foot are being frequently used for conveying haptic feedback to the user. Besides constraints bound to the physical resolution of actuators applied on the skin, haptic perception is also affected by the use of signal length, intensity and rhythm [BB04]. Although haptic feedback is much more than just vibrational feedback, researchers commonly make use of vibrotactile feedback because it yields a very high noticeability.

In literature, we can find four application scenarios for abstract information delivery of vibrotactile feedback, which are Communication, Navigation, Mobile Devices and Vehicles as set out by Choi et al. [CK13]. Especially navigation scenarios, such as for pedestrians in urban space, can substantially benefit from alternative feedback. Nowadays, the task of navigation still mainly relies on the sensor channel of our visual perception, which is however also demanded to focus on traffic and other surroundings. Therefore, researchers

[HSD11, Wic02] believe that considering other channels should reduce the visual load significantly in order to create safer interaction when being involved in traffic. Additionally, enabling the user to interact free-handed would enable the user to accomplish real-world tasks, such as carrying bags, pushing a pram or interacting with the environment. In particular, waiving on the use of the primary interaction channels, while instead focusing on short hands-free and eyes-free interactions, is the key for a successful *Reflexive Interaction*.

#### 5.2.2.1 Vibrotactile

Because vibrotactile feedback is among all haptic feedbacks most noticeable, many researchers make use of vibration motors in order to provide feedback. Velázquez et al. [VBM09, VBV+12] integrated 16 vibration motors in a design of a matrix into a shoe insole to provide vibration patterns underneath the foot for the purpose of navigation. However, recognisability of vibration patterns is comparably low. Velázquez et al. reports accuracies below ~65-80% for directional pattern and ~15-55% for shape patterns. To see the difference: Alvina et al. [AZP+15] evaluated vibration patterns on the waist, arm, palm and thigh, while the results demonstrate that vibrational patterns can be reliably recognized (>80%) across these body parts. A reason for this may be the relatively thick cornea under the foot. In another research project: *Shoe me the Way* [SHBE15] two vibration motors have been attached the side of the foot just next to the foot ankle. Because of this position and while they used binary feedback for changing directions, they were able to report high recognition (99.7%). However, these high accuracy rates are questionable, or seem to be results of a lab study, in which the users were sitting or standing still. In a more realistic scenario, when the user is walking Karuei et al. [KMF+11] reported a significant decrease of vibrotactile perception at the foot. Own studies also confirm this: a speed increase up to 5 km/h results in a decrease of accuracy of about -15%.

#### 5.2.2.2 Pulling Force

A very different research prototype called *CabBoots* has been introduced by Frey in 2007 [Fre07]. The prototype contains an electro motors in a very thick insole that changes the weight distribution within the shoe sole. In this way, path navigation can also be enabled as demonstrated. This work aims to create a subtle pulling force at the foot, which would automatically drag the user in a predetermined direction.

#### 5.2.2.3 Thermal

Quite recently, Watanabe et al. [WK16] introduces a study, in which thermal feedback has been applied to the user's foot sole using *Peltier Elements* while being in a standing position. When applying dissimilar temperatures to different areas of the user's foot sole, it has been found that users had the illusion of standing on a slope. Therefore, dynamic thermal change in sole might influence standing position.

These projects show that our feet still yield unexplored potential for interaction.

### 5.2.3 Study Setup

#### 5.2.3.1 Overview

There have been many investigations made on vibrotactile feedback for the purpose of navigation. However, most concepts have only been tested in lab environments and there is no evidence whether vibrotactile feedback is beneficial or even applicable to actual pedestrian navigation tasks where many external influences are present.

Firstly, it had to be determined which body positions of the proposed concepts would work best and are feasible to be implemented in a real product. In a second step in our study, we evaluated two designs for foot interfaces proposed in literature and whether wave-like patterns or simple vibration patterns are preferred as feedback. Thirdly, we investigated the influence of different walking speeds and the effect of an additional precursor signal. Subsequently, we conducted a stress test to find out the difference between visual and vibrotactile feedback in a stressful situation while navigating. Finally, we conducted an in-situ field study in which we wanted to evaluate the applicability and capabilities of such vibrotactile systems for the purpose of pedestrian navigation in urban space. The following five studies will give answers to our five hypotheses, which have been successively developed.

#### 5.2.3.2 Hypotheses

**H1**: Vibrotactile on-body feedback is better interpretable on the foot than on the wrist or waist, due to the higher resolution for haptic perception at this body area.

**H2**: Vibrotactile on-body feedback will be better perceive-able on the insole than on top of the foot.

**H3**: Vibrotactile on-body feedback at the foot is equally perceivable while moving around or standing.

**H4**: Vibrotactile on-body feedback in comparison to a visual handheld device can significantly reduce visual load and thus reduces stress occurring during the task of navigation.

**H5**: Vibrotactile navigation systems, such as the one we proposed, can replace previous pathfinding systems.

#### 5.2.3.3 Methodology

For our evaluation, we made use of three established methods [Züh12] and measured:

- Quantitative data (Error-rates – recorded by the study leader)
- Quantitative user feedback (subjective rating: required concentration & perceived strength of vibration)
- Qualitative user feedback (post questioning)

#### 5.2.3.4 Procedure

At the beginning of each test phase, the subjects have been briefly introduced to the prototypes and the four vibration stimuli (left, right, forward and back). After completion of the test, all test subjects were asked to fill out a questionnaire in which they had to state demographic data and rate subjectively the perceived strength of vibration, their required level of concentration and the wearing comfort of the prototype on a 11 – bipolar point Likert scale (from strong / high: +5, neutral: 0, to weak / low: -5). Due to the limited space, not all ratings are reported here but those instances that yielded interesting insights.

A qualitative interview followed after the test. Hereby, further details on the user experience such as positive feedback or problems, or requests and suggestions have been reported. The interview and observations have been internally discussed, but are not being presented here due to the limited space.

#### 5.2.3.5 General Construction of the Apparatus

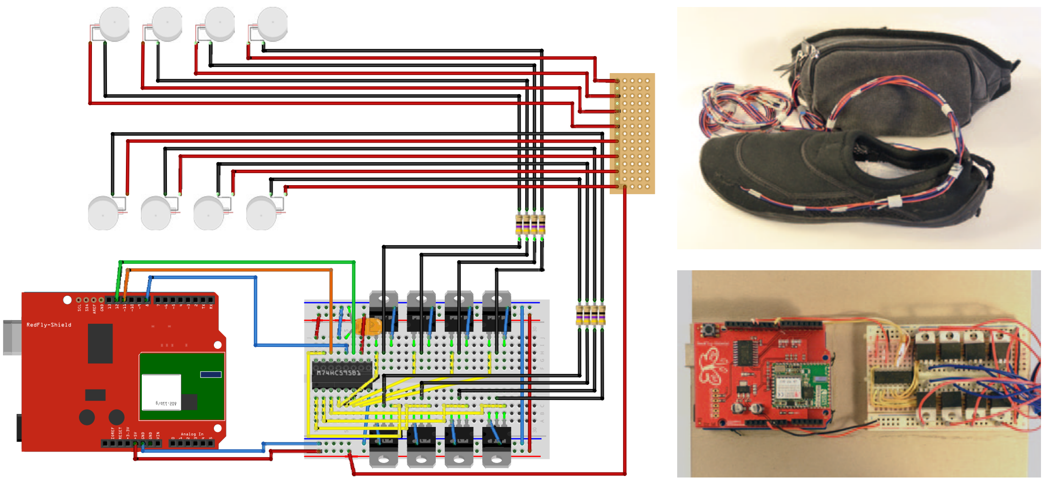


**Figure 81. General Infrastructure of the Hardware Prototypes (sketch by fritzing.org).**

We built five different prototypes (*see Figure 79*): 2x Shoes, Sock Bandages, Wristband and a Belt, which we will evaluate based on the stated hypothesis. We utilized 4–12 off-the-shelf vibration motors (ROB-08449, which provide 1G vibration at 12,000 rpm at 3V), which were controlled by an Arduino Uno (*see Figure 81*). The hardware (breadboard, Arduino + Wireless shield, battery) had to be carried in a bumbag by the participants. In a Wizard of Oz style, vibrations were triggered wirelessly (OSC protocol) via smartphone by the study leader.

### 5.2.4 Study 1: Evaluating Body Positions

As we could learn from literature, there have already been made investigations on vibrotactile feedback for the purpose of navigation. In this study, we want to answer which position is most suitable for perceiving vibrotactile feedback for a path finding task while the user is walking (*see Figure 82*).

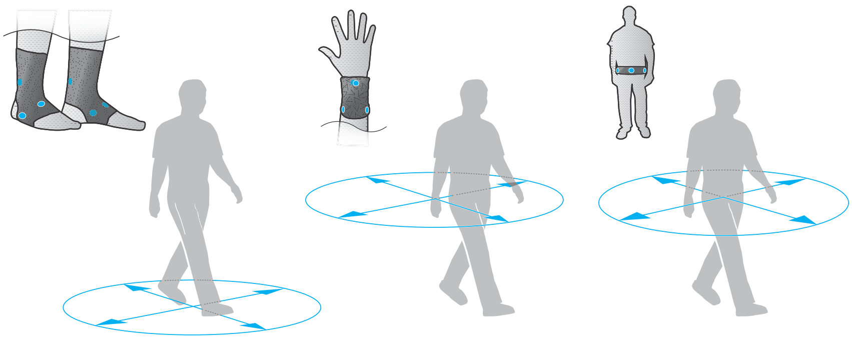


**Figure 82. Four vibration motors were attached at each of the three body positions. Each vibration motor was assigned to a specific direction; therefore, the left vibration motor indicates the user to turn left.**

We selected three positions common in literature:

a) **Foot** (Shoe/Sock): highest resolution of haptic perception – Deetjen et al. [DSH05]

b) **Wrist** (Wristband): most reliable body part of vibrotactile sensation – Karuei et al. [KMF+11]

c) **Waist** (Belt): most frequently used position of vibrotactile feedback for navigation/directional tasks – [CSC14, HHBP08, TY04, VVJD05]

**Figure 83. The implementation of our prototypes: sock bandages, wristband, belt (white). Since our prototype is mobile, the hardware had to be worn in a black bumbag. Even though the wrist is the most agile body part of these, we did not dynamically adjust the vibrations in respect to the wrist's orientation.**

We neither did pursue the concept of a handheld device, since it possibly prevents the user to take part in peripheral real world tasks; nor that of jewelry, because the implementation is unrealistic for a current product. Moreover, we also did not consider vibrations at the hand, because we do not want to disable the user from using their hands for different real world tasks. Another issue with gloves would have been low social acceptance.

