Fakultät II – Informatik, Wirtschafts- und Rechtswissenschaften
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# Wrist-Worn Light-Based Smart Digital Jewellery

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# Zusammenfassung

In den letzten Jahren ist bei Verbrauchern der Trend zu am Körper tragbaren Geräten, sogenannten *Wearables*, stetig gewachsen. Aktuelle Studien in den USA zeigen jedoch, dass ein Drittel der Besitzer eines *Wearable* dessen Nutzung bereits innerhalb von sechs Monaten einstellt. Als Gründe werden u.a. ein Mangel an nützlichen Funktionen, Ästhetik und Komfort angenommen. Der Ansatz des *Smart Digital Jewellery* (übers.: "Smarter Digitaler Schmuck") könnte durch die Kombination von Funktionalität und dekorativem Erscheinungsbild das Problem der Nutzungsaufgabe lösen und die Langzeit-Akzeptanz tragbarer Geräte verbessern. Smarter Digitaler Schmuck beschreibt am Körper getragene, dekorative Objekte, welche wie Schmuck aussehen und gleichzeitig computergestützte Funktionen bieten. Forscher haben einige Konzepte für verschiedene Arten von Smartem Digitalen Schmuck vorgestellt. Umfangreiche Untersuchungen fehlen jedoch. Es werden spezifische Design-Richtlinien benötigt, die Entwickler dabei unterstützen, weitgehend akzeptierte tragbare Technologie in Form von Smartem Digitalen Schmuck zu erstellen.

In dieser Dissertation wurde untersucht, wie am Handgelenk getragener Smarter Digitaler Schmuck gestaltet sein sollte, um alltagstauglich zu sein und die Bedürfnisse von Nutzern zu befriedigen. Nach der Exploration des Gebiets Smarter Digitaler Schmuck wurde untersucht, wie Smarter Digitaler Schmuck geformt sein soll, wie Informationen präsentiert werden können und wie ein Nutzer mit Smartem Digitalen Schmuck interagieren kann. Die Untersuchungen wurden anhand von Prototypen durchgeführt, welche entworfen, implementiert und in Labor- und Feldstudien evaluiert wurden. Verschiedene Szenarien veranschaulichen die Anwendung von Konzepten bzgl. der Form von, sowie der Informationsdarstellung und der Interaktion mit Smartem Digitalen Schmuck auf die Anwendungsdomänen Gesundheitsförderung, Alltagswerkzeuge und nicht-verbale Kommunikation.

Die Beiträge dieser Arbeit sind (1) die im Rahmen des Forschungsprozesses erstellten Artefakte als physikalische Repräsentanten der untersuchten Konzepte, (2) ein detailliertes Verständnis vom menschzentrierten Design und der Evaluation von am Handgelenk getragenem Smarten Digitalen Schmuck für verschiedene Anwendungssfälle, (3) konkrete Designempfehlungen hinsichtlich am Handgelenk getragenem Smarten Digitalen Schmuck in Bezug auf Erscheinungsbild, Informationsdarstellung und Interaktion, und (4) die Reflexion über die Eignung verschiedener menschzentrierter Prototyping- und Evaluationsmethoden zur Erforschung von Smartem Digitalen Schmuck. Die Designempfehlungen liefern einen wesentlichen Beitrag für die Entwicklung akzeptierter, tragbarer Technologie. Sie ermöglichen es Entwicklern, ansprechende und komfortable Geräte zu erstellen, die sich gut in den Alltag integrieren. Die Reflektion der eingesetzten Forschungsmethoden hilft Forschern, passende Methoden für ihre Untersuchungen auszuwählen und identifiziert Potentiale für zukünftige Forschungsarbeiten.

# Abstract

In recent years wearable devices have become an emerging trend in the consumer market. However, recent studies in the U.S. show that a third of owners of a wearable device abandon its use within six months. Supposed reasons are, among others, a lack in useful functions, aesthetics, and comfort. Smart Digital Jewellery (SDJ) has been proposed as an approach that could overcome the problem of abandonment and increase long-term acceptance of wearable devices by joining functionality with a decorative appearance. The term describes decorative objects worn on the body, that appear as jewellery and at the same time offer useful, computerised functions. Researchers have proposed a number of concepts for different types of SDJ, but thorough investigations are missing. Specific design guidelines are needed that tell developers how to design broadly accepted wearable technology in the form of SDJ.

In this dissertation we investigated how wrist-worn SDJ should be designed in order to be everyday suitable and meet the users' needs. After having explored the scope of SDJ, we investigated how wrist-worn SDJ should look like, how information could be presented, and how a user could interact with SDJ. We investigated single-purpose as well as multi-purpose SDJ. The investigations were carried out by means of concrete SDJ systems, which we designed, built and evaluated in the lab and in real-life situations. Several scenarios illustrate the application of concepts regarding the form of, as well as information presentation and interaction with wrist-worn SDJ to the domains of health promotion, everyday tools, and non-verbal communication.

The contributions of this work are (1) the artefacts that were created during the research process as means of physical representations of the investigated concepts, (2) detailed insights into the human-centred design and evaluation of wrist-worn SDJ for several use cases, (3) concrete recommendations on how to design wrist-worn SDJ, i.e., according to appearance, information presentation, and interaction, and (4) the reflection on the applicability of a variety of human-centred prototyping and evaluation methods for researching SDJ. The insights into the design and evaluation of wrist-worn SDJ and the design recommendations provide a good step in pointing us towards designing acceptable wearables. They enable developers of wrist-worn technology to create appealing and comfortable devices that integrate well into everyday life. The reflection on the methods used helps researchers to choose appropriate methods for their studies, and identifies potential areas for future work.

# Contents

# 1 Introduction

> *"Fashion First – It does not matter what the device does unless the user is willing to put it on the first time"* [Bil15].

A wearable computer, wearable device or "wearable" is defined as computational and sensory technology that is worn on the body, i.e., under, over, or in clothing [Man13]. In recent years, wearable devices have become an emerging trend in the consumer market. In 2015, the wearable market grew more than 189% compared with 2014, i.e., 79 million wearables devices were shipped, from which 71.5 million units belonged to wristwear. Forecasts predict that in 2016, worldwide wearable shipments will reach 101.9 million units, of whom watches and wrist bands together will hold 91.5% of the market [Int16]. Wearable devices are designed to be worn all the time during daily life. Thus, aesthetics, as well as physical and social comfort are important quality criteria of a wearable device. However, recent studies in the U.S. show that a third of owners of a wearable device abandon its use within six months [Led14]. Supposed reasons are, among others, a lack in useful functions, aesthetics, and comfort. Thus, currently, many wearable devices perform bad in user experience, which is defined as "a person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service". It includes all the users' emotions, beliefs, preferences, perceptions, physical and psychological responses, behaviours and accomplishments that occur before, during and after use [ISO10]. A major challenge for wearable devices is their appearance in terms of decoration and fashion. Researchers state that people will not wear wearable devices that do not address their aspirational and style needs [IBM14, Bil15, Sta01b]. Market researchers assume that a large share of the market remains untapped because of design limitations and that currently, wearable devices do generally appeal to early tech adopters [Was15, IBM14].

Humans generally identify with body-worn things and use them for self-expression [WDF07]. Jewellery is something that humans have been using for thousands of years for adorning and self-expression. Thus, combining jewellery and wearable technology would provide an obvious solution to the problem. Smart Digital Jewellery (SDJ), an approach to seamlessly integrate technology into appealing, body-worn objects, has been proposed as an approach that could overcome the problem of abandonment and increase long-term acceptance. **We define SDJ as decorative objects that are worn on the body, appear as jewellery, and at the same time offer useful, computerised functions.** The idea is to make wearable technology look more like jewellery, as being something humans have been adorning their bodies with for thousands of years. Jewellery is socially accepted, particularly worn for expressive, often decorative reasons, and available in various forms and designs. This makes jewellery a well-suited basis for wearable technology.

Recently, industry started the attempt to create more appealing wearable technology that seamlessly integrates into everyday life. E.g., the activity tracker *Misfit Shine* became available in 2013 and was one of the first consumer wearables explicitly emphasising decorative aspects. In the following years, further products, such as bracelets, necklaces, and rings followed and several crowd funding campaigns were announced. Figure 1.1 shows, e.g., the recently announced Aries bracelet [Rin16]. The majority of SDJ products relies on companion smartphone applications, offers simple point light or vibration displays, and does not enable direct user input. However, the number of available SDJ products is still small, as several products are currently in funding or development process, and several announced products never made it to market or were discontinued after a short time.

*Figure 1.1: The Aries bracelet appears as jewellery and displays notifications from a smartphone via vibration patterns and a flashing light shining through a hole on the side of the bracelet. Image source: urbanwearables.technology*

Researchers have proposed a number of concepts for different types of SDJ. These particularly include bracelets, wristwatches and rings, and present information, among others, by point light displays, icon displays, and vibration. Research found, that the wrist is a promising body location for SDJ in many aspects. The wrist is the preferred body location for jewellery [PLEG13], and wrist-worn and embedded in jewellery are popular ways to wear wearable technology [For14]. Further, the forearm belongs to the most unobtrusive areas for wearable objects regarding wearability [GKS$^+$98]. The wrist was found to be a socially accepted location for using touch controls for wearable accessories in public [HSP$^+$08]. Besides, wrist and arm are the best perceived locations for wearable light-based information displays in terms of reaction time performance [HLSH09]. Related Work on SDJ investigated in particular light and vibration displays. Traditional output modalities, such as graphical displays, are not suitable for SDJ because they would interfere with the design of the piece of jewellery, and require the focussed attention of the user at any time they present information. This would conflict with the "unmonopolizing" attribute of a wearable computer, where SDJ belongs to [Man98]. Sound displays are too obtrusive and disturbing, especially in the various environments SDJ is worn. Light and vibration displays have great potential for presenting information on SDJ. While vibration displays have been explored comprehensively and found to be overall well-suited for wearable technology, few research exists on light displays. But, the existing research shows light is a promising modality to present information on SDJ for several reasons. Light displays that consist of single light spots can be useful for supporting information awareness on mobile devices [TCXD03, HHHH12]. Light can be expressive, but also perceived in the periphery of attention, i.e., in an ambient way [MDM+04, Wic02]. It offers a huge range of encodings [MFP+12], and has been valued for its encrypting characteristic, i.e., that its meaning can be clear to a user, but unintelligible to observers [KG06, WFC06]. Light has aesthetic value, and aesthetic visualisations have been valued for higher effectiveness and efficiency than less aesthetic visualisations [CM07]. Further, light is an essential part of human life and thus, socially and personally accepted. Initial evaluations of light-based SDJ prototypes indicate that light is a promising output modality for wearables.