The prototypes (*see Figure 83*) were basically consisting of 4 vibration motors (VM), in which each is being assigned to a specific direction; VM 1: left, VM2: right, VM3: back, VM4: forward. To evaluate a suitable position for the vibration motors, we conducted a pilot study with 3 participants, in which we could confirm the minimum distances (*see Figure 80*) that are necessary to distinguish differences on the surface of the skin. Taking this into consideration, we further evaluated the position on the stated wearing comfort and a subjectively good felt distinctness. We found out that the vibration motor on the back had to be adjusted a bit left from the spine to lie tightly at the body in order to be perceived.

To exclude an adaptation effect, the prototypes have been tested by 24 users in a between subject study. Hence, each user did only test one prototype.

- *Group A* – Foot: 8 users (2 females, 6 males) aged between 24 and 72 years (Ø 37 years)
- *Group B* – Wrist: 8 users (4 females, 4 males) aged between 25 and 70 years (Ø 35 years)
- *Group C* – Waist: 8 users (3 females, 5 males) aged between 24 and 72 years (Ø 44 years)

To reduce the influence of external factors, this first study took place in a lab-like environment. Each user was exposed to 13 direction changes in which the user had to state the perceived direction change resulting from the vibration. All users of each group received the same stimuli at different positions, which were (A) both feet, (B) right wrist and the (C) waist.

#### 5.2.4.1 Results

*Accuracy rate.* Due to the signal distribution of both feet, all users wearing the foot interface did not misinterpret any of the provided directional signals. However, a *one-way ANOVA* did not show any significant differences in terms of accuracy across all locations ($F_{2,21}$=2.12; $p$>.05).

*Required level of concentration.* Running a *Kruskal-Wallis Test* ($k$=3) indicated none of the ratings to be statistically significant ($H_2$=1.05; $p$=0.59) due to the small sample size. However, an *F-Test* presented a significantly high variance between *Group A* ($M$=-3.625; $SD$=1.302) & *B* ($M$=-1.875; $SD$=3.399) ($F_{7,7}$=16.43; $p$=.01) and between *A* & *C* ($M$=-1.375; $SD$=3.739) ($F_{7,7}$=8.24; $p$=.006), which indeed indicates a difference in rating.

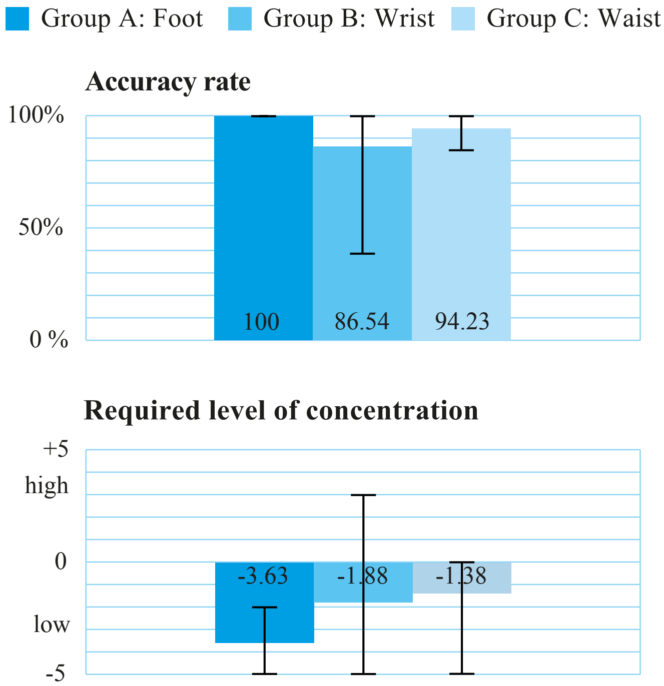



**Figure 84. Performance comparison of three positions. (Error bars show the extreme values)**

In conclusion, every 104 vibration signals have been successfully identified without any errors for the foot interface. Even though both diagrams (*see Figure 84*) indicate that the users perceived the vibrotactile feedback slightly better at the foot than on the other parts of the body that we tested, the foot interface did not yield a better statistically significant performance. We cannot absolutely support the findings of Karuei et al. [KMF+11], who figured the wrist and spine to be able to perceive vibrations more reliably than the foot. Furthermore, Karuei et al. reported that walking significantly reduces the odds of detecting a vibration. However, in their conducted experiments, the participants were walking on a treadmill, which on the one hand leads to an unnatural walking style and on the other hand interferes with the experiment through additional vibrations from the treadmill itself. Another explanation for the occurred disparity is that Karuei et al. only attached a single vibration motor to the top of the foot – we put four vibration motors tightly on different spots of the foot instead.

### 5.2.5 Study 2: Actuator Layout

Based on our previous findings and the fact that the foot has more sensing cells than the other tested positions, we decided to focus on the foot and did a literature review about vibrotactile foot interfaces accordingly. Velázquez et al. [VBM09] proposed a shoe sole in which the vibration motors are arranged in a matrix layout to stimulate the foot sole. Furthermore, they proposed wave-like vibration patterns (*see Figure 85*), which could be used for giving directions. Other approaches, such as from Karuei et al. [KMF+11], attach vibration motors on the top of the foot.

Here we wanted to evaluate whether Velázquez et al. insole matrix approach performs better than vibration on top of the foot, while we were using the approach of wave-like vibration patterns, in accordance to Israr & Poupyrev [IP11].

The participants (7 males, aged between 19 and 45 years, Ø 28 years) tested both prototypes in a within subject study:

- **Prototype A** (*Figure 85 & Figure 86 top*): Insole, matrix-layout with 12 vibration motors (similar to Velázquez et al. [VBV+12])
- **Prototype B** (*Figure 85 & Figure 86 bottom*): Shoe, 8 vibration motors were attached to the inside of the shoe wall.

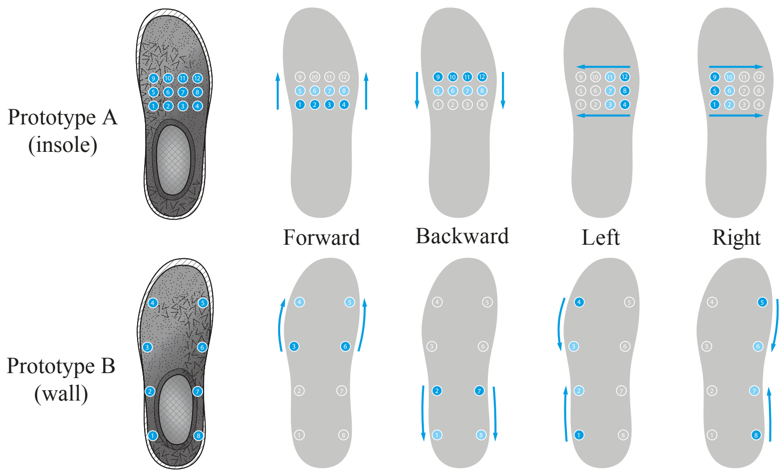



**Figure 85. The participants were at first introduced to the signal patterns, which were different for each prototype, as indicated in this figure.**

While the participants were standing, 4 (transitioning) vibration patterns were executed (*see Figure 85*) and the participants were asked to interpret the pattern.

Each test subject was exposed to fourteen vibration patterns, which indicated directions: 1. back, 2. right, 3. left, 4. forward, 5. back 6. left, 7. right, 8. forward, 9. left, 10. back, 11. forward, 12. right, 13. back and 14. forward. The response of the test subjects to the perceived vibration pattern was indicated by turning in the appropriate direction and also through an oral response from the user. The performance was evaluated by recording error rates.

**Figure 86. Prototype A: upper pictures – insole matrix. Prototype B: middle bottom picture – actuators at the shoe wall. The different levels of pressure between body and actuators have been compensated with elastic rubber caps.**

#### 5.2.5.1 Results

It has been shown that the accuracy of correctly identified directional changes dropped quite a lot in this test; *prototype A* ($M$=68.36; $SD$=27.92) and prototype *B* ($M$=58.16; $SD$=27.79). We believe this to be caused by the wave-like vibration patterns, since Velázquez et al. [VBM09, VBV+12] reported similar accuracy rates for these kinds of vibration patterns. Arranging the actuators underneath the feet achieved slightly higher accuracy (+10.2%), which was however found out not to be statistically significant via a *t-Test* ($p$=.5). Therefore, we cannot say that arranging the actuators in a small matrix underneath the feet does provide better feedback than distributed vibration motors on top of the foot. Even though the foot sole has more sensing cells than the topside, the dry and thick cornea makes a very precise sensation rather difficult. Having sensation underneath the foot sole, a designer must take into consideration that some people do not touch the whole insole when they hyperpronate [Gou83]. Attaching the vibration motors on top of the foot requires the vibration motors to also touch the foot, which is more easily provided with sock-style prototypes.

### 5.2.6 Study 3: Walking Speed & Precursor Signal

Due to the results of our second study and the mentioned general drawbacks of having feedback underneath the foot, we decided to proceed with the second vibration layout and to forfeit wave-like vibration patterns due to their low performance (*see Figure 87*).

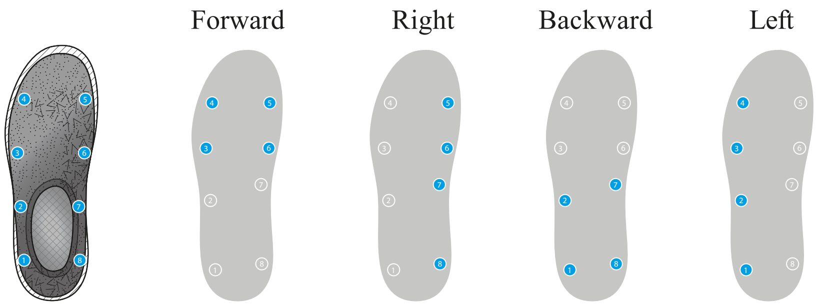



**Figure 87. In blue indicated spots show active vibration motors actuating at the same time.**

In the previous test, participants stated to have had problems identifying the wave-like pattern, because they were surprised of the suddenly occurring vibration, which, as already mentioned, requires a lot of concentration. We wanted to investigate this issue and added a precursor signal (a 600ms long vibration), while the participants had to increase their speed level from standing to walking and jogging. The users were given again directional changes as mentioned above. To avoid having a learning effect between both conditions, we once more conducted a between subject study with 16 participants. Each group only tested one condition, while walking a distance of 50 meters on a lawn. The test was repeated for three different speed levels from standing, normal walking (~3km/h) and jogging (~5km/h).

- **Group A** – vibration pattern [vibration (600ms) – no vibration (150ms) – vibration (600ms)]
  8 users (2 female, 6 males) aged between 27 and 52 years (∅ 37.5 years)
- **Group B** – precursor signal [vibration (600ms) – no vibration (1000ms)] - vibration pattern [vibration (600ms) – no vibration (150ms) – vibration (600ms)]
  8 users (3 female, 5 males) aged between 24 and 50 years (∅ 34 years)

#### 5.2.6.1 Results

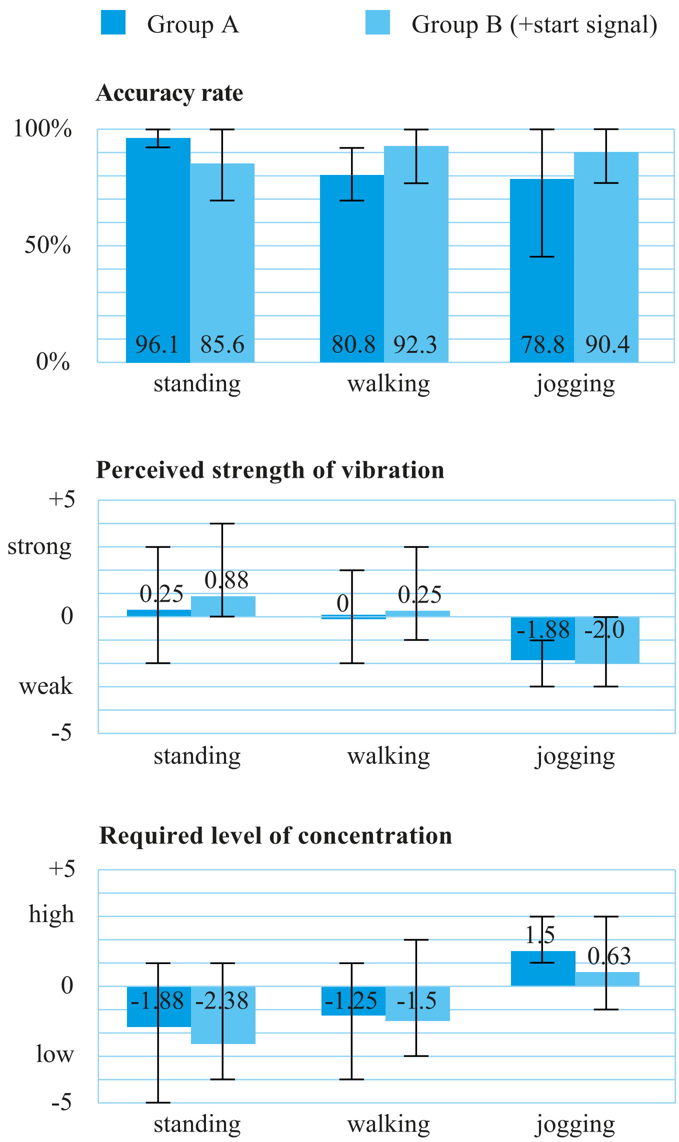



**Figure 88. The influence of a precursor signal in comparison to the change of speed. (Error bars show the extreme values)**

*Accuracy rate*. Compared to the previous test, the accuracy rate dramatically increased again, which confirms our assumption that the wave-like vibration patterns should not be deployed.

The difference between both conditions was confirmed to be statistically different by pair-wise *t-Tests* (*see Figure 88*). While standing ($p$<.05), *Group A* (*M*=96.15; *SD*=5.85) was producing less error rates than *Group B* (*M*=85.62; *SD*=12.3). While walking, the accuracy rate of the first condition, tested by *Group A* (*M*=80.8; *SD*=10.84) surprisingly dropped below the second condition with the precursor signal (*M*=92.3; *SD*=10.07), which was also found (out) to be statistically different ($p$<.05). While jogging, the difference between *Group A* ($M$=78.85; $SD$=19.15) and *Group B* ($M$=90.38; $SD$=9.85) minimized, so that a statistical difference could not be confirmed ($p$=.15). However, a *one-way ANOVA* and a *Tukey HSD Test* ($F_{2,21}$=4.15; $p$<.05) could confirm the increasing speed to significantly decrease the accuracy between standing and jogging for *Group A*. However, once the users in *Group B* got to know the precursor signal, this described negative effect did not appear that strongly anymore.

*Perceived strength of vibration.* A *Friedmann Test* ($k$=3) confirmed a significant difference in perception of the strength of vibration, depending on postures ($\chi^2(2)$=13, $p$=.0015). A *pairwise Wilcoxon signed-rank test* with *Bonferroni Correction* suggests that the vibrotactile perception while jogging is significantly harder to perceive than while walking ($p$<.05) and standing ($p$<.05). No statistical differences were found between walking and standing ($p$>.05). Furthermore, the additional precursor signal did not change the subjective perception of the strength of vibration, which was confirmed by a *Mann Whitney test* that showed no significant difference ($p$=.7).

*Required level of concentration*. Respectively to the perceived strength of vibration, the required level of concentration raised accordingly. A *Friedmann Test* ($k$=3) confirmed a significant difference for the required level of concentration depending on postures ($\chi^2(2)$=10.75, $p$=.0046). A *pairwise Wilcoxon signed-rank test* with *Bonferroni Correction* suggests that vibrotactile perception while jogging required significantly more concentration than while walking ($p$<.05) and standing ($p$<.05). Any differences between both groups could not be found to be statistically significant by a *Mann Whitney test* ($p$=.8).

### 5.2.7 Study 4: Stress Test – Vibrotactile vs. Visual Feedback

In this study, we wanted to investigate the capability of vibrotactile feedback to possibly reduce stress for the purpose of pedestrian navigation. A similar experiment has been conducted by Bial et al. [BKAS11] with vibrotactile motorbike gloves while cycling. Their qualitative results reveal that vibrotactile feedback is preferred in combination with visual feedback, but not alone. In this study, we aimed at finding quantitative performance differences while generating an artificial stress situation. We more or less simulated situations in which the user is focused on a different task, such as reading/writing a message, walking through a crowded pedestrian precinct or focusing on a pedestrian running in front. We provided the user with pictures (*see Figure 89*), in which the user had to find and count the correct letters (odd-man-out task).

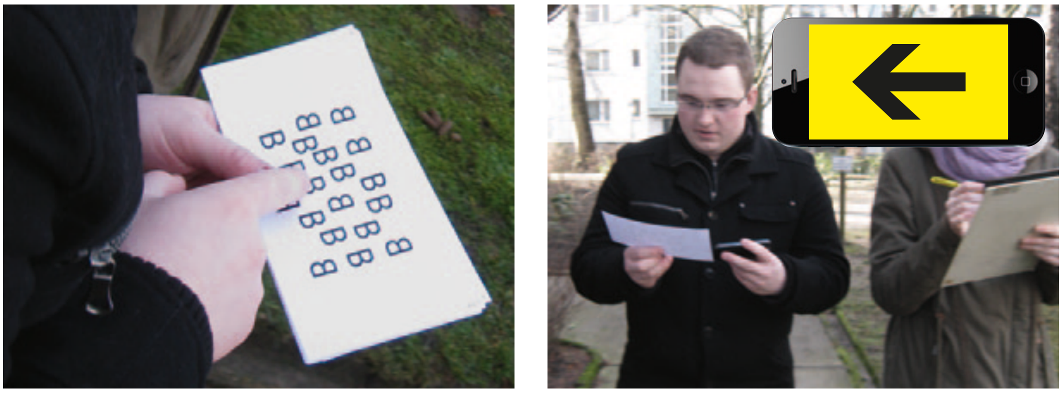


**Figure 89. Left: The odd-man-out tasks – counting the correct "B" letters. Right: Group B had to visually focus on the smartphone for direction changes.**

While the user had the task to walk straight until perceiving a direction change, the user also had to follow the direction change, which was either provided by A: vibration patterns at the foot with the sock prototype, or via B: visual feedback while using a handheld smartphone in landscape-mode. The direction changes occurred constantly after a while within a time frame of 7 seconds. To make performance differences between vibrotactile and visual feedback easier to measure, we measured the 1) Accuracy rate (navigation), 2) Number of completed tasks, and 3) Correctly solved tasks.

To avoid the user being biased, we conducted a between subject study with 18 participants in total:

- **Group A** – Vibrotactile: 9 users (1 female, 8 males) aged between 24 and 36 years (Ø 30 years)
- **Group B** – Visual: 9 users (4 females, 5 males) aged between 24 and 72 years (Ø 36 years)

#### 5.2.7.1 Results

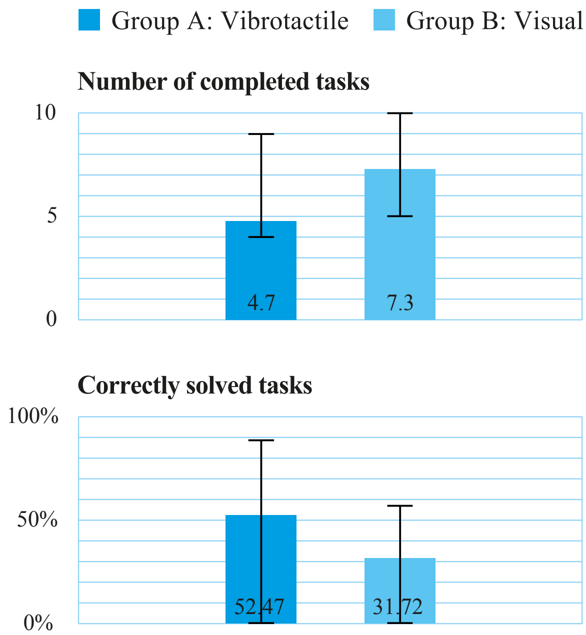



**Figure 90. Vibrotactile vs. Visual Feedback. Even though Group B solved almost double the tasks, in average Group B solved 2.3 and Group A solved 2.4 tasks correctly. (Error bars show the extreme values)**

*Accuracy rate (navigation).* Only 1 out of 117 direction changes have been erroneously identified at the vibrotactile feedback condition (99.14%). The visual feedback group made 3 mistakes (97.43%), which indicates no statistical difference in comparison to vibrotactile feedback ($p$=.5).