Altogether, research indicates that wrist-worn and light-based wearables are promising designs for usable wearables. Very few research investigated these designs as part of SDJ. Thorough investigations of the design of usable SDJ are missing. Up to now, we do not know, which designs do and do not work well, and how SDJ should be designed so that it provides a good user experience. Specific design guidelines are needed that tell developers how to design broadly accepted wearable technology in the form of SDJ. This thesis contributes to the question how jewellery-like, wrist-worn, light-based wearables should be designed in order to offer a good user experience. In particular, we investigate the aspects form and appearance, information presentation and interaction concept of SDJ.

## 1.1 Challenges

While the idea of SDJ sounds promising, its implementation brings certain challenges. First, pieces of jewellery are small. Thus, the electronics to be integrated have to be very small, too. Second, jewellery is decorative. Thus, the electronics have to be integrated in a way that they do not interfere with the design of the piece of jewellery. Third, functional jewellery must be operated and display information. Thus, methods for input and output must be provided that fit the small and appealing nature of jewellery. However, no systematic description has been developed yet that tells developers which designs do and do not work well, and how SDJ should be designed so that it offers a good user experience.

We identified three key challenges from an HCI perspective, that need to be addressed to create accepted SDJ with a good user experience: Form and Appearance, Information Presentation, and Interaction Design. In the following, we describe each challenge in detail.

### 1.1.1 Form and Appearance

The physical look and feel is critical for SDJ. As with all objects that people wear close to their body, they identify with and use them for self-expression. Particularly jewellery is used to adorn oneself. This leads to high expectations regarding the jewellery's appearance [WDF07]. Researchers and market analysts confirm that these expectations have not been met yet with current wearable technology and that there is a large room for improvement [Bil15, IBM14, Was15, Led14]. A challenge is to discreetly integrate technology into appealing, body-worn objects, i.e., in a way that the computer disappears into the object [The01]. Research indicates, that bracelets are promising candidates for accepted SDJ as being worn on the wrist. Their form must allow interaction with the object while the user is following their daily routine.

### 1.1.2 Information Presentation

The idea of SDJ is that it offers certain computerised functionalities. This requires a user interface for input and output. Related work indicates, that light is a promising way to present information on wrist-worn SDJ. A challenge is to design information displays that satisfy the user's information needs while not monopolising their attention. Further, information must be presented in a way that is appropriate for a dynamic environment, i.e., it must be perceivable as well as comfortable, e.g., in changing lighting conditions, and with different audiences. Besides, information displays have to be integrated in a way they do not interfere with the jewellery's appearance.

### 1.1.3 Interaction Design

In order to be operated, a piece of SDJ must accept certain input by the user. This can be done through, e.g., indirect input methods, such as sensors or radio transmitters, as well as through direct manipulation on the piece of jewellery itself. The user must be able to control the piece of jewellery in a way that satisfies her control needs and makes her feel comfortable in any environment. Further, as the interaction with wearable technology is a secondary activity, interruptions from the user's primary task should be minimised while interacting with SDJ

[Man98]. Thus, designing for microinteractions, i.e., interactions taking four seconds or less, helps to meet this goal [Ash10]. Hardware needed to enable input must not interfere with the design of the piece of jewellery. The challenge is to define a holistic interaction design that fits the decorative nature of SDJ, the user's needs for information and control, the dynamic environment in which the piece of jewellery is worn, and does not monopolise the user's attention.

## 1.2 Research Questions and Contributions

The challenges described lead to four key research questions. In the following, we describe the questions addressed in this thesis and summarise our contributions.

**Q1** Which are the user requirements for wrist-worn SDJ?

**Q2** Which form and appearance support a comfortable wearing experience?

**Q3** How can information be presented on wrist-worn SDJ?

**Q4** Which interaction design is suitable for wrist-worn SDJ?

### 1.2.1 Q1: Which are the user requirements for wrist-worn SDJ?

To be able to design useful and suitable SDJ, we need to figure out the user requirements for SDJ. SDJ combines the fields of jewellery design and wearable computing. Thus, requirements must be derived from both fields. However, it is unclear to what extent user requirements from both fields do apply for SDJ, i.e., how important certain user requirements are for SDJ.

To gather the user requirements, we did a literature analysis in both fields. Further, we conducted an interview with a goldsmith about the feasibility of SDJ. Moreover, we interviewed potential users as part of the human-centred design process of several SDJ prototypes that we developed during the research presented in this thesis. The analysis resulted in a comprehensive list of user requirements. Often, developers cannot address all requirements satisfactorily due to time and budget constraints. Hence, requirements that are perceived most important from a user perspective should be highly prioritised. Therefore, we conducted a survey to identify the importance of certain requirements. We contribute an importance ranking of user requirements for SDJ that shows which requirements are important and how important certain requirements are perceived. We found that certain requirements have different importance: user requirements addressing functionality, form and appearance, as well as interaction and display design were considered distinctly more important than those addressing body location, context awareness, and customisability. Remarkable is the great importance that participants gave to decorative aspects.

### 1.2.2 Q2: Which form and appearance support a comfortable wearing experience?

SDJ is worn on the body and in various social and physical environments. Thus, its form and appearance is crucial. The user must feel comfortable wearing the SDJ at any time. This includes physical and social comfort, i.e., physical dimensions of the SDJ, as well as how it affects movement and pain, and emotions of the wearer while wearing [KBSB02]. This high demand requires a well-considered design. To our knowledge, no design recommendations exist that tell developers and designers of SDJ which form and appearance are suitable.

In this thesis, we conducted a series of workshops, as well as lab and field studies with wrist-worn SDJ prototypes that we developed during our research to investigate which form and appearance is suitable for SDJ. We investigated this question for single-purpose as well as for multi-purpose wrist-worn SDJ. From our studies, we found bracelets to be a very suitable form for SDJ. Particularly for multi-purpose SDJ, we found the design of a modular bracelet that consists of tangible elements, each representing a single application, to be a suitable concept. From the study results, we conclude that SDJ should offer a high order of customisability regarding its form and appearance, e.g., different shapes, colours and styles.

### 1.2.3 Q3: How can information be presented on wrist-worn SDJ?

SDJ is worn on the body and in various social and physical environments. Usually, the user performs other tasks and often also moves while using SDJ. Thus, information must be presented in a pleasant way, unobtrusive enough to not distract from a primary task, but conspicuous enough to gain attention when needed.

We conducted a series of workshops, as well as lab and field studies to investigate how information can be presented on wrist-worn SDJ. From our studies, we conclude that light is well-suited to notify and to present information on wrist-worn SDJ. Our results show that light patterns should be designed according to specific rules to ensure good understanding and good user experience. We found that adapting the light's brightness level to the context of the user increases user and observer comfort. Further, vibration was found to serve as a useful, supporting modality to gain the user's attention immediately when needed. We contribute a set of concrete recommendations for the design of light patterns for wrist-worn SDJ. We argue that the implementation of the design recommendations will improve the user experience of SDJ.

### 1.2.4 Q4: Which interaction design is suitable for wrist-worn SDJ?

SDJ is worn on the body and in various social and physical environments. Usually, the user performs other tasks and often also moves while using SDJ. Thus, the user must be able to operate SDJ while doing other everyday tasks, such as walking, i.e., interactions must be short and incomplex. Also, the user must feel comfortable when making input in various social environments.

To investigate which interaction design is suitable for SDJ, we involved participants in design workshops, as well as lab and field evaluation studies. We found simple input methods, such as a push button, to be very usable for wrist-worn SDJ. The interaction with push buttons is easy, well-known, can be done one-handed, and push buttons can be discreetly integrated into SDJ. From our studies, we conclude that a push button is easily usable to control two to three different input instructions. We contribute a set of concrete recommendations for the interaction design for wrist-worn SDJ.

## 1.3 Methodology

We investigate the form and appearance, information presentation, and interaction design of wrist-worn, light-based SDJ from an HCI perspective. The underlying principle of our research is human-centred design. This process is defined in the ISO standard 9241-210:2010 [ISO10]. Following a human-centred design approach means that users are involved throughout the design and development of an interactive system, and that the design is driven and refined by user-centred evaluation. We applied the principles of human-centred design to investigate our research questions along several SDJ prototypes. Because we did not apply the human-centred design process to develop products, but to investigate research questions along research prototypes, we did only go through one iteration of the process for each prototype.

Therefore, this work is based on a series of user studies and user feedback. To collect meaningful feedback, we confronted potential users with easy to understand and realistic scenarios. Specific scenarios were implemented by a number of physical prototypes that we developed as objects of research. We did this for two reasons. First, when conducting this research, SDJ was still in its rudimentary stages, i.e., we could not have studied the challenges described above with existing systems. Second, the process of designing, implementing, and evaluating prototypes by itself stimulates a deep analysis, and raises design and interaction issues in the very beginning of the development cycle. This helped us to understand and explore the design space of SDJ, as well as the interaction with it according to our research questions. Further, this process produced research artefacts, i.e., prototypes, that illustrate possible solutions to the research problem. By exposing potential users to the prototypes, we got insights into the user experience towards the proposed solutions. This design-led methodology shows many commonalities to the research through design approach proposed by Zimmermann et al., in which the process of making is seen as a method of inquiry [ZFE07]. Applying this approach has the consequence that the insights and knowledge produced are not to be seen as “objective universal knowledge about certain realities” [Sto15]. Rather, applying this approach results in showing possible solutions or alternatives to solve a problem or to improve realities.

In order to answer our research questions, we used specific methods from both approaches, human-centred design and research through design. Participants were involved in the development of research prototypes from the beginning. We conducted semi-structured interviews to gather user requirements on SDJ objects, and to get qualitative feedback after participants used our prototypes in lab as well as field studies. Through an online survey we gathered further user requirements, and collected quantitative assessments of the importance of certain user requirements. Participants took part in Lo-Fi prototyping sessions, in which they used pen and paper, as well as various everyday materials to edit and to newly create interaction and light designs for SDJ objects. Within these design sessions, participants and the director of studies got into discussions on the objects created. In a lab study participants evaluated a working physical SDJ prototype along a predefined scenario. This ensured that all features of the prototype were tested during the study, and allowed us to assess user experience of the design and interaction design. In field studies, we evaluated several working physical SDJ prototypes regarding user and observer experience under real-life conditions, and measured how effective a working physical SDJ prototype supports a user’s fluid intake behaviour in comparison to a state-of-the-art mobile application. In the lab and field studies, we used the standard questionnaires *AttrakDiff* [HBK03] and *System Usability Scale* [Bro96] to assess user experience and usability. Additionally, we used the *Comfort Rating Scales* [KBSB02] to specifically asses the comfort of a wearable prototype.

Within the research of this thesis, we developed four SDJ prototypes as objects of research. The first prototype was a simple point-light bracelet that we used to investigate research question Q3. As we focussed on the modality light to present information, we dedicated a single prototype to investigate research question Q3 in detail. With this prototype, we studied the design of light patterns for a bracelet. The next prototype we developed was the *WaterJewel* bracelet, by which we investigated the research questions Q2-Q4 regarding single-purpose wrist-worn SDJ by the use case promotion of healthy fluid intake behaviour. With a modified version of the *WaterJewel* prototype, we researched the influence of a light’s brightness adaption on user and observer experience, and thus contributed to research question Q3. The last prototype developed was the *TangibleApps bracelet*, by which we investigated the research questions Q2-Q4 regarding multi-purpose wrist-worn SDJ by three different use cases.