*Number of completed tasks.* A *t-Test* showed a significant difference in terms of completed tasks ($p$=.02). The *Group B* ($M$=7.3; $SD$=2.29) completed significantly more tasks than *Group A* ($M$=4.7; $SD$=1.98;) – *see also Figure 90*.

*Correctly solved tasks.* While *Group A* ($M$=52.47) could almost solve significantly ($p$=.065) more of the completed tasks correctly than *Group B* ($M$=31.72), an *F-Test* found a statistically high variance ($F_{1,16}$=3.44; $p$=.49) between *Group A* ($SD$=33.72) and *Group B* ($SD$=18.2).

Participants of both groups stated to have been irritated when direction changes were indicated. Therefore, they had to start the odd-man-out counting task all over again, as reported. While performing the study, we could clearly recognize that the users with visual feedback seemed to be much more in a rush and were thus able to complete significantly more tasks than the vibrotactile group. These users stated to have often lost (their) focus on the sheet due to the frequent switching back to the smartphone display. This split attention might be the cause for the high error rate of this group. As a matter of fact, the visual feedback group did not solve more tasks correctly (Ø 2.3) than the vibrotactile feedback group (Ø 2.4).

### 5.2.8 Study 5: In-Situ Field Study – Stand Alone

Since our system was proposed to help the user to navigate through unknown environments, it is also needed to evaluate the feasibility of our system out in the field. To really gather valuable insights, we selected 3 experts (2 males and 1 female aged between 34–38 years) to test our system and provide us with unique qualitative feedback. The participants had a professional background (for at least 8 years) in the field of navigation or space and design.

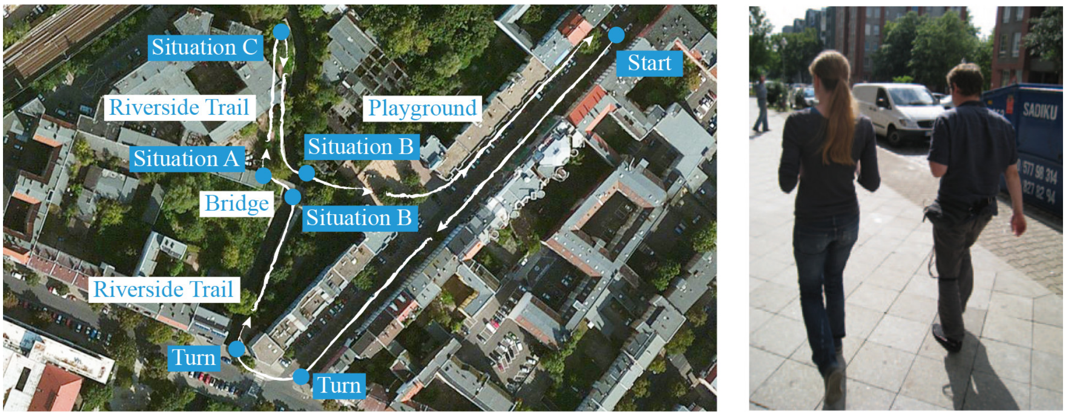



**Figure 91. We provided 7 stimuli, which the user had to interpret. A study leader was logging the users' qualitative feedback on paper and a camera followed the study to track possibly appearing issues.**

All participants were wearing the shoe prototype from study 3 (stimuli: *see Figure 86*), while walking a certain route which was ~ 650 meters long. We chose the route to be quite heterogeneous with different ground surfaces (e.g. paving stone, asphalt, wooden planks and sand), while the user had to cross a bridge, roads and a playground.

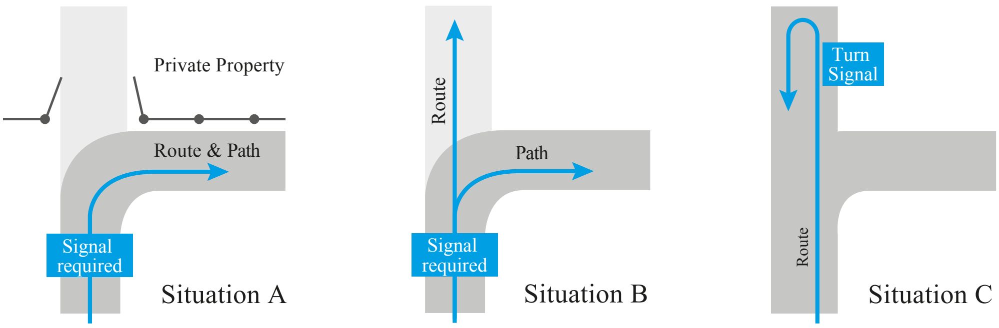



**Figure 92. We encountered 3 situations, in which the user was provided with feedback.**

Three different situations occurred (*see Figure 92*), in which the user was provided with a signal. Situation A was most obvious to the user, since it was very unlikely that the system would give the command to enter a private property. Situation B was more complicated, since the system would either provide a forward or a turn signal. In Situation C, the user was provided with a repeating turn pattern to turn back.

#### 5.2.8.1 Results

Even though different surfaces could possibly create imagined vibrations, the users did not perceive "*ghost vibrations*" or missed them either. Overall, the tests were very productive; the experts pointed out many problems, which were not considered before:

- The request to continue walking straight was often not identified. In such cases, the user was asking for a repetition of the vibration pattern. To generally overcome this problem, a forward pattern should be unique, such as triple vibrations of all motors.
- The experiment showed that users tend to follow the path direction, even if there is another way transposed. We suggest running a vibration pattern for each change of ground surface.
- Contrary to our assumption, Situation A was prone to error when we did not give any vibrations at all. It occurred that the user was walking straight into the private land and believed to have reached his/her destination. Hence, a) for Situation A (*see Figure 92*), a signal has also to be emitted and b), a certain vibration pattern should indicate when the user reached her desired destination.
- The directional statement for returning should only be given after a crossing (*see Figure 92*: Situation C) or at straight lane. Giving the statement before an intersection could lead to possible misunderstandings (e.g. turn left/right).
- All experts agreed that the system works stunningly well, but probably not sufficiently for a stand-alone assistance, since urban environments can be very ambiguous and situations such as Situation A (*see Figure 92*) can occur quickly, which make decisions very difficult without more detailed hints.

### 5.2.9 Summary

*Comparing common approaches did not reveal the foot to perform best in perceiving vibro-feedback while walking*
We cannot confirm **H1** with our first study, even though we learned that vibrotactile feedback at the foot has been interpreted with a higher accuracy than at the wrist or waist while walking in space. In contrast to the other interfaces, all study participants reported the foot to require less concentration with a significant lower variation.

*No significant difference of perception between the top of the foot and the insole*
**H2** could not be verified as correct in our tests. In Study 2, the feedback underneath the foot did not yield significant improvements to the vibrotactile feedback on top of the foot. However, we could perceive that attaching vibration motors very close to the skin has an important influence on the recognition.

*Increasing walking speed influences the accuracy negatively*
That vibrotactile feedback is equally perceivable at different speed levels could not be confirmed with Study 3, and therefore **H3** needs to be rejected. Higher speed levels showed

users to perceive the strength of vibration less, which caused higher concentration in return. However, our investigation indicates that – even though perception drops with higher speed – the accuracy is still sufficient to suggest using this setup for navigation while walking.

*Relying on vibrotactile feedback instead of visual feedback potentially influences the level of stress*
In our fourth study, we could perceive that users with visual feedback seemed to be much more stressed, which is indicated by the significantly higher number of completed tasks and the significantly higher error rate they produced. Having vibrotactile feedback on the foot had a positive effect and significantly reduced the error rate, while the user was not hectically solving the task. Thus, we confirm **H4**, vibrotactile feedback at the foot does reduce stress and the needed visual attention for the purpose of pedestrian navigation.

*A directional system for pedestrian navigation in cities cannot only rely on vibrotactile feedback*
At last, we conducted an in-situ field study with experts in which we encountered several weaknesses of a vibrotactile pedestrian navigation system. When it comes to navigating in unknown territory, visual hints, such as a map, are required to deal with ambiguous situations that one encounters in the city. Therefore, we reject **H5**. Experts unanimously suggested using vibrotactile assistance complementary to existing guiding solutions. However, training trails might improve the user experience.

### 5.2.10 Conclusion

In this part of the chapter, the design and an evaluation of vibrotactile on-body feedback at different areas of the body has been described. Here, the foot provided the most promising results for the recognition of vibration patterns while walking in space. It was found out that the user's walking speed affects vibrotactile perception, although not massively and thus it is still operable for its intended use. A pedestrian navigation system based on simple vibrotactile feedback for guidance might not be sufficient in an urban context with complex geographical situations. Further research is needed to either provide an extended "*language*" for vibrotactile clues to cover more complex geographical situations, or alternatively to explore how such vibrotactile clues can be integrated into multimodal navigation systems. The studies indicated that vibrotactile feedback is potentially able to reduce stress of certain visual multitasks while navigating as a pedestrian. While such vibrotactile systems may not yet stand on their own, it is to assume that they can complement current modalities very well. However, according to literature there are certain scenarios in which vibrotactile navigation systems seem to be able to be used on their own, such as while driving a car [VV04] or a motorcycle [PTGH14] or when being on a boat [VVJD05], because these environments are mostly homogeneous or clearer to the user.

This research indicates that the foot is also an interesting position for perceiving notifications in form of vibrotactile feedback, since the haptic channel at this position is not occupied yet and therefore enables eyes-free and hands-free interaction, which is the basis for a *Reflexive Interaction*. With the raising trend of *Wearable Computing*, also on-body feedback may be soon an integral part of everyday wearables, as it is to assume that smart insoles and smart shoes may permeate the market soon. In the near future, a smart insole may already enable a *Reflexive Interaction* by providing the user with subtle vibrations, such as to signal a notification like a call, while enabling foot tapping gestures to mute the call. Although this concept may follow Shneiderman's theory of a *Direct Manipulation* [Shn97], it should be questioned whether distributing input and feedback on the body make sense. However, besides vibrotactile feedback, we should also consider utilizing different feedback modalities to also stimulate other senses through pressure, heat, cold, and EMS, which can provide unique sensations and different levels of noticeability. In summary, it is to conclude that the foot can be an interesting feedback channel as well as an important source of context information.

# 6. Conclusion

This thesis introduces a variety of new wearable prototypes that augment the human body while enabling a wider range of inputs and expanding the human's perception ability. These technologies pave the way for an applicable *Reflexive Interaction* in a mobile context, which substantially expands the user's interaction capabilities without limiting the performance in real world applications. This chapter (1) partially reiterates the *Reflexive Interaction* concept by answering the previously introduced research questions, and (2) breaks down the most relevant contributions by further extrapolating general implications – the *Thesis Statements*.

It is crucial to note that the findings presented are derived from comparably small lab studies, and thus may not cover all aspects of a real situation. Long term studies will inevitably be needed in order to confirm all assumptions made in this thesis. Still, the results can provide valid indications of future directions in HCI and how it may look.

## 6.1 Answering Research Questions

Interacting with any kind of mobile device, such as smartphone, has become a usual modern day occurrence and viewed as a natural part of life. However, interacting in a mobile scenario can yield significant limitations, such as when the user is on the go; a user's perception when walking is different compared to being still and the input of commands can in an instant become a tricky task, due to the change of contextual variables. The interaction process during mobile situations can become complicated, inconvenient, and even dangerous when too much attention is drawn to the device compared to the surroundings (e.g. a road one is crossing). When observing a user's interaction behaviour in a truly mobile scenario, such as being on the go, we can identify these and many other mobility issues (*see also: 1.2.1 Challenges Today*). Five Research Questions (RQ) were initially created from these observations, and are now being answered in regards to related work and through the proposed concept of a *Reflexive Interaction*.

**RQ 1:** *How can we make interaction less attention drawing to enable safer mobile computing?*

Making mobile interactions safe is an essential concern. As implied in this research question already; reducing the user`s attention level dedicated to using mobile computational devices is the primary key. The easiest way to accomplish this would be to disable the user's ability to interact with a computational device when participating a situation with raised risk. Another solution presented in related work is in making use of sequential multitasking [STB09] by making use of the human's ability to handle multiple tasks with divided attention [WM07], proprioception [BKT86] and spatial memory [Tve93]. While several tasks can coexist, literature classifies two types of tasks; the primary task like paying attention to the traffic on the road, and the secondary task like being interacting with a smartphone. However, both tasks usually compete for the user's attention and thus the more demanding task can be completed but only though the use of role reversal (e.g., the secondary tasks experience more attention than the primary task). If dedicating more attention to the secondary task, using a smartphone, within a time period of four seconds, such as valid with *Microinteractions* [Ash10], the user can become significantly endangered when taking part in traffic. Another concept, *Peripheral Interaction*, encounters this problem while aiming to *«minimize interaction time, interruptions, focus switches, and cognitive load»* [Hau14]. However, attention shifts between the primary task and secondary task still occur, which can be clearly seen at an example work *"The Unadorned Desk"* by Hausen et al. [HBG13]. In this work, the user interacts with a workstation while quickly interrupting the primary task through the use of the left hand hovering to a certain position on the table and selecting via tapping on imaginary pictures. The stopping mouse movements, which can be seen in their video figure, indicates that the primary task was interrupted. Furthermore, the user's visual focus quickly leaves the screen and switches to the secondary task which is in this example the left hand interacting on the table.

A *Reflexive Interaction* is being proposed that enables the center of attention to fully remain on the primary task to overcome task interruptions. This is achieved by not overloading interaction channels. Thus, the secondary task should rely on different interaction channels that completely exclude the primary task channels. The hands and eyes are mainly occupied by the primary task and therefore cannot be used. Instead we can utilize the whole body due to its unique properties of always being available for use and well known by the user. We can make use of proprioception and the body's wide range of abilities by using our motor periphery and of perceiving information in our periphery. In order to keep the cognitive load low, we should rely on more simplified interactions (the size of gesture sets and of information density should not exceed two bits) and quicker interactions than proposed by Ashbrook [Ash10] (an interaction should not last much longer than around a second). Taking these things into consideration would enable the user's attention to remain with the real world, such as when crossing a road and thus make mobile computing safer.

**RQ 2:** *How do wearable interfaces need to be designed in order to facilitate low distraction that is also socially acceptable by users?*

This question is twofold, the first part – *enabling low distraction* – can be addressed by significantly reducing the attention required by the computational device. This can be achieved best by minimizing interruptions, interaction time, focus switches, and cognitive load by designing a *Peripheral Interaction* or by going a step further and applying a *Reflexive Interaction*. The second part of this question pertains to the well known issue of social acceptance. Many alternative interaction concepts may not prevail in our daily lives because they appear awkward to other viewers. [MAMS10]. However, social perception can also change over time. For example; talking into thin air while on a phone call may be socially acceptable now, however, huddling around with exaggerated arm gestures [GBB10] to control functions such as a slide presentation may still be seen as awkward. Moreover, context plays a major role when it comes to social awkwardness. For instance, hand and arm gestures or commands may be socially acceptable [BMR+12], but not always appropriate when being involved in a conversation.

This thesis envisions a better solution which incorporates the use of subtle gestures, such as quick foot gestures or tapping gestures on the hip and belly [MPUZ15, YFS+16] instead of sliding with a finger on a glasses frame or through the use of a touch screen. As stated before, the success of these input techniques is context dependent and may not be practical in every situation. For instance, there may be cases in which feet are occupied, such as when; walking, driving, or riding a bike. Here, one could make use of an eye wink or head gestures, which could be acceptable depending on the situation. Undoubtedly, facial and head gestures may not be the optimal solution when being engaged in a conversation since these gestures yield social meanings and thus would irritate others involved.

In terms of feedback, a ringing and vibrating phone lying on a desk may be perceived as highly disturbing and awkward especially during a meeting, because it addresses more people than intended. Moving a notification closer to the human body, such as using haptic on-body feedback can be very beneficial in terms of social acceptance. In this thesis, several haptic feedback modalities have been tested, such as mechano-pressure, thermal, and electrical feedback, which are found to be scalable to a subtle level, so they are perceivable by the user and not distracting the primary task. A notification can be increased up to a *forcing level*, however this could be perceived as morally questionable and thus not socially acceptable. Integrating technology into clothing and clothing accessories such as shoes yields the power for notifications to be subtle and almost invisible by other parties. Similar to input techniques, notifications are also context dependent and should be scaled accordingly to the user's state and environmental factors. For instance, the accuracy of perceiving vibration notification patterns significantly drops with an increasing walking speed. Therefore, a future design should consider varying feedback modalities and changing body positions in dependence to the context. The utilization of the peripheral vision as an alternative to haptic feedback looks promising by way of high perception accuracy, low distraction and possibly increased social acceptance. Because a *Reflexive Interaction* is generally quickly performed it favours social acceptance, although it depends on the situation that relates to the implemented design.

**RQ 3:** *How can we simplify and expand interaction modalities at the same time while extending the limited capabilities of a mobile device?*

Every computational device has limitations. From an HCI perspective a computer cannot be sensitive towards the user's moods due to feeling and hearing problems. In addition, all computers limit the range of expressions, wishes, and demands of the user. Although mobile devices are equipped with a great variety of sensor, they are not noticeably more sensitive to the user' state. These high functional electronic devices barely detect gentle strokes, are usually inflexible, quite tiny, and require high precision finger dexterity to carry out tasks. Moreover, the device's breadth of knowledge relating to commands and kinaesthetic relationships may not be congruent to the user's mental model [CAN87]. The incongruence between technology and the human's reception and understanding is a fundamental problem in HCI. Therefore, it makes sense to fall back on well-known real-world metaphors that simplify interactions, and thus decrease cognitive load. Transferring metaphors to the body (e.g., tapping the head to create a reminder, quit a notification by stomping the foot, and nodding to accept a phone call) may improve the remembrance of shortcuts significantly. Such interactions are deemed as natural because they are perceived to be intuitive. Moreover, we can expand the rather small input space and feedback channel of a mobile device by expanding the interaction capabilities to the entire body, such as using the arms, torso, legs, feet, and the head. Exploiting the body's surface for the purpose of on-body input gestures was initially sketched by Harrison [Har13], who also sees on-body interaction to be natural. Expanding input space to the wrist [ZZLH16] or by using several other body parts for on-body tapping gestures is promising and is within the current scope of state-of-the-art research in HCI.

In summary, we can significantly expand input space using our skin and simplify interactions by creating a variety of natural tiny gestures, such as *head nodding* (interpretable as a positive command), or *head* shaking (negative command), or *eye* winking (indicating a neutral command such as to skip/mute). At the same time, we can also expand feedback to all areas of our body. For instance, the foot has more sensory cells than the human face and thus it seems logical to also expand feedback to this particular area of the body. Nonetheless, when doing so, we must consider that feedback is always perceived in a very diverse way across body parts [KMF+11], across different individuals [KMM16], and impacted by contextual factors. While we can spatially extend feedback to the entire body, we can also vary the type of feedback modality. In general, distributing information on multiple modalities has shown to reduce cognitive stress and this tendency favours the concept of *Reflexive Interaction*.