The different use cases illustrate how we applied concepts regarding the form, information presentation and interaction of SDJ to the domains of health promotion, everyday tools, and non-verbal communication. We researched these domains because they receive ongoing attention in academia and industry, in particular in the field of wearable computing. Investigating the design of SDJ for different use cases enables us to amplify the scope of our research beyond a specific use case. Therefore, we address several potential use cases. Further, we investigate our research questions in different stages of development by involving users in the requirements, design, and evaluation phase. Moreover, we combine lab and field studies to be able to, both explore the design space under controlled conditions, and test design solutions in real-life settings. Finally, on the basis of our findings, we derive recommendations for the design of SDJ that offers a good user experience.

## 1.4 Thesis Outline

Overall, this thesis consists of seven chapters. Figure 1.2 illustrates the structure of the thesis. The first two chapters cover the introduction and the background and related work of the research presented in this thesis. Chapters 3 to 6 present the studies that we conducted to answer the research questions. The last chapter discusses our findings and contributions to the research questions.

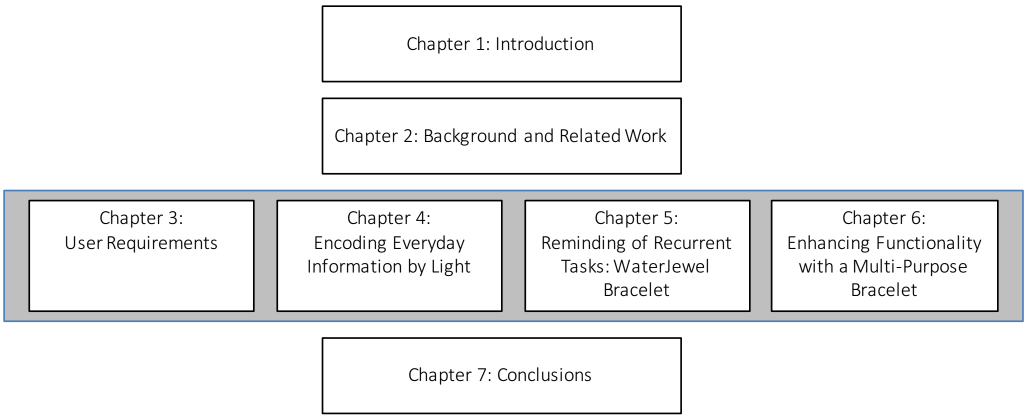


*Figure 1.2: Outline of the thesis. Chapters 1 and 2 cover the introduction as well as background and related work. Chapters 3 to 6 present the studies conducted to answer the research questions Q1-Q4. Chapter 7 provides a discussion of results and highlights the contributions of the thesis.*

In the first chapter, we introduced the topic and motivated the research presented in this thesis. We continued with a description of the challenges, our research questions and contributions, as well as the methodology of our research. The next chapter, Chapter 2, gives a comprehensive overview of the background and related work of this research. We start with a definition of SDJ, and then present the evolution of SDJ. Afterwards, we introduce related work, which we present according to different input and output methods, with a focus on light-based wrist-worn SDJ. Because SDJ has gained a huge interest in the consumer market in recent years, we also show related products and concepts that have been promoted in crowd funding campaigns.

Chapter 3 covers the user requirements of SDJ. First, we present the user requirements that we gathered from literature on wearable computing and SDJ. Second, we summarise an interview with a goldsmith in which we gained insights into the feasibility, challenges, and specific requirements on SDJ from the perspective of a goldsmith. Further, we show an online survey in which we investigated the importance of certain user requirements (Q1).

In Chapter 4 we report on a user study in which we explored encodings for the presentation of everyday information on a lighting up bracelet. The study was a mixed lab- and field study in which participants designed and evaluated light patterns for the use case physical activity feedback. On the basis of the specific use case, we propose a configuration for conveying four types of information. Further, we derived six general implications for the design of light patterns on a wrist-worn display (Q3).

Chapter 5 presents the design process and two evaluation studies of the light-based bracelet *WaterJewel*, that serves as a reminder of recurrent tasks, i.e., it promotes a healthy fluid intake behaviour. The first part of the chapter deals with the user-centred design process of the bracelet and a field experiment in which we firstly, investigated the user experience of the bracelet, and secondly, compared it to a prevalent mobile fluid intake reminder application. From the results we gathered insights into the suitability of certain forms and appearances, information encoding and interaction design of SDJ (Q2, Q3, Q4). We found that participants appreciated *WaterJewel* as a decorative, discreet, and practical wearable object. Further, participants drank more in total and more regularly using the bracelet. The second part of the chapter presents a field study in which we compared a modified version of *WaterJewel*, that adapts the lights' brightness to an ongoing calendar event, to a non-adaptive version. The aim of the study was to explore if a brightness-adaptive light display can improve user's and observer's experience. The results indicate that users and – particularly distinct – also observers experienced the adaptive bracelet more positively (Q3).

Chapter 6 is dedicated to answering research questions Q2, Q3, and Q4 from the perspective of multi-purpose SDJ. It shows the user-centred design process, and lab evaluation of the multi-purpose *TangibleApps bracelet*. In the presented research we explored how multiple applications, i.e., a reminder, a communication tool, and a physical activity feedback display can be integrated into a single piece of wrist-worn SDJ. Our results show that a modular bracelet that offers multiple applications embedded in tangible elements threaded on a string offers a high usability and user experience, and thus is a suitable concept for multi-purpose SDJ. Further, from the results we specified concrete implications for designing the form and appearance, light-based output, and input on multi-purpose SDJ (Q2, Q3, Q4).

Chapter 7 discusses the research conducted within the scope of this thesis. We highlight the contributions to the research questions, and present recommendations for the design of wrist-worn SDJ, that we derived from our research. Further, we reflect on the research methods we used. We conclude the thesis with a summary and ideas for future work in the field.

## 1.5 Publications

Excerpts of this work have been published in peer-reviewed scientific conferences, and workshops. We list the core publications in the following and clearly point to these excerpts within the thesis.

Jutta Fortmann, Wilko Heuten, and Susanne Boll. User Requirements for Digital Jewellery. In Proceedings of the 2015 British HCI Conference, 2015 (British HCI '15). – ISBN 978–1–4503–3643– 7, pages 119–125. ACM.

Jutta Fortmann, Heiko Müller, Wilko Heuten, and Susanne Boll. How to Present Information on Wrist-worn Point-light Displays. In Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational, 2014 (NordiCHI '14). – ISBN 978–1–4503–2542–4, pages 955–958, 2014. ACM.

Jutta Fortmann, Vanessa Cobus, Wilko Heuten, and Susanne Boll. WaterJewel: Design and Evaluation of a Bracelet to Promote a Better Drinking Behaviour. In Proceedings of the 13th International Conference on Mobile and Ubiquitous Multimedia, 2014 (MUM '14). – ISBN 978–1–4503–3304–7, pages 58–67.

Jutta Fortmann, Benjamin Poppinga, Wilko Heuten, and Susanne Boll. Reallife Experiences with an Adaptive Light Bracelet. In Proceedings of the 2015 British HCI Conference, 2015 (British HCI '15). – ISBN 978–1–4503–3643–7, pages 138–146. ACM.

Jutta Fortmann, Erika Root, Wilko Heuten, and Susanne Boll. Tangible Apps Bracelet: Designing Modular Wrist-Worn Digital Jewellery for Multiple Purposes. In Proceedings of the 2016 Conference on Designing Interactive Systems. ACM, 2016 (DIS '16). – ISBN 978–1–4503–4031–1/16/06, pages 841–852. ACM.

Further publications on related topics, that might also have contributed to the idea and outcome of this thesis have been published by the author:

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During the work on this thesis, the author supervised several Bachelor's and Master's theses. Of these, some served as basis for the research presented in this thesis. Most notably, the author refers to [Str12, Cob13, Roo15].

# 2 Background and Related Work

> *"Wearable technology will be increasingly hidden behind stylish designs, that will have a wider appeal than the technology-forward gadgety devices in the market today"* [Led14].

In this chapter, we introduce the field of *Smart Digital Jewellery* (SDJ), lying at the intersection of wearable computing and jewellery design. After defining the term SDJ, we show the historiography of SDJ. Afterwards, we give an overview of related work and SDJ products on the market.

## 2.1 Definition of Smart Digital Jewellery

Jewellery describes a wide variety of objects: from individual, hand-crafted, high-quality pieces, to experimental pieces of art, and from emotionally charged items, such as heirlooms or wedding rings, to mass-produced, fashionable objects that are worn to complete an outfit [VvdHH16]. Further, the motivations to wear jewellery are manifold. Humans wear jewellery to adorn their body, to show prosperity and keep their valuables close, to express identity, social status, believes and affiliation, and as mementos of, e.g., events or persons. One piece of jewellery can combine several motivations [UdB10].

SDJ has been proposed as an approach to seamlessly integrate technology into appealing, body-worn objects. Miner coined the early term *Digital Jewellery* that he describes as:

> *"It [Digital Jewellery] starts with aesthetically appealing jewellery design and forces the technology to subtly blend in or disappear"* [MCC01].

Other terms that have been used are, e.g., technojewelry [IDE01], computational or smart jewellery [SH15], and interactive jewellery [VvdHH16]. In this thesis, we use the term *Smart Digital Jewellery* (SDJ), because it covers all important characteristics, which are

- *Smart* = functional, useful,
- *Digital* = computational, electronic, and
- *Jewellery* = decorative objects that people wear on their body, in particular for personal adornment.

Altogether, we define SDJ as adornment artefacts that are worn on the body, appear as jewellery and at the same time offer useful computerised functions. As such, SDJ lies at the intersection of Wearable Computing and Jewellery Design.

Unlike the definition of digital jewellery by Miner et al. [MCC01], we see the piece of jewellery and not the technology as the base. This view is also proposed by Wallace et al., who go a step beyond and state that people identify with things they wear on their body, that the things can hold personal emotional significance, and that therefore, aesthetic, comfort, but also behaviour and functionality are important aspects to consider when designing SDJ [WDF07]. McCarthy et al. [MWWD06] take this up and argue that enchanting technology [Ros14] like SDJ can make a user more willing to wear and use it. The contemporary jeweller and researcher Kettley argues that craft as a creative process for the design of everyday wearable computers leads to products with more authenticity and less 'borg'-like aesthetics [Ket07].

As our definition shows, we focus on jewellery as being adorning artefacts. The investigations within this thesis focus on the design of SDJ, particularly from a decorative, fashionable, wearable, and usable point of view. We did not research jewellery with regard to emotional values and personal significance.