**RQ 4:** *How can we reconsider interactions for smart devices to enable an adequate input for binary tasks that are feasible when the user is involved in real world tasks?*

In particular smartphones have become increasingly powerful, although, there are still some mobile interactions that demand unnecessarily high attention, such as: confirming the change of route, noticing a message, changing a song, or responding to a phone call. Elaborating on the last example; current notification and input strategies are not adequate. While a loud ringtone addresses everybody else in the user's vicinity, however depending on the situation it may also be perceived as highly bothering. The supposedly quick control, such as accepting, muting, and rejecting a caller can be seen as inappropriate when considering the aimed effect in contrast to the effort taken. Until now, the user has been required to take out the phone by hand, to visually focus on it, and interact by making use of a finger. Sometimes both hands can be required for a rather thin and almost binary interaction, which can be considered as an inadequate interaction strategy.

A *Reflexive Interaction* is perfect for these kinds of minor-complex interactions because it offers a scaled notification just subtle enough to be recognized and provides a quick response without drawing great attention to the task. This interaction type does not use already occupied interaction channels and would not interrupt a real world interaction, such as when the user is involved in a conversation or on the go. For instance, when involved in a conversation, subtle vibrations under the foot would notify the user on an incoming phone call, and a simple heel tapping gesture could be the command used to reject the call. When feet are already involved in other tasks, such as walking or driving, different channels such as the visual peripheral perception or facial and head gestures would be enabled for a *Reflexive Interaction*. While a *Reflexive Interaction* requires a certain time for conditioning, the learning phase is reduced when sticking to well-known metaphors and low-complex gesture sets.

**RQ 5:** *How can we increase the user's ability to interact at any time?*

Technology is truly ubiquitous and about to penetrate the entire human body. Even though Si-Fi fantasy fiction romanticizes cybernetic organisms, Maes [Mae17] states the human to have already reached the cybernetic level. Indeed, Neuromodulators and Neurostimulators are already being implemented to increase life style of impaired users today. While these devices work mostly independent from a person's will, these devices in the future will be implanted into the body and directly augment a human's skills and capabilities by also involving explicit interaction. This thesis, by means of using wearables, sketches how a future *body-melted computing* may look. Therefore, the first part of the answer is: the technological infrastructure of computers must be ubiquitous and resting on and possibly in the human body.

The second part of the answer addresses the technique we may use in order to unfold the potential power of technology. Although technology, such as smart glasses, may always be available, we cannot ensure the user to be enabled to always flawlessly interact in this great variety of mobile scenarios. This is related to ambiguous contexts and because of the user's limited mental and physical resources. Cognitive overload can quickly occur when facing non-familiar tasks or a too high number of tasks due to attention being split among multiple tasks. In conclusion, interactions may fail or result in longer tasks completion times and have potentially significant high error rates [ATH14, MMUW15]. Although a *Reflexive Interaction* is aimed to enable an omnipresent interaction at any time, the aforementioned constraints also apply here. A very demanding primary task or a great number of parallel tasks may also disable a well-trained *Reflexive Interaction*.

## 6.2 Thesis Statements

This section summarizes most important key findings of the conducted series of researchers in regard to *Reflexive Interaction*. The findings are condensed into two subsections: *6.2.1 Input* and *6.2.2 Feedback*.

### 6.2.1 Input

**1.1** **Low complexity of a gesture set:** The quality and volume of a gesture set that is used for control should remain minor-complex. Gestures requiring longer than a second, and sets containing more than five entities may not enable a *Reflexive Interaction*. This is because the user would start thinking about the gesture assignment, which creates significantly added cognitive load. Therefore, technologies do not need to be capable of distinguishing 25 facial and head gestures, for instance.

**1.2** **Applicability of facial and head gestures:** Specific facial and head gestures can be successfully implemented in critical mobile scenarios, such as when riding a bike. In this example controlling a music player by facial gestures has shown to enable the completion of the primary task without a distraction.

**1.3** **Using the ear canal to register facial activity:** Facial and head gestures can be detected inside the ear canal through the use of electric or optical sensing technologies.

**1.4** **Electrical Field Sensing technology can be wearable:** A differential amplification EFS can be sensitive enough towards minimal changes in electric fields of the human body in order to sense facial-related and other kinds of gestures and activities, furthermore it is applicable in a wearable scenario.

**1.5** **Gaining context information from inside the ear canal:** A sensor resting inside the ear canal can detect the skin's conductivity, ear canal deformations, muscle contractions, and even brainwaves. These sensing possibilities yield a great quantity of indications on the user's mental state, (e.g., indicating tiredness, determine sleep state,...) and physical state (e.g., indicating physical exhaustion through facial gestures, detecting walking activity by created artifacts,...).

**1.6** **Social acceptability of on-body tapping:** Tapping on one owns body doesn't feel awkward and is potentially social acceptable (also depending on body position). For instance, tapping on the stomach area or side of the body is experienced to be more natural than raising the hand towards the head and tapping on the frames of a person's own glasses. Speech input can be used for low-complex commands, but may be also less preferred than a quick on-body tapping gesture.

**1.7** **On-body interaction is a personal activity:** Mapping the execution of a phone call or the control of an image browser to a desired body part varies upon each person's personal preference. Expanding input space for possible gestures relating to interactions on one owns body parts may be more feasible than expanding it to another person's body due to societal stigmas, cultural faux pas, religious laws, and personal privacy.

**1.8** **Expanding the variety of on-body gestures:** We can expand input space with supporting input techniques for eye- and hands-free interaction. On-body interaction can go beyond binary tapping gestures and be enriched by using soft or long touches, hovering gestures on the limbs and body, using arms for tapping on the hip, or with the use of leg gestures. It is to note that precision is generally reduced when gestures do not include the use of the fingers. Also, when shifting towards hands-free input on our body, input space might not increase.

**1.9** **Mobile availability of on-body interaction:** On-body interaction yields a high surface area of availability, unless interaction on the bare skin while wearing clothing is required. Based on proprioception, users are not necessarily required to visually focus on the input gesture, thus a primary task may remain uninterrupted, which is an important basis for a *Reflexive Interaction*.

**1.10** **Alternative control through explicit foot gestures**: Explicit foot gestures based on plantar pressure exertion do not occupy resources of commonly used primary interaction channels, such as heel tapping and weight shifting, which provides additional input for control. Making use of simple foot gestures may not disturb the user's main task and thus abet a *Reflexive Interaction*.

**1.11** **The foot can reveal current context:** Identifying the current context can substantially favour a *Reflexive Interaction*. With the use of a capacitive insole, the position of the foot is suitable to infer and determine context through detecting the user's current body posture, specific walking activity, and the floor type the user is walking on. This environmental and user specific information indicates the readiness of a user to become involved in a parallel task, so to perform a *Reflexive Interaction*.

**1.12** **Utilizing the individual footprint:** The generation of an individual footprint based on foot shape, weight, and style of walking enables the creation of an implicit user authentication. User habits and cognitive resources are very individually pronounced. And therefore, adjusting input and feedback modalities individually can help to create better user experience.

**1.13** **Subtle foot gestures yield social acceptance:** Foot gestures are subtle and not usually recognized by others during a conversation. Quick foot gestures can be more discreet in non-use foot scenarios and thus tend to be socially acceptable.

**1.14** **A *Reflexive Interaction* is compatible with *Microgestures*.** Complex input and feedback is not possible to be executed in a manner of a *Reflexive Interaction* due to the increase in cognitive demand. It is assumed that in future, complex feedback will still require visual focus by our eyes, while complex input will remain with a coordination by the fingers. However, *Microgestures* proposed by Wolf seem to be successfully executable in a manner of a *Reflexive Interaction* when fingers are not occupied by the primary task.

### 6.2.2 Feedback

**2.1** **High noticeability of visual feedback:** When being outside on the go, notifications, such as audio or haptic notifications (e.g., a ringing or vibrating phone) are quickly overlooked. This also applies to other stimuli when high level of noise is present. In contrast, visual feedback, such as displayed in our peripheral vision, yields a major advantage of being highly noticeable, also in mobile situations.

**2.2** **Exploiting visual peripheral perception:** Visual peripheral perception does not limit the user to performing real world tasks, but instead provides an additional feedback channel that should be exploited in HCI more in depth.

**2.3** **Recognisability and display position:** The display position of a PHMD has a major impact on the level of recognisability. The Middle-Center arrangement provides high noticeability, which favours a quick response, but can quickly interfere with the primary task. Using a low-complex stimulus, such as a colour change, makes the Middle-Right, Top-Center, and Top-Right positions also interesting for a *Reflexive Interaction*.

**2.4** **Recognisability and visual stimulus:** Stimuli make a difference and should be carefully designed when aiming to enable *Reflexive Interaction*. Motion and colour are perceived more quickly with a lower error rate, than detailed information, such as text, which is normally recognized very late or may even be overlooked.

**2.5** **Scaling feedback to a subtle level:** Scaling feedback down to a subtle but still perceivable level can be challenging because users have varying individual sensitivity thresholds. However, the benefit of subtle feedback is that it does not negatively influence the primary task. Based on the design it can even significantly support the task, such as reducing reaction time.

**2.6** **Noticeability-distraction trade-off:** We can clearly see that highly noticeable feedback like heavy vibrations, draw a great amount of attention. In contrast, very subtle feedback is less distractive but sometimes overlooked. We face the challenge of providing subtle but noticeable feedback, as well as selecting a suitable modality.

**2.7** **The perception of subtle feedback is affected by background noise:** When a high level of noise is present, such as external vibrations or audio, subtle feedback will be overlooked more often. However, overloading the user with multiple tasks does not negatively affect the perception of subtle feedback.

**2.8** **Supporting the user with *forcing feedback*:** Forcing the user to react to a notification favours recognisability, minimizes reaction time, and improves task completion times, thus supporting the execution of a gesture in a way that favours a *Reflexive Interaction*.

**2.9** **Social and ethical considerations with *forcing feedback*:** Applying a *forcing feedback* may raise ethical responsibility concerns. A significant amount of users would prefer not to use a system that scales a notification alert up to a forcing level.

**2.10 Preferences for feedback modalities:** Feedback is perceived different across individual body parts. Certain combinations of feedback modality and location of the body part are not equally applicable to all users. Although users have an individual preference for modalities, there are also similarities, such as none preferred feedback at the head.

**2.11 Using notification patterns:** Using stimuli patterns to convey complex information, such as vibrational patterns under the feet, generally requires longer actuation time and yields higher error rates which work contradictory to a *Reflexive Interaction*.

**2.12 Using vibrotactile feedback for minor-complex notifications:** Haptic notifications can replace visual feedback, but only in limited ways. For instance, a vibrotactile turn-by-turn pedestrian navigation is possible without obstructing the user. However, when it comes to navigating in unknown territory, visual hints, such as a map, are required to deal with ambiguous situations that people would encounter in cities.

**2.13 Distributed feedback for stress reduction:** Overloading the visual channel with too much information can result in a cognitive overload and thus create stress. We can reduce stress by presenting information within different types of modalities while distributing information to multiple body parts.

**2.14 Walking speeds influence haptic perception:** Using alternative feedback modalities in a mobile scenario enables the visual focus to remain on the street. Haptic feedback can serve as an alternative channel here, although increasing walking speed will influence haptic perception negatively.

**2.15 Vibrotactile feedback at the foot:** Even though the foot is exposed to vibrations from the impact when touching the ground with each step, it is still capable in perceiving vibrotactile signals precisely and not significantly worse than other body parts.

**2.16 Feedback in shoes is subtle:** Implementing feedback in a shoe or in an insole is silent, thus it does not disturb others when engaged in real world tasks. Notifications, such as incoming phone calls, will be recognizable without the disturbing of others in an inappropriate situation such as during a business meeting.

**2.17 Improving immersion with foot interfaces**: A foot interface, such as an insole, enables for natural leg movements to be used and tends to increase immersion. Haptic sensation under the foot, for instance, could simulate collisions and ambient information from the ground surface, such as gravel or hot sand in a desert. Moreover, a rising temperature in the shoe can make the user to unconsciously feel uncomfortable.

**2.18 Adaptive perception and perception latency:** While being on the go, vibrotactile feedback may be missed or only perceived after a short period of time, this can be caused by several reasons, one reason being the unfaivoured type of floor one is walking on. A rising temperature, such as created by a *Peltier Element*, may also not be quickly perceivable due to the built in adaptation of our bodies' "*central adaption phenomenon*", which makes a person unable to recognize slight changes in temperature. Nerves have this unique ability to acclimate to discomfort until becoming numb

# 7. Summary & Outlook

In this thesis, the idea of a *Reflexive Interaction* has been proposed, it is underlined by several interaction concepts that involve the human body in its entirety. Because each body zone yields its specific unique qualities, a variety of interaction concepts are demonstrated covering each body zone. For example, in the region of the head; besides the enablement of facial and head gesture, we can perceive visual information within our peripheral field-of-view. On our body, we can perform a quick tapping and hovering and we can use haptic, thermal, or electrical feedback on our skin in order to perceive different escalations of notifications. The last zone, our foot, enables quick foot tapping gestures as well as the possibility to perceive vibrotactile feedback under the foot's sole. In particular, the foot and the face both generate unique information which can be utilized to infer on the user's context, such as physical activity or emotional state. To enable a successful *Reflexive Interaction*, we should consider the user's current context. Moreover, it is important to rely on minor-complex input gestures and notifications. To keep technology in the background we must avoid having the user overthinking the intended interaction, but that may require a longer training phase. It is evident that high density input and information presentation interfaces, such as a touchscreen, are not replaceable by the wearable prototypes and mobile interaction techniques proposed. Instead, the approaches demonstrated in this thesis should be seen as a complementation of current interaction techniques to further enrich common input and feedback strategies in mobile situations.

How mobile interaction will look like in the future is unclear, however, we must assume that alternative interaction techniques involving more than fingers and eyes will become the new norm. Current user interfaces, such as touchscreens, will not be replaced soon because they are considered to provide a natural interaction that matches the criteria of Shneiderman's *Direct Manipulation* [Shn97]. In particular, the finger will remain the primary input channel because the finger is the most agile external organ and also because BCI's won't prevail very soon due to technical and ethical aspects. Therefore, interaction will still remain to and with our bodies involving an activation of our neuro-muscular system. Alternatively, mobile interaction could also be expanded onto our bodies as envisioned by Harrison, who sees the human body as an interactive computing platform [Har13]. On-body interaction yields a wide spectrum of advantages, such as two square meters of skin that can be manipulated in various ways (e.g., pressed, squeeze, inked etc.) [Wei17]. Still the hand seems to be the most preferred input location among other body parts since it yields high familiarity with similar tasks and because it yields greater social acceptance when used in public situations [Oh16]. It is not just a matter of technical feasibility, but also a matter of social acceptance that helps to decide which interaction techniques are going to prevail in future. However, the perception of technology may change over time.

This thesis contributes to the idea of a *Reflexive Interaction* as a possible answer to the challenges of interacting in mobile context, in particular when the user is on the go. However, there are still questions left to explore. Some are listed here to serve as a thought-provoking impetus for future research.

- What is the optimal number of assigned input gestures, that can be internalized while still enabling a *Reflexive Interaction*?
- How long is the learning phase until a conscious execution of a gesture becomes internalized so it can be executed quick enough in a reflexive and reactive pre-attentive way?
- What would the context look like in order to not disturb the user while presenting feedback while having the possibility to input gestures for a secondary task truly in parallel?
- What is the limit of complexity pertaining to gestures and notifications in order to still enable a *Reflexive Interaction*? How can notifications be conveyed that would have a higher complexity but would not have a distracting influence on the user?
- How subtle can a feedback be made to not distract the user but also not to be unintentionally ignored?
- How can a future system escalation scale give the notification an appropriate level based on the urgency of information? What type of feedback modality is preferred in which context?
- What is the social acceptance of new input gestures, such as using facial expressions and head gestures on-body tapping gestures and foot gestures? And how can we improve social acceptance?
- Is *forcing feedback* going to be accepted by the user? What is the social impact in terms of ethics and legal responsibility?
- How deep should wearables penetrate our bodies? Are wearables just the step before implants? Should we see technology as an extension of our bodies or as a co-worker and friend?

# Glossary

| | |
|---|---|
| 10-Fold-Cross-Validation | a technique to evaluate any predictive models by partitioning the original sample into a training and test set, while using 10 folds and 1 repetition |
| **A** | |
| Accelerometer | an electric sensing technology used to record motion through acceleration |
| Accuracy Rate | a weighted arithmetic mean of Precision and Inverse Precision as well as a weighted arithmetic mean of Recall and Inverse Recall |
| Action | the ability of a motor control, such as movement of limbs, tongue,... |
| Activity Recognition | an important field in Computer Sciences that deals with recording human movements and interpreting them |
| Actuator | any type of electrical component emitting a mechanical signal, such as a spinning force, by electrical power |
| ANOVA | Analysis of variance, which is a collection of statistical tests used to analyze the differences among group means |
| AR | Augmented Reality, which is a technology superimposing virtual image on a user's view of the real world, thus providing a composite view |
| Arduino | an open-source electronic prototyping platform using mainly ATMEL microprocessors |
| Attention | the behavioural and cognitive process of concentrating on information |
| Audioception | scientific term standing for the human sense of hearing |
| Augmented Human | the idea of complementing human intellect by expanding his senses and actions |
| Azimuth | scientific term meaning the geographic location in width (X-Axis) |
| **B** | |
| Between Subject Study | a study design in which two or more groups of participant test a single or more conditions |
| Binocular Rivalry | describes the phenomenon, which occurs when dissimilar images are presented to the human eye |

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|---|---|
| Bio-acoustic Sensing | the investigation of sound production, dispersion and reception in living bodies |
| Bio-feedback | a technique to gain information one's body functions, which is not based on a specific technology |
| **C** | |
| CAVE-like-installation | based on the CAVE: audio visual experience automatic virtual environment, which is an immersive room, such as a five-display wall room |
| Cognition | the mental process of understanding |
| Cognitive load | the total amount of mental effort being used in the working memory |
| Confusion matrix | table visualization that is used to describe the performance of a classifier on a set of test data |
| Consciousness | the state of being aware of and responsive to our surroundings |
| Context | characterizes a situation, which incorporates the user (e.g., activity, mental state), the environment (e.g., current place), and other objects that can be described as an entity |
| CRT | Cathode Ray Tube, which is a display technology to produce images in a vacuum tube that contains one or more electron guns and a phosphorescent screen |
| CS | Capacitive Sensing, an electric sensing technology charging an electrode in certain intervals in order to detect conductive object or subject, such as a human |
| **D** | |
| Dense Sensing | sensing technology spatially distributed in a certain area |
| **E** | |
| EEG | Electroencephalography, an electric sensing technology used to record brain waves |
| EFS | Electric Field Sensing, an electric sensing technology used to record electric charges in proximity |
| Electrode | any conductive material having the potential of absorbing and emitting electrons |
| Electromagnetic Sensing | an electric sensing technology used to record magnetic fields |
| Elevation | a scientific term meaning the geographic location in height (Y-Axis) |

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|---|---|
| EMG | Electromyography, an electric sensing technology used to record muscle activity |
| EOG | Electrooculography, an electric sensing technology used to record corneo-retinal standing potential around the human eye |
| Equilibrium | scientific term standing for the human sense of balance |
| Error rate | the lowest possible error rate for the classifier, which is usually the False-Positive Rate |
| Explicit Interaction | the focused and goal directed interaction between the human and computer involving the user's center of attention |
| Eye-Dominance | used to describe the phenomena that one eye is predominantly used, while the other eye is used to make corrections and provide additional spatial information |
| Eyes-free Interaction | interactions that aim in not involving user's visual attention |
| **F** | |
| False-Negatives | all items which were not labeled as belonging to the positive class but should have been |
| False-Positives | all items incorrectly labeled as belonging to the positive class, although being negative |
| Features / Feature Set | are mathematical algorithms describing a signal by their properties, such as highest amplitude, zero-crossings, mean, SNR... |
| Feedback | strictly seen an output of a system based on routed back inputs from a user, however, in this thesis, feedback involves any type of a system's output which may also be independent from a user input |
| Feedback Modality | a generic term describing any sensory modality that addresses; auditory, visual, tactile, or olfactory sensation |
| FFT | Fast Fourier Transformation - transforming a spatial or time signal into a frequency domain |
| Field Study | a method for collecting any kind of user data outside of an experimental or lab setting, which is done in a natural environment |
| Focal Attention | when the user's center of attention is being demanded on a task |
| FOV | Field-of-View, which is the physical range of visual perception of a user's eye that in average covers a viewing angle |