## 2.2 Towards Smart Digital Jewellery

Human beings have been adorning their bodies for thousands of years. Already in the Stone Age, people adorned their bodies with wood, stones, clams, animal bones, fruit, and pearls. In the beginning of the Bronze Age (2200-800 B.C.), when people learned the processing of metals, they started making precious adornment artefacts out of gold, silver, bronze, gems, and diamonds. Jewellery became a status symbol for the rich. Necklaces, earrings, and bracelets were worn. Besides its decorative function, jewellery has been worn for functional reasons, too. Examples are key rings with a small key mounted on top of the ring, and signet rings used to authenticate documents (see Figure 2.1).

It was not until the 19th century that jewellery became affordable for the general populace. With the invention of plastics, and the processing of cheap metals, such as iron and brass, fashionable jewellery became popular. Stones made of glass and plastics found their way into fashionable jewellery that impressed with new shapes and colours. The taste of jewellery has been varying between different cultures and decades, but at any time, humans liked to adorn their bodies with artefacts.

In the second half of the 20th century, the era of wearable computers began. In the early exploration phase between 1960 and 1990, custom-built devices were developed. The first wearable computer was revealed in 1966 by Ed Thorp and Claude Shannon [Tho98]. It was a cigarette pack-sized analogue device connected to switches in the user's shoes and a tiny loudspeaker in the user's ear, and used to predict roulette. In 1975, the first calculator wristwatch was introduced by Pulsar, offering a six-digit red light-emitting diode (LED) display [Bal15]. In the early 1980s, the wearable computing pioneer Steve Mann designed and started

*Figure 2.1: Left: Ancient key ring, probably Roman; Right: Greek signet ring, 4.-2. cent. B.C. Image source: Wikipedia*

researching a backpack-mounted computer to control photographic equipment attached to a helmet. It followed the first digital hearing aids in 1987. In the 1990s, particularly academic and military wearable computing research was conducted. Steve Mann developed the first wearable wireless webcam in 1994. In the same year, the first wrist-worn wearable system was built by the researchers Edgar Matias and Mike Ruicci [MMB96]. It consisted of a half, one-handed keyboard and a display, strapped to the user's forearms, as well as a computer carried in a pouch (see Figure 2.2). During this time, in 1991, Mark Weiser proposed the idea of Ubiquitous Computing. He described the idea that most everyday objects embed computational technology, leading to a world in which computational devices are pervasive and invisibly interwoven into everyday life. Thus, wearable computers are a specification of Ubiquitous Computing. Weiser envisioned the computational devices to be linked by high-speed networks, connected wirelessly via radio links [Wei99]. Six years later, in 1997, Wi-Fi was established as a standard for wireless local area networks. Today, Wi-Fi is the standard technology used to provide internet access to, particularly mobile, devices within the range of a wireless network that is connected to the internet. In 1997, the first International Symposium on Wearable Computers took place as a full academic conference, storing up the premier event for wearable computing researchers, designers, manufacturers, and professionals, which still takes place today.

The commercial use of wearable computers started about 1995 for niche industry applications and military. The ongoing process of miniaturisation made it possible to integrate micro electronics into smaller and smaller wearable objects. Since about 2006, consumer applications entered the market, starting with the *Nike+iPod Sport Kit* [Nik16a] as one of the first fitness oriented consumer wear-

*Figure 2.2: The first wrist-worn wearable computer consisted of a half, one-handed keyboard and a display, strapped to the user's forearms [MMB96].*

ables. Marked by the *JawboneUp* wristband [Jaw16], 2011 was the beginning of a series of wrist-worn consumer devices, many of them addressing the fitness domain (see Figure 2.3). In 2012, Google introduced the head-worn display and tiny computer *Google Glass*, which was controlled by voice, head movements and a touch pad.

*Figure 2.3: Left: The Nike+ iPod Sport Kit consists of a wireless transmitter put into a shoe (left) and a receiver plugged into an iPod music player (right) and offers the functionality of a pedometer; Right: Fitness and sleep tracker wristband Jawbone UP. Image sources: CNET, Taputapu Gadget Blog.*

Upcoming wearable electronic prototyping platforms, such as *Arduino LilyPad* in 2007 [Lil16, Mak14] and *Adafruit Flora* in 2012 [Ada16, Ada12], led to the evolvement of a huge community of hobby tinkerers and to many research projects and crowd funding campaigns in the field of wearable computing (see Figure 2.4).


*Figure 2.4: Left: Wearable electronics prototyping platform Arduino LilyPad. Right: E-Traces, a LilyPad project with a ballet shoe that captures dance movements and transforms them into visual sensations [Lil16].*

In 2013, the crowd-funded smartwatch *Pebble* became available, which became popular due to its fully functional and always-on e-paper display. In 2015, the wearable market grew more than 189% compared with 2014, i.e., 79 million wearables devices were shipped, from which 71.5 million units belonged to wristwear. Forecasts predict that in 2016, worldwide wearable shipments will reach 101.9 million units, of whom watches and wrist bands together will hold 91.5% of the market [Int16].

## 2.3 Related Work on Smart Digital Jewellery

In this thesis, we focus on wrist-worn SDJ because the wrist is a promising body location for SDJ in many aspects. In terms of wearability, the forearm belongs to the most unobtrusive body locations for wearable objects [GKS+98]. From Holleis et al. we know, that users accept touch input in public when applied on the wrist [HSP+08]. Harrison et al. found that, in general, wrist and arm as body locations for a wearable, visual display were found to be very suitable to present information effectively and efficiently [HLSH09]. Further, from Perrault et al. we know that wrist is the preferred location for jewellery [PLEG13]. Altogether, these findings make wrist-worn SDJ a promising field to investigate.

Several concepts for wrist-worn SDJ have been proposed in research. They range from holistic concepts consisting of different pieces of jewellery, such as the wearable mobile phone, where each item implements a specific function [MCC01] (see Figure 2.5), to specific pieces of jewellery, such as bracelets, that are used for, e.g., non-verbal communication [WFC06, AM08, KG06] and notifications

*Figure 2.5: IBM Wearable Mobile Phone: a ring lighting up to notify of an incoming call (centre), a bracelet to display detailed information on the caller (left), as well as an earring and a necklace serving as speaker and microphone with another ring enabling TrackPoint input (right) [MCC01].*

[HL00]. In the following, we present related work in the field of SDJ that we separate into three areas. These are individual, design- and craft-focussed work, explorations from researchers with a technological background, and commercial products. According to the focus of this thesis, we give a brief insight into the design-focussed work, as well as into commercial products. We describe explorations from a technological research perspective in detail, that we structure along different output and input methods.

### 2.3.1 Design and Craft-Focussed Work

Wallace and Kettley, explored from a practitioner's point of view how technology can be used in combination with jewellery to enhance emotional connections. Central idea of their works was that the technology stimulates the interaction with a piece of jewellery in a meaningful way for the holder. E.g., with *Sometimes*, Wallace created a necklace that triggers short videos holding personal significance for the holder on public or personal displays that are close to the necklace. The necklace itself appears as an ordinary piece of jewellery, using other devices and displays as vessels for interactions [WDF07, Ket07]. The idea of digital enchantment was also explored by Vones, who introduced the concept of creating digital enchantment with body-worn objects through playful interactions. These were influenced by changes in the body of the wearer and the environment. She, e.g., developed the *Geotronic Brooch*, a decorative brooch with an integrated light spot simulating the heart beat of its wearer through pulses and thereby creating synergy effects between the piece of jewellery and its wearer [Von15]. These works are to be seen as individual pieces of art, rather than as research artefacts used to generate new knowledge regarding the design of SDJ.

### 2.3.2 Research on Output for Wrist-Worn Technology and SDJ

In this section, we present related work that explores the output modalities light and haptics for SDJ. Both modalities are suitable to present information on the wrist in an unobtrusive, personal way and can be integrated into a decorative piece of SDJ. While haptic displays have been explored comprehensively, light displays are underexplored up to the present.

#### 2.3.2.1 Light Displays

Light is a well-suited output modality for wrist-worn SDJ. It is an essential part of human life and thus, socially and personally accepted. It can be perceived in an ambient, aesthetic way and offers a huge range of encodings [MFP+12]. Light can be modified in various parameters. From the perception oriented colour model HSV (Hue, Saturation, Value) we can derive the basic parameters of light: colour, saturation and brightness [Smi78]. These parameters can be extended with regard to time and space. Time can be expressed in the duration for which a light is presented. Furthermore, when manipulating the parameters it is possible to create various rhythms with varying colours, saturations and brightness. Space can be expressed in the spatial location of a presented light.

A requirement for wearable technology is that it must not occupy, i.e., monopolise the user's attention [Man98]. Peripheral, or ambient displays, allow unobtrusive information presentation in the periphery of a user's attention. Such a display "shows information that a person is aware of, but not focused on". Thus, its supports divided attention [MDM+04]. An ambient display can move from the periphery to the focus of attention and back again. Also, ambient displays are aesthetically pleasing [PS06]. An ambient light system is a system positioned in the periphery of a person's attention that conveys information using light encodings in a non-distracting way most of the time [MRC+15]. When providing information to the ambient visual information channel, ambient light keeps free focal vision for primary tasks [LP82, Wic02]. Besides, due to their small form, light spots can easily and unobtrusively be included into a decorative wearable object, which is essential for SDJ.

Tarasewich et al. showed that low-information rate displays, which consist of single light spots, can be useful for supporting information awareness on mobile devices. They investigated the tradeoff between complexity (states per light spot) and size of a display (number of light spots) regarding information encoding. They found, that the position of a light spot is most intuitive, that multi-coloured light spots are suitable to encode a small number of categories, and that blinking is only suitable to encode attention grabbing information [TCXD03]. Related work investigating persuasive communication found, that ambient light displays that make use of pre-existing colour associations, such as red encoding negative, and green encoding positive information, can enhance their persuasive potential

[LHM14]. Harrison et al. emphasised the expressivity of point lights and proposed a set of eight light behaviours recommended for the presentation of particular types of information on mobile devices. They used a single-colour light spot with varying light intensity over time to encode, e.g., an incoming call or a low battery. Their results show that even subtle changes of light behaviour can have high impact on its interpretation. However, the investigations were done by means of a web- and screen-based study and thus do not consider any contextual factors [HHHH12].

In the following, we present previous work in which different kinds of wrist-worn, light-based SDJ have been investigated. The shimmering smartwatch concept uses a visual, non-graphical display, embedded into a regular wristwatch, to present information in a more jewellery-like way. Two smartwatch prototypes, one consisting of 12 circularly arranged light spots, and the other consisting of four backlit icons integrated into the watch face, were built as a proof of concept (see Figure 2.6). The displays were used for typical smartwatch functions,

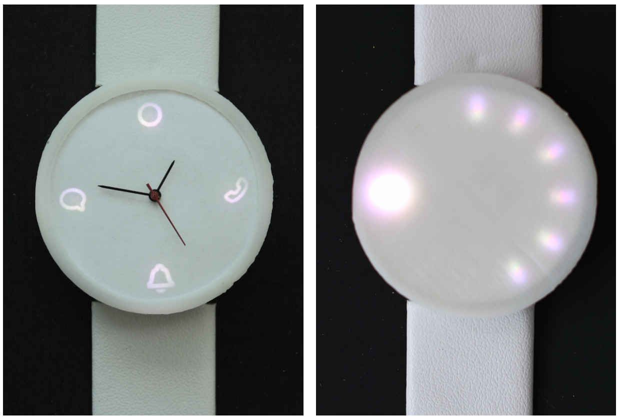

*Figure 2.6: Prototypes of the "Shimmering Smartwatches": backlit icons (left) and circularly arranged light spots (right) [XL15].*

such as showing the time, and notifying of an incoming message, a call, or an upcoming calendar event. To encode information, the parameters light intensity (over time), colour, and the number of illuminated light spots were varied. E.g., notifications were encoded by flashing, the number of messages was encoded by the number of illuminated light spots, and contacts were indicated by colours. As the prototypes have not been evaluated, we do not know how they perform. The work serves as a proof of concept for non-graphical smartwatch displays, showing ideas on how to extend the design space of smartwatches [XL15].

Ahde and Mikkonen describe their vision of communicating spatial proximity of friends by using interactive light bracelets. Their *hello* bracelets consist of single light spots integrated into studs that represent certain friends by a specific light colour (see Figure 2.7, right). A light spot illuminates when the corresponding friend is close [AM08]. Hansson and Ljungstrand provide some ideas on how to use a bracelet for displaying calendar reminders in an unobtrusive way. Their bracelet uses three red light spots that change intensity over time to notify of an upcoming event. An early field study with four participants showed that participants perceived the light as subtle and non-intrusive, and preferred it over typical alert sounds [HL00]. With their studded bracelet *Damage*, Williams et al. [WFC06] present a concept for displaying social group activity cues via light spots on a decorative bracelet. A bracelet consists of six studs, of which five represent the activity of individual friends, and one that of a whole group (see Figure 2.7, left). Light colour indicates a certain message type, and light intensity shows

*Figure 2.7: Design sketches of the studded bracelets "Damage" [WFC06] (left) and "hello" [AM08] (right).*

overall group activity and unread messages, that can be retrieved from a corresponding smartphone application. Early feedback gathered from focus groups indicated that the bracelet should provide greater flexibility in style, number of studs and group affiliations. Similarly to *Damage*, the *BuddyBeads* bracelets provide a way for non-verbal communication within a social group. There, the illumination of specifically shaped elements and vibration signals indicate messages by group members. Participants in an early evaluation of *BuddyBeads* appreciated the encrypted and thus "private" display, the bracelet's fashionable appearance, and the increased fun factor compared to sending messages via a mobile phone. Further, they highlighted that the bracelet allows to send messages in situations when it is not possible or appropriate to send messages via a mobile phone [KG06]. Like Hansson et al., Williams et al. emphasise the particular valuableness that ambient light displays can have for wearable technology. Further, they point to the chances that come with the semi-public nature of a wrist-worn light display, i.e., that the display's meaning can be clear to a group of users being in the know, but unintelligible to strangers, who may even regard it as purely decorative [WFC06]. Exactly this encrypting characteristic was also highlighted by participants of an early evaluation of *BuddyBeads*.

#### 2.3.2.2 Haptic Displays

Previous work investigated the feasibility of haptic displays for wrist-worn technology. The research in this thesis focusses on light displays. During our research, we found a vibro-tactile display to be a useful supplement to a light display and thus, integrated a vibro-tactile display in some of the research prototypes presented in this thesis. In the following, we present research addressing vibro-tactile, as well as thermal and pressure displays worn on the wrist and embedded in SDJ.

Wrist-worn, haptic displays that use vibration to present information have been investigated comprehensively and have been valued for their suitability to unobtrusively present information in everyday life. Chen et al. investigated the human ability to localise tactile stimuli on the dorsal and volar sides of the forearm near the wrist. In their experiments, three participants tested a wristband with a 3x3 actuator array on each side, the dorsal and the volar side of the wrist. On average, participants could correctly identify two actuator locations on the dorsal side and also two on the volar side of the wrist. When both sides were combined, participants could correctly identify a total of four locations and did correctly identify the side of the wrist in 93% of all trials. The results indicate that, based on the location only, a combination of two actuators on the dorsal and two actuators on the volar side of the wrist is suitable to present tactile stimuli in a reliably identifiable way [CSG+08]. Similarly to Chen et al., Matscheko et al. investigated the effectiveness of different actuator placements on the wrist. Instead of testing tactile stimuli triggered separately from single actuators, they tested tactile patterns displayed by four differently located actuators. Imagining a watch-type vibro-tactile display, they explored the perception of tactile patterns for two locations: underneath the face of a wristwatch, and embedded into the wristband, i.e., inside and along the wristband. A user study showed that participants could perceive the tactile patterns significantly better when performed around the wrist compared to underneath a watch face. Also, the work load for perceiving and processing the tactile patterns in the watch face condition was higher than in the wristband condition. To conclude, the results indicated that the placement around the wrist is more suited for wrist worn tactile displays, than the placement underneath a watch face [MFRL10]. While Chen et al. and Matscheko et al. explored tactile displays with constant tactile intensities, Lee et al. investigated the perception sensitivity of tactile patterns that varied in four different parameters. They explored how easily participants can discriminate 24 tactile patterns when delivered by three actuators on the volar side of the wrist. They found that participants could discriminate 24 tactile patterns with up to 99% accuracy after 40 minutes of training. Among the parameters intensity, starting point, temporal pattern, and direction, the parameter intensity was the most difficult to distinguish, and the temporal pattern was the easiest. A second experiment showed that, in a visually distracted condition, the reaction time to perceive three different tactile patterns on the volar side of the wrist did not deteriorate. On the basis of the results, the authors recommend to use wrist-worn tactile displays for alerts on multitasking mobile user interfaces [LS10].

From their studies with a haptic wristwatch, Pasquero et al. found that single actuator feedback provided to the skin underneath a watch face could be detected in 97% of all trials. Further, their results showed that shorter vibration signals of 256ms were more often detected and perceived less irritating than longer vibration signals of, e.g., 768ms [PSS11]. Paneels et al. investigated the effect of orientation on the detection of vibro-tactile stimuli on the wrist. From their studies, which were conducted with a four-actuator wristband in static and mobile conditions, they conclude that the orientation of the user's wrist does not have a strong effect on the detection of vibro-tactile directional cues. Overall, the recognition rates in both conditions were reasonably good, and thus, support the suitability of vibro-tactile stimuli for providing feedback on the wrist [PBS13].

Other research has explored vibro-tactile SDJ in form of two rings, of which one translates the user's heartbeat to a vibration pattern. The vibration pattern is displayed on the partner's ring when he or she touches their ring and thereby closes a circuit (see Figure 2.8). An evaluation showed that the heartbeat vibration provided a feeling of strong connectedness and closeness and was particularly valued for moments of physical separation [WWH08].


*Figure 2.8: Concept sketch of the United-Pulse rings. When the gap in the ring is touched with a finger, a circuit is closed and the partner's heartbeat is displayed by a vibration pattern [WWH08].*

A different way of haptic feedback was explored by Song et al.. They compared thermo, vibration, and squeeze cues provided by a wristwatch-like prototype. Thermo and vibration cues were provided on the dorsal side of the wrist. Squeeze cues were provided by tightening the watch strap. Evaluation results showed that vibration and squeeze performed almost equally well in terms of errors, whereas thermal cues performed relatively poorly [SNY+15]. Squeeze cues were also explored by He et al., who propose the *PneuHaptic* band, a wrist band that provides squeeze cues by gently pressing on the skin using shape-changing nodes that are arranged around the user's wrist. Early user feedback showed that users were able to distinguish several haptic cues with an overall accuracy of 93% [HXXB15].

### 2.3.3 Research on User Input for Wrist-Worn Technology and SDJ

Being a secondary activity, interaction with wearable technology should happen in a way, that interruptions from the user's primary task are minimised [Man98]. Thus, wearable technology is primarily operated by microinteractions. Ashbrook defines these as "[...] interactions with a device that take less than four seconds to initiate and complete." [Ash10]. Using microinteractions, a user can return to their primary task quickly, after having interacted with a wearable device. In the research presented in this thesis, we investigate mechanical input in terms of pushing a button. In the following, we present previous research investigating touch, mechanical input, and hand gestures as techniques for unobtrusive user input on wrist-worn SDJ supporting microinteractions.

#### 2.3.3.1 Touch Input

Perrault et al. investigated the wristband as a means for touch input. In a user study, participants performed a set of 15 gestures including pointing and sliding gestures with one and two fingers on one or both sides of a wristband (see Figure 2.9). The results showed that the techniques are effective in eyes-free usage scenarios. In general, one-contact gestures were faster than two-contact gestures [PLEG13].

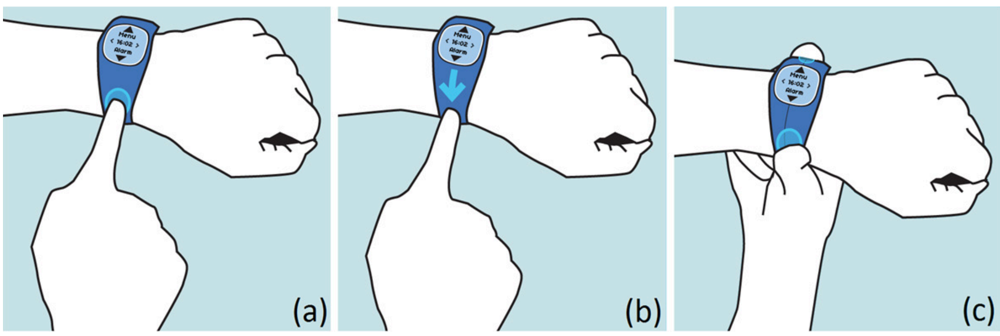


*Figure 2.9: WatchIt gestures: pointing on strap (a), sliding on strap with a finger (b), and holding two fingers on opposite straps (c) [PLEG13].*

In how far a user's skin can be used as an input surface was explored by Laput et. al. [LXC+14] and Harrison et al. [HTM10]. In their work, Harrison et al. studied the feasibility of touch input performed by finger taps on the forearm and the hand. To localise touch input on the user's skin, they analysed mechanical vibrations that propagate through the user's body using a sensing array built into an armband. User studies showed that overall, the accuracy of the system was good for a series of gestures and worked well in static contexts as well as in whole-body motion conditions, such as when the user was walking [HTM10]. Laput et al. combined the idea of touch input on the skin with wrist-worn devices. They proposed the idea of *Skin Buttons*: Tiny projectors integrated into a smartwatch project icons on the user's skin which are touch sensitive (see Figure 2.10). Touch events are captured by infrared proximity

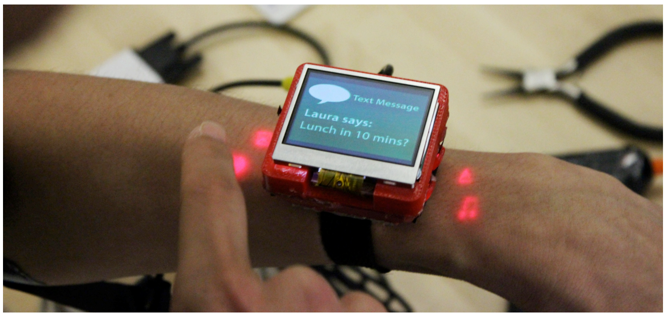


*Figure 2.10: Skin Buttons: Tiny projectors integrated into a smartwatch project touch-sensitive icons on the user's skin [LXC+14].*

sensing. Ideas for use strategies are, e.g., the mapping of on-screen labels to skin buttons, and dedicating skin buttons to key actions. Studies showed the system performs well in terms of projected icon recognisability, touch sensing accuracy, and power consumption. Participants experienced the concept as compelling and useful [LXC+14]. Knibbe et al. combined the idea of using single and multi-finger tapping gestures on the back of the hand, as well as whole-hand gestures to control a wrist-worn device. Early user feedback was positive, in particular regarding the large input area on the back of the hand [KMPB+14].

#### 2.3.3.2 Mechanical Input

The earlier presented lighting-up bracelet *Damage* enables user input by metal snaps mounted on the bracelet. A user can open and close three metal snaps to send "light messages" to their contacts. If a snap is closed, a certain light colour illuminates on the contact's bracelet to indicate a pre-defined message. If the user opens the snap again, or a certain time has elapsed, the light switches off. This interaction design enhances non-digital components of an ordinary bracelet, i.e., snaps, with digital functionality. The authors do not report any evaluation results on the snap input [WFC06].

As part of the *Wearable Mobile Phone* introduced in Section 2.3.2, the *Track-Point Ring* enables its wearer to, e.g., navigate, scroll, and select, by pushing a tiny joystick-like surface on a ring in different directions. Another idea was that a wearer could send coloured "light messages", similar to those of the *Damage* bracelet, to a contact's ring by pushing a light spot in the corresponding colour on their own ring. The author does not report any evaluation results on this input concept [MCC01].

Xiao et al. proposed a proof of concept for a smartwatch-like device that enables mechanical interactions, such as pan, twist, tilt and click. In their approach, the watch face itself is used as a mechanical interface that can be physically manipulated by the user. Having typical smartwatch applications in mind, the authors propose to use the mechanical interactions for, e.g., panning, zooming, navigating and selecting. The authors do not report any user evaluations [XLH14].

The idea to integrate squeeze-based interaction techniques into SDJ was explored with the *Squeezy Bracelet* by Pakanen et al. (see Figure 2.11). The bracelet

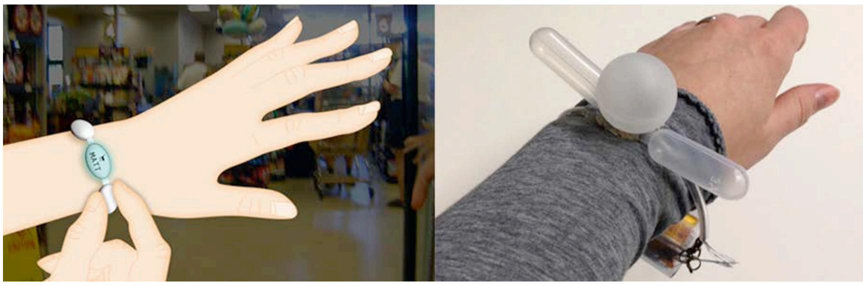

*Figure 2.11: Squeezy Bracelet: Interaction concept (left) and prototype implementation (right) [PCH+14].*

consists of three balls arranged in a row. The translucent central ball acts as a display that presents information by illuminated light spots. The outer balls act as input medium and accept user input in form of squeezing gestures. For the prototype, input balls were implemented by pasteur pipets with air pressure sensors placed inside to measure the deformation state of the pipet. Two interaction mechanisms were implemented. In the first option, selection was done according to three different pressure levels that a user could apply to a pipet. In the other option, the number of squeezes determined the selection. In a user study, participants used the bracelet to send pre-defined messages from their mobile phone. Results showed that toggle-based interaction was perceived to be easier to use and less demanding than pressure level-based interaction. Overall, the concept was valued as an innovative, simple, and quick interaction method suitable for eyes-free usage [PCH+14].

Other eyes-free input techniques, such as rotation and sliding, were explored by Ashbrook et al. with the ring *Nenya*. By twisting a finger ring, a user can make a selection, which he or she confirms by sliding the ring along their finger. Tracking is implemented by a magnet inside the ring which is tracked by a sensor worn on the wrist. User studies testing one-handed and two-handed use indicated that users can control up to eight choices in a menu by rotating the ring. Further, participants perceived one-handed operation to be considerably harder than two-handed interaction [ABW11].

#### 2.3.3.3 Hand Gestures

*GestureWrist* is a wristband that allows user input by hand gestures and forearm movements. Changes of the arm shape on the inside of the wristband are capacitively measured and forearm movements are measured by an accelerometer. The authors propose a set of simple gesture commands that vary in the shape of the hand, such as making a fist and pointing, as well as in arm positions, such as palm up, down, left and right, and forearm up and down. Evaluations were not reported [Rek01].

Other work investigated the suitability of finger movements for user input on small, wearable devices, such as wristwatches. In their work *Abradabra*, Harrison et al. capture finger movements by a magnet placed on the user's finger which is tracked by a magnetometer included into a wristwatch. An evaluation with 15 users showed that they were able to select radial targets of 16° or greater with an accuracy of 92%. Thus, *Abradabra* outperforms direct, touch-based finger input, which performs significantly worse for small targets around 16° [HH09]. Finger movements have also been explored in similar work by Kienzle et al. [KH14], and Jing et al. [JCZ+13]. Ogata et al. presented *iRing*, a proof of concept implementation of a system allowing finger gestures such as bending a finger, clenching the hand, applying pressure externally by, e.g., other fingers, as well as rotating the ring in different directions and to different degrees. Example applications were, e.g., a music controller, and manipulating objects on a screen [OSOI12]. Yoon et al. transferred the idea to a finger-worn textile input device. *TIMMi* enables its wearer to perform bending, pressing, and swipe gestures using only one finger. It consists of elastic fabric, conductive carbon elastomer and conductive thread. Like *iRing*, *TIMMi* allows eyes-free interaction and provides intuitive tactile feedback by the users themselves, touching their skin while performing the gestures. A preliminary user study showed participants were able to effectively use *TIMMi* for triggering various inputs [YHNR15].

Later work went beyond and proposed, e.g., a ring-based system allowing rich interactions by whole-hand and context-aware interactions [CCH+15]. The system of Chan et al. enables its user to perform input gestures such as on-finger pinch-and-slide input, in-air pinch-and-motion input, and palm-writing input. Use strategies for such rich interactions are particularly interacting with real-world and virtual-reality objects, and manipulating and operating screen-based content. An experiment with a set of seven hand gestures showed a recognition rate of 84.75% [CCH+15]. With *PinchWatch*, Loclair et al. [LGB10] presented a wearable gestural input system for one-handed use, consisting of a wrist-worn display and a chest-worn camera. The camera tracks hand gestures, such as pinching two fingers, sliding or dialing motions on the palm, and whole-hand movements, whenever the wrist-worn display is in sight of the camera. By performing a gesture, the user can control content displayed on the wrist-worn display, or invoke a certain application. Single purpose gestures allow menu-free interaction and immediate use. Similar to *iRing* and *TIMMi*, the one-handed interactions by pinching gestures provide immediate tactile feedback and thus, minimise interference with the user's primary task. Thus, the approach is particularly suited for microinteractions [Ash10].

## 2.4 Commercial Products

In the last years, crowd funding campaigns for SDJ emerged and the first SDJ consumer products entered the market. In 2013, the *Misfit Shine* [Mis16b] became available as one of the first fitness trackers explicitly addressing decorative aspects. It consists of a round core element that can be attached to a wristband, a necklace, or clipped onto clothes. It displays information by circularly-arranged light spots and can be triggered by touch. In 2015 and 2016, Misfit introduced *Misfit Swarovski Shine* and *Misfit Ray* [Mis16a], and thereby went a step further in creating more stylish and jewellery-like wearables. *Misfit Swarovski Shine*, e.g., hides the light spots of *Misfit Shine* beneath a crystal and comes with various bracelets equipped with crystals. Further examples for health-tracking SDJ are the masculine-designed *Fossil Q Reveler* [Fos16], the modular *Bellabeat LEAF* [Bel16], the lighting up and vibrating ring *Ringly* [Rin16], the announced *Aries bracelet* [Rin16], and the concealing encasements of *Tory Burch for Fitbit* [Fin14]. Figure 2.12 shows *Fossil Q Reveler*, *Misfit Swarovski Shine*, *Aries bracelet*, and *Bellabeat LEAF*.

*Fossil Q Reveler* hides the electronics beneath a silver metal case and presents information, such as battery status and smartphone notifications, by several coloured light spots on either side and by vibrations. *Fossil Q Reveler* is an activity tracking device and display only, i.e., no direct user input is enabled. The decorative pendant *Bellabeat LEAF* is a health tracker that can be worn as a necklace, bracelet, or clip. Tracking information is delivered through a companion application running on a smartphone. The only display integrated is a vibration motor that can be triggered for regular alarms or inactivity alerts. Like *Fossil Q Reveler*, *Bellabeat LEAF* serves as a tracking device and limited display only and does not enable direct user input. *Ringly* is a ring consisting of a big decorative stone. It displays notifications via different vibration patterns and a flashing light that can be set to different colours and shines through a hole on the

*Figure 2.12: From left to right: SDJ consumer products Fossil Q Reveler [Fos16], Misfit Swarovski Shine [Mis16a], Aries bracelet [Rin16], Bellabeat LEAF [Bel16]*

side of the ring. Notifications are triggered by a companion smartphone application. *Ringly* serves as a display only, i.e., no direct user input is enabled. The *Aries bracelet* is offered by the same company as *Ringly* and transforms *Ringly* to the shape of a bracelet. *Tory Burch for Fitbit* is no SDJ by itself, but a series of encasements concealing the Fitbit Flex fitness tracker that come as pendants and bracelets. Besides Misfit and Bellabeat LEAF, further modular jewellery concepts are available or announced, such as *Altruis* [Vin16], that consists of a ceramic stone that can be worn in a ring, bracelet or necklace and vibrates to notify of calls, messages and alerts (see Figure 2.13).

*Figure 2.13: From left to right: SDJ consumer products Purple Locket [Art16], Netatmo June Bracelet [Net16], Altruis worn as a ring [Vin16], AH!QUA Bracelet [Gug]*

Further SDJ products forebear from visual displays, and use, e.g., tactile displays instead, or no display at all. *AH!QUA* [Gug] is an output-only fluid intake reminder bracelet jewelled with rhinestones that regularly vibrates to remind its holder to drink. The sun protection bracelet *Netatmo June* [Net16] consists of UV sensors integrated into a metal element, and sends notifications via a smartphone application when the total measured sun exposure gets critical (see Figure 2.13).

*Kiroco* [Kir16] and *Purple* [Art16] introduced the idea of a locket to store and reveal personal information and images in terms of keepsakes from friends and family. *Kiroco* does not offer any direct user input or output. Instead, it uses NFC technology integrated into jewellery to show personal messages on a smartphone. In contrast, the locket *Purple* (see Figure 2.13) offers its own high-resolution display, that shows images and accepts touch gestures in the inside of the locket. Similarly, the *MICA* bracelet [Cer16] integrates a high-resolution screen on the back of a decorative bracelet, i.e., the screen sits on the inside of the user's wrist. It displays text and vibrates to notify of incoming messages and upcoming events. Input is done by touch and limited to, e.g., selecting preset messages. *MICA* has its own cellular data connection, i.e., it works independently from a smartphone. However, as user input is very limited, for, e.g., adding contacts, a user has to resort to a web interface. The bracelet came onto the market in late 2014 but is no longer available. The *Ritot Watch* [Rit16] became popular through a successful crowd funding campaign in 2014 and today, i.e., two years later, is still being developed. It is a bracelet that projects information on the skin of its wearer. It is wirelessly connected to a smartphone application and displays, e.g., time, calendar alerts, and notifications. The projection can be controlled by either a touch sensitive button or a shaking gesture with the wrist. Aiming to meet the decorative requirements of wrist-worn objects, it is offered in different styles and colours. Figure 2.14 shows *MICA* and *Ritot Watch*.


*Figure 2.14: High-resolution screen on the back of the MICA bracelet [Cer16] (left) and sketch of the Ritot Watch [Rit16] (right).*

Besides *MICA*, further SDJ products that had been announced or been on the market, have been abandoned. E.g., the *Olive* Bracelet [Lab16], which was announced as a bracelet that measures stress indicators, such as heart rate and skin temperature, and notifies of high stress levels by vibration and light spots. By touch gestures, such as swiping, tapping, and rubbing, a user could launch a stress management exercise on their smartphone, or enter her current feeling.

After a successful crowd funding campaign in 2014, *Olive* was abandoned in 2015. The official reason was that the development turned out to be more expensive and additional funds could not be raised due to a tough investment climate on the wearable market. Another example was the modular system *Cuff* [CUF15]. *Cuff* was announced as an interactive module that fits into various pieces of jewellery. By pressing the module, it should send an emergency alert including the user's GPS location to preset contacts. Further, it should notify of incoming notifications on the user's smartphone by vibration. The company developing *Cuff* started to accept pre-orders in 2013, but their product had faults and most customers never received it. Today, the company is out of business without leaving an official statement.

## 2.5 Summary

In this chapter, we introduced the field of SDJ and showed how SDJ evolved as a combination of the fields jewellery design and wearable computing. We presented previous work related to the research presented in this thesis and gave an overview on commercial SDJ products.

Jewellery has been worn for thousands of years in various forms and designs, such as necklaces, earrings, rings, and bracelets. Jewellery is socially accepted, and particularly worn for expressive, often decorative reasons. In the second half of the 20th century, the era of wearable computers began. Starting with single, custom-built devices, the field developed over academic and military research towards commercial products. In the beginning of the 21st century, Smart Digital Jewellery (SDJ) was proposed as an approach to seamlessly integrate technology into appealing, body-worn objects. We define SDJ as decorative objects that are worn on the body, appear as jewellery, and at the same time offer useful, computerised functions. Since 2012, when the research presented in this thesis started, a big movement took place in the wearable computing market, heading slowly from gadgety and sporty wearable devices towards decorative, jewellery-like wearables. Particularly in the last one to two years, wearable technology that put stronger focus on decorative aspects was promoted in crowd funding campaigns and entered the market. The majority of SDJ products relies on companion smartphone applications, offers simple point light or vibration displays, and does not enable direct user input. However, the number of available SDJ products is still small, as several products are currently in funding or development process, and several announced products never made it to market or were discontinued after a short time. This indicates, that the market of SDJ is challenging. The ongoing progress towards decorative, jewellery-like wearables shows that the research presented in this thesis addresses a highly relevant topic.

Research found the wrist a promising body location for SDJ in many aspects, such as wearability [GKS+98], social acceptance [HSP+08], and visual information presentation [HLSH09]. A number of concepts for different types of SDJ have been proposed. These particularly include bracelets, wristwatches, and rings and present information, among others, by point light displays [AM08, HL00, WFC06, KG06, XL15], icon displays [XL15], and vibration [WWH08]. While haptic displays have been explored comprehensively, light displays are underexplored up to the present. However, light is a well-suited output modality for SDJ. It is an essential part of human life and thus, socially and personally accepted. It can be perceived in an ambient, i.e., unobtrusive, and aesthetic way and offers a huge range of encodings [MFP+12]. Further, light displays can be used in an encrypted way in that their meaning can be clear to a user, but unintelligible to observers. Proof-of-concept implementations and initial evaluations of light-based wrist-worn prototypes indicate that light is a promising output modality for SDJ that is worthwhile to be investigated further.

Wrist-worn, haptic displays that use vibration to present information have been investigated comprehensively and have been valued for their suitability to unobtrusively present information in everyday life. Researchers investigated suitable number, locations and durations for tactile stimuli on the forearm [CSG+08, MFRL10, PSS11], as well as the perception sensitivity of different tactile patterns on the wrist [LS10]. Results showed that a combination of two actuators on the dorsal and two actuators on the volar side of the wrist is suitable to present tactile stimuli in a reliably identifiable way. Further, the placement around the wrist is more suited for wrist worn tactile displays, than the placement underneath a watch face. Moreover, short vibration signals of 256ms were more often detected and perceived less irritating than longer vibration signals of, e.g., 768ms. Also, from their results, Lee et al. recommend to use wrist-worn tactile displays for alerts on multitasking mobile user interfaces. Furthermore, researchers found that the orientation of a user's wrist does not have a strong effect on the detection of vibro-tactile directional cues on the wrist [PBS13]. Investigations of thermo, vibration, and squeeze cues provided to the wrist showed that vibration and squeeze both performed well in terms of errors, whereas thermal cues performed relatively poorly [SNY+15]. Further, users were able to distinguish several squeeze cues on the wrist [HXXB15]. Overall, the comprehensive research on haptic displays shows that haptic, particularly vibration, displays are well suited to present information on wrist-worn wearables, as they offer a big range of encodings, and can be perceived well, also in visually distracted conditions.

Previous research investigated different user input methods for wrist-worn devices, such as touch and mechanical input, as well as hand gestures. Touch input on wristbands was found to be effective in eyes-free usage scenarios [PLEG13]. Touch input on the skin of the user's forearm to control a wrist-worn device was shown to be feasible [HTM10], accurate [LXC+14] and performable with single- and multi-finger tapping gestures [KMPB+14]. Besides touch input, concepts for mechanical input have been proposed, such as opening and closing snaps on a bracelet [WFC06], and pushing a joystick or a light spot mounted on a ring

[MCC01]. Other work implemented a proof of concept for a smartwatch-like device that allows mechanical interactions, such as pan, twist, tilt and click that altogether enable a variety of instructions [XLH14]. Pakanen et al. studied squeeze-based user input on a bracelet and found that it is a simple and quick interaction method suitable for eyes-free usage [PCH+14]. Besides, making input by rotating and sliding a ring along the finger was explored and found to be feasible and most easy when using two hands, i.e., one on which the ring is worn and the other to move the ring [ABW11]. Further research proposed user input by hand gestures and forearm movements measured by, e.g., sensors in a wristband, such as Rekimoto [Rek01]. Whole-hand interactions combined with context-aware interactions were explored by Chan et al. [CCH+15], who found a ring-based hand gesture recognition system to be effective for a set of seven hand gestures. Besides, researchers proposed a wearable system for one-handed interactions performed with and on one hand, that allows a completely modeless and menu-free interface where all functions can be immediately invoked [LGB10]. Other work proposed finger movements for user input on wrist-worn devices [HH09, KH14, JCZ+13, OSOI12, YHNR15]. Initial evaluations indicated that finger movements can effectively be used to trigger several input instructions, and that they outperform direct touch-based finger input, particularly for small targets. Overall, several user input methods for wrist-worn devices have been explored. Investigations show that touch-based input on wristbands as well as on the skin is feasible and effective. Mechanical input concepts have been proposed, but only few have been evaluated. Squeeze-based input was shown to be simple and quick and allowed eyes-free usage. Different systems proposed for user input by hand gestures and forearm movements were shown to be effective and fast. However, no user evaluations have been reported that investigate the user experience of these input methods.

# 3 Requirements for Smart Digital Jewellery

Various research has been conducted that evaluated wearable devices to gain an understanding of the requirements and design space for wearable devices. Mostly, investigations have been done for specific applications and specific display concepts of wearables (see Chapter 5, and [LSHH11, BLB12]). Few research tried to derive general guidelines for the design of wearable devices. These strongly focus on specific aspects, such as wearability [GKS+98], and touch input [HSP+08], or are formulated on a more general level addressing aspects, such as context awareness, appearance and affordance [Sta01a, PCH+14]. To investigate the design space and application areas for SDJ, Perrault et al. [PLEG13] conducted an online survey. They asked people what kind of jewellery they wore, how much they were interested in various kinds of SDJ, and what kind of tasks they could imagine to use SDJ for. 79% of participants wore at least one piece of jewellery daily, whereas overall, wrist was the preferred location, followed by finger and neck. About 60% of participants were in general interested in SDJ. For participants wearing jewellery daily, this proportion rose to 74%. The most stated reasons for a lack of interest were the redundancy with smartphones, and the concern that integrating technology into jewellery would compromise its decorative characteristic. Preferred tasks to use SDJ for were playing music, reading and sending text messages, GPS navigation, and phoning, i.e., tasks users typically perform with smartphones.

When we aggregate the various suggestions for improvement and defined requirements, this forms a long and unfocused list of requirements. For a designer, addressing all the requirements appears to be an impossible task. Further, it remains unclear, which requirements are more important than others and thus, should be considered with higher priority when designing SDJ. Thus, we see two important things missing. On the one hand, we need the definition of requirements related to specific characteristics of wearable devices, such as form, interaction, users, and use cases. On the other hand, we need to specify in how far requirements for wearable computing do also apply for SDJ, and define an importance ranking for the requirements. Altogether, this would enable designers of SDJ to focus firstly, on the right and secondly, on the most important user requirements.

In this chapter, we present the user requirements that we gathered from literature on wearable computing and SDJ. Further, we summarise an interview with a goldsmith in which we gained insights into the feasibility, challenges, and specific requirements on SDJ from the perspective of a goldsmith. Lastly, we present an online survey in which we investigated the importance of certain user requirements for SDJ. We contribute to research question Q1 with a ranked list of user requirements that helps designers of SDJ to focus on the - from a user perspective - more important aspects. We highlight differences in the requirements for males and females, and differences in different age groups.

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## 3.1 General Requirements for Wearable Computers and Smart Digital Jewellery

When designing SDJ, certain requirements have to be considered. Interpreting SDJ as a specification of wearable computers, we gathered the requirements from literature on general requirements for wearable computers and SDJ. Some requirements that we draw on are requirements that were advanced for wearable computers about 15 years ago, in particular [Man98] and [Sta01a]. Today, these still serve as the fundamental requirements for wearable computers. The requirements described in the following were the relevant and most related requirements for SDJ at the time of our research.

A wearable computer has to be mobile and unrestrictive **(R1)**, i.e., it must not restrict the user in her daily activities, such as walking [Man98]. Also, it must not occupy the user's attention **(R2)** [Man98]. This means the user should be able to follow her primary tasks and attend to other matters while using a wearable computer. It should not cut the user off from the outside world. Besides, a wearable computer's output medium should be constantly perceptible by the user **(R3)**, and the device has to be controllable by the user at any time **(R4)** [Man98]. That is, it is responsive and the user can grab control at any time. Further, a wearable computer should be attentive to the environment **(R5)** [Man98, Sta01a]. This includes multimodality as well as contextual sensing and adaptation. Another attribute of a wearable computer is that it can be used as a direct or indirect communications medium, being an expressive object worn on the body **(R6)** [Man98]. Besides, a wearable computer should be always on and always ready for use **(R7)** [Man98]. Power is a critical factor for a wearable computer, i.e., power supplies should last long, and charging – if needed – should require low effort **(R8)** [Sta01a]. Further, a wearable computer should be personal, i.e., closely attached to and coordinated with a single user who decides if others can observe or control it **(R9)** [Man98]. This includes the need for privacy, i.e., that the user can control the collection and use of personal information [Sta01b]. A wearable computer must be comfortable to wear **(R10)** [KBSB02, GKS+98]. This includes factors, such as physical dimensions, as well as how the wearable computer affects movement and pain, and emotions of the wearer when wearing [KBSB02]. Comfort is affected by aesthetics, shape, size, weight, and emitted heat of a wearable computer, how it interworks with the moving human body, and how a wearer can access and interact with it [GKS+98]. With their design principles for wearable devices, Pakanen et al. [PCH+14] pick up on that. As worn on the body, the appearance of a wearable computer is crucial, i.e., it must be fashionable and decorative **(R11)** [Bil15, Sta01b]. It should be as small as possible **(R12)** [PCH+14] and fit to the user's clothes and jewellery fashion **(R13)** [PCH+14, Sta01b, MFWH15]. This relates to the requirement that a wearable computer should encourage personalisation **(R14)**, not only regarding decorative aspects, but also interaction and functional issues [Sta01a]. Also, it should not get entangled in the user's clothes **(R15)** [PCH+14]. It should enable one-handed interaction that is simple and fast **(R16)** [PCH+14], e.g., Starner [Sta01b] proposes two seconds as acceptable delay in accessing a wearable interface, and Ashbrook four seconds for initiating and completing an interaction [Ash10]. Further, if its design invites the wearer to play around with it, it should allow this without causing unintentional input events **(R17)** [PCH+14]. Other work found that the wrist is among the most suitable and most popular body locations for a wearable computer and for jewellery [HLSH09, PLEG13].

## 3.2 Interview with a Goldsmith

To get an idea about the design space, acceptance, and the feasibility of SDJ from a designer's and craftsman's perspective, we conducted a semi-structured interview with a local goldsmith. The insights from the interview served as additional input for the design of our SDJ prototypes that we developed within the research presented in this thesis. The interview focussed on aesthetics, shapes, and materials of jewellery, compatibility of jewellery and electronics, and their everyday suitability. The goldsmith was male, had a working experience of about 30 years and owned a goldsmiths in Oldenburg, Germany. He was known to personal contacts of the research team. Because of his comprehensive knowledge and long experience, and his careful consideration of the questions during the interview, we decided to not interview further experts.

### 3.2.1 Procedure

The interview took place in the goldsmiths after work and lasted for about an hour. Before the interview, we explained potential use cases for SDJ, e.g., supporting a healthy lifestyle, and showed some up-to-date wearable consumer technology, such as *Nike+ FuelBand*[1], *JawboneUp*[2], and *Misfit Shine*[3]. We explained possible modalities for the display of information, such as light (LEDs), vibration, audio, and temperature. Further, we explained the idea of SDJ and showed sketches of SDJ design concepts. After the introduction, we conducted the interview. We asked about the target group of SDJ, trends, as well as timeless jewellery. Also, we asked about experiences on combining technology with jewellery, the feasibility of SDJ from a craftsman's perspective, and which kind of jewellery would be suitable for SDJ. Further, we asked about typical user behaviour, e.g.,

[1] http://www.nike.com/us/en_us/lp/nikeplus-fuelband
[2] https://jawbone.com/up
[3] http://www.misfitwearables.com/

wearing time, influences for wearing jewellery, and reasons for repairs, as well as the acceptance of SDJ and the importance of aesthetics and functionality. During the interview, the interviewer took notes on the responses. For analysis, the interview notes were coded and summarised according to the interview questions.

### 3.2.2 Results

The goldsmith dissociated himself from a jeweller in that his customers are not much fashion oriented. Instead of, they ask for individual pieces of jewellery that often have a personal meaning and are not obtainable in a shop. Timeless jewellery are rings in general, adjustable bracelets, lockets, and signet rings. The goldsmith has not yet integrated electronics into a piece of jewellery. While a goldsmith deploys various trades, electrical engineering would be an alien field for him.

A goldsmith makes jewellery out of noble metals. To process the material, a certain minimum thickness is required. Hence, size and weight are big challenges. A heavy ring is less obtrusive than a heavy bracelet, because arm-worn jewellery moves more and thus produces more resistance. Besides noble metals, the goldsmith uses wood, ceramics, plastics and gems to create jewellery. Non-ferrous heavy metals, such as brass and copper are rarely used because they tarnish. The light metal aluminium would be suited for SDJ because it is lightweight, but it would have to be glued because it cannot be welded. Silver and copper have a high electric conductivity and could be used to create electric circuits. Hollow bodies would be useful to contain electronic components. Ideally, they are factory-made, because than they can be much finer and lighter than when made manually. Particularly suited for SDJ would be items with big surfaces and hollow spaces which can contain electronic components. These would, e.g., include a wide bangle, a ring with a big gem, necklaces with balls, lockets, or an interchangeable clasp. Through a hollowly cut gem, an illuminated LED would shine through. Overall, the goldsmith named material, size, and weight as the biggest challenges for creating SDJ: The bigger a piece of jewellery, the more electronic components can be integrated and the bigger the display can be. However, the bigger a piece of jewellery is, the heavier and more obtrusive it becomes.

Jewellery is exposed to movement, dirt and moisture. Many people like to play around with their jewellery, e.g., they turn their rings or repeatedly open and close the clasp on a bracelet. Especially in hollow spaces, dirt collects. Thus, the piece of jewellery should stand to be cleaned with water, and it should stand minor repairs. For SDJ, the attrition of the noble metals could be problematic, e.g., in case electric lines are damaged.

We asked the goldsmith about guidelines for the design of jewellery. He named the proportion theory and the golden ratio. These theories define rules that describe how parts of a work of art must be in proportion to each other to appear harmoniously, e.g., a bangle could be 3cm wide on the top side and 1.5cm wide on the bottom side. Form and colours also depend on personal characteristics, such as, e.g., the hair colour of the wearer, and are often designed by instinct.

In general, the goldsmith estimated that fashionable jewellery is not worn for longer than a year. However, jewellery produced by a goldsmith is usually worn for a much longer period because of its higher worth and very often high personal value for the owner. The goldsmith assesses SDJ more as a potential mainstream product that needs to be advertised. Thus, it would better be sold at jeweller shops than at a goldsmiths. He also said that there is no universal piece of jewellery. For SDJ, there was even more variability because besides aesthetics, its functionality needs to please the user. However, in his view aesthetics would always be more critical than functionality, which is consonant with the views of Billinghurst [Bil15] (see Chapter 1) and Starner [Sta01b].

### 3.2.3 Conclusions

From the interview we learned there are several challenges from a craftsman's perspective regarding the creation of SDJ. The integration of electronic components into small, decorative pieces of jewellery brings major challenges with regard to material, size, and weight. SDJ is less likely to be made by a goldsmith. A goldsmith usually crafts individual pieces of jewellery that are financially valuable, hold personal significance for the wearer, and are expected to last for decades. Crafting technology-enhanced jewellery appears to be a very big challenge for a goldsmith. Done by hand and out of noble metals, size and weight of handcrafted jewellery cannot be as small as of factory-made jewellery. This conflicts with SDJ, that particularly needs reasonably big hollow spaces and surfaces to hold technical components and displays. Also, technology usually becomes obsolete within a few years, and this conflicts with the idea of everlasting, expensive, hand-crafted jewellery. Thus, SDJ might be more feasible in terms of fashionable jewellery as a mainstream product, that is factory-made, cheaper, and expected to last for just one or a few years. Besides, we learned there are only a few guidelines for designing jewellery and that most aspects of a piece of jewellery - as being a piece of art - are designed by instinct. Further, the interview revealed another requirement for SDJ, i.e., robustness **(R18)** in that it must be cleanable with water and stand minor repairs. Also, it showed specific challenges, such as the attrition of noble metals that could affect the conductivity of electric lines.

## 3.3 Importance of Specific User Requirements

In this section, we present the design and results of an online survey on user requirements for SDJ. We investigated, how important potential users considered specific requirements for SDJ. We found that there are differences in the perceived importance of different requirements for SDJ. We also found differences in the importance ratings, that are related to sex and age. Overall, participants considered functionality, form, and interaction and display design as very important, whereas they found body location, context awareness and customisability less important.

### 3.3.1 Online Survey

To verify, rank, and complement the previously gathered user requirements for SDJ, we conducted an online survey. We defined the target group as young to middle aged adults, because this age group is especially interested in fashionable jewellery and new technologies. People could take part if they were at least 18 years old. The survey was provided in German through an online survey tool. Participants completed the survey during a period of eight weeks between June and August 2014.

#### 3.3.1.1 Survey Design

The survey started with an introduction in which we explained the term SDJ. Participants should imagine a new technology that looks like a real piece of jewellery. This digital jewel could offer one or more useful functions. It could, e.g., support them in keeping a healthy lifestyle, in that, e.g., it helps to drink enough water, or to move regularly over the day. As an illustrative example for the display of such a piece of SDJ, we gave single light spots hidden in the jewels, e.g., under gems in a ring, a bracelet, or a watch. These light spots could light up to indicate that, e.g., the wearer has been sitting for a (too) long