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| | of 94° from the center and 62° (horizontally). The vertical angle is about 60° upwards and 75° downwards. |
| Fritzing | an open-source hardware initiative to document electronic circuits readable for non-engineers |
| FSR | Force Sensitive Resistor, which is a sensing technology in which the resistor is changed based on the exerted pressure |
| **G** | |
| Gait | the individual style of walking |
| Gustaoception | scientific term standing for the human sense of taste |
| Gyroscope | an electric sensing technology used to record motion through rotation acceleration |
| **H** | |
| Handheld Device | describes a mobile computing device being able to hold while weighting below 0.7kg |
| Hands-free Interaction | interactions that aim in not involving user's hands and fingers |
| Haptic Feedback | describes a touch-like stimuli at the user |
| HMD | Head-Mounted Display, which can be a pair of goggles, such as the Oculus Rift |
| HUD | Head-up Display, which is an image projection in front of the user (often on a windshield) while not requiring the user to angle his head down (Head-down Display) |
| Human Computer Integration | is the idea of creating a symbiosis between human and technology |
| **I** | |
| Implicit Interaction | an interaction concept that is not involving the user's attention |
| Input | strictly seen any outer manipulation of a system, however, in this thesis input refers to any type of user entry, such as gesture control |
| **L** | |
| Lab Study | Laboratory Study, which is a study under controlled conditions in an artificial environment, in order to study and analyse a certain effect in a better way without great external influences |
| LCD | Liquid-crystal-display, which is a display technology to produce images |

| | |
|---|---|
| LCos | Liquid crystal on silicon, which is a display technology to produce images for microdisplays |
| Leave-k-Out | a technique to evaluate any predictive models by partitioning the original sample into a training and test set, while k can be an instance or a user |
| Loading Mode | usually used in a capacitive sensing setup, while a single electrode is cyclical charged and discharged |

**M**

| | |
|---|---|
| Magnitude | the relative size, such as the length of a vector |
| Microgestures | any tiny gestures, such as finger movements |
| Microinteractions | any interaction lasting no longer than four seconds |
| Mobile Context | when the environment is highly dynamic, such as when the user is on the go |

**N**

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|---|---|
| NASA TLX | Task Load Index test developed by NASA in order to assess the perceived workload of a task |
| Natural Interaction | has a vague meaning in HCI, but usually means to make use of by the human well known "gesture-languages", such as using foot/leg movements for locomoting in a VE, or using head nodding/shaking to accept/reject a request |
| Neuromodulator | a type of true implant, which senses and stimulates, such as using EEG for measuring and EMS for a deep brain stimulation |
| Neurostimulator | a category of implant such as a Pacemakers, implant basically penetrates our nervous system without the user being consciously involved |
| Notification | in context of this thesis, it describes the alerting of a user with low-complex information using a certain feedback modality, such as a vibration to signal an incoming call |

**O**

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|---|---|
| Obtrusiveness | the perceived level of pungency, awkwardness, and disruption |
| OLED | Organic Light-Emitting Diode, which is a light-emitting display technology to produce images |
| Olfacception | scientific term standing for the human sense of smell |
| On-body Computing | utilizing the human's physical body, such as using the skin for tapping input and perceiving tactile feedback |

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|---|---|
| Ophthalmoception | scientific term standing for the human sense of sight |
| Optical Sensing | a technology used to detect light, such as RGB cameras |
| OSC | Open Sound Control, which is a protocol for networking sound synthesizers, but nowadays used for communication of any multimedia devices |
| OST-HMD | Optical See-Through Head-Mounted Display, which is a transparent display mounted to the user's head |
| **P** | |
| Peltier element | a thermoelectric component converting electric current into thermal energy and the other way round |
| Percentage Split | a technique to evaluate any predictive models by training the classifier with a certain percentage of the complete set |
| Perception | the ability to interpret senses, such as vision, audio, smell,... |
| Peripheral Attention | the ability to perceive the environment in parallel without focusing (co-exists to focal attention) |
| Peripheral Interaction | an interaction concept that is partly involving the user's attention, such as for a secondary task |
| Peripheral Perception | often equated with Peripheral Vision, however, it also includes the perception of any other body's sense |
| Peripheral Vision | the outer limit of the user's FOV, which remains at around 40 degrees each side (horizontally) |
| PHMD | Peripheral Head Mounted Display, which is a display resting in the periphery of the user's field of view, such as Google Glass |
| Phoria | describes a muscle state of the eye, when the eyes are not focusing on a specific point |
| Pilot Study | a pre-study in a small scale in order to evaluate feasibility, time, cost, adverse events, and effect size to predict the appropriate study conditions and sample sizes |
| Precision | an arithmetic calculation of True-Positives divided by (True-Positives + False Positives) |
| Processing | an open-source software sketchbook and a language based on Java |
| Proprioception | the unconscious perception of movement and spatial orientation of our bodies arising from internal stimuli |
| **R** | |
| Recall | an arithmetic calculation of True-Positives divided by (False-Negatives + True-Positives) |

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|---|---|
| Recognition Rate | informal denotation of a positive detection, which can be either precision, recognition or simply a true-positive rate |
| Resistive Sensing | a sensing technology in which the resistor changes based on an impacting variable, which is often a mechanical force (see FSR) |
| RP | Retinal Projection, which is an imaging technology to producing an image directly onto the retina of the human's eye |
| **S** | |
| Sample Size | in social sciences and empirical research: number of users, in computer sciences: the length of a data query per second |
| Sensor | a device capable of recording any type of change, such as a force, while converting it into a computer-readable data format |
| Shunt Mode | usually used in a capacitive sensing setup, allows electric current to pass around another point in the circuit by creating a low resistance path |
| Signal Energy | describes the total power of a signal |
| Smart Devices | summarizing a large group of wearable and mobile devices that communicate with each other |
| SNR | Signal-to-Noise Ratio, is used to describe the signal quality and an important feature for the description of a signal |
| Statistical Significance | a statistical significance is given when the applied test results in a probability value <=0.5, thus the comparison of at least two groups is different |
| Stimulus | (Plural: Stimuli), in this thesis, it solely describes a stimulation of the human sensory perception, such as by the means of feedback modalities |
| **T** | |
| t-Test | also denoted as the Student's t-test, which is a statistical test based on a pairwise variance and mean comparison of two groups |
| Tactioception | scientific term standing for the human sense of touch |
| Transmit Mode | usually used in a capacitive sensing setup, allows electric current to pass from one to another opposite point in a direct path |
| True-Negatives | all items correctly labeled as belonging to the negative class |
| True-Positives | all items correctly labeled as belonging to the positive class |

**V**

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|---|---|
| VE | in computer sciences: virtual environment, which is usually an immersive 3D scene |
| Vibrotactile | the haptic sensation based on high frequent mechanical stimuli |
| Visual Interference | describes the phenomenon when both eyes perceive different images that are overlapping, but the brain is not able to distinguish between those |
| VR | Virtual Reality, which summarizes several technologies creating a virtual space |
| VRD | Virtual Retina Display, which is an imaging technology producing an image directly onto the retina of the human's eye |

**W**

| | |
|---|---|
| Wearable Computing | defined term that sketches affordances and properties of computing with wearables |
| Wearable Sensing | sensing technology worn by the user |
| Wearables | any computational devices worn on, at, and near the body |
| Within Subject Study | a study design in which two or more conditions are tested by the same group of subjects. |

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# Acknowledgements

Undoubtedly, the creation of a work of this calibre is not only an individual effort, in fact it involves the support of thirds who held different roles in my life. While the way was characterized by great excitement and success, it was also stony, as it yielded many moments of frustration and also misunderstandings, which also once lead to a loss of a friend. I admit that keeping the balance between working towards a higher goal and maintaining social contacts is something I have failed too often. Therefore, I would like to take this opportunity to apologize to those people feeling addressed.

My deepest thanks go to my parents, who furthered my inspiration for computers at an early stage of life. Apparently, your very own strategy of motivating me has worked out well. I would like to thank my supervisor Professor *Bodo Urban*, who was convinced of my research proposal and who provided me with the necessary freedom to pursue my ideas over the past years. Your loyalty and trust in me as a researcher is something I always appreciated. Thank you, *Marian Haescher*, for a longstanding friendship, for listening, and for bringing up important impetuses just at the right moments. Moreover, I am indebted to thank the following co-authors, who held substantial contributions: *Anita Meier, Bernhard Arthur Strecker, Laura Milena Daza Parra, Soon Hau Chua*, and Professor *Simon Tangi Perrault*, who is by the way the most humorous and supportive French I know. I am grateful to have met *Thijs Roumen*, an officially CHI-awarded "*Excellent Reviewer*", who has been my one and only feedback source providing me quite often with valuable reviews just before the submission deadline. I would like to thank Professor *Shengdong Zhao* for offering me the unique opportunity to work at the NUS HCI Lab and for getting me in touch with all those nice people in the lab – it had been a formative and joyful time for me!

Moreover, there is a number of individuals, who may not be aware that I have been inspired by them during my academic career, such as Professor *Reto Wettach*, who initially drew my attention on HCI research in the domain of Physical Computing, *Gerald Bieber*, who constantly amazed me with his creativity and exciting side projects, and *John N.A. Brown*, who by chance shared the same *«unseen, yet crescive»* perspective on *Peripheral Interaction*.

My final words of thanks go to those I had joint publications with and also to everyone that supported me in my academic activity.

# Author's Declaration

I declare in lieu of an oath that this PhD Thesis submitted has been produced by myself without illegal help from other persons. This work as a whole piece has never been part of any other examination nor it has been published before the date of defence. Passages, which have been taken out of third party publications of all means, either in whole or in part, in words or ideas, have been clearly marked as quotations in the relevant passage.

Rostock, 27.10.2017

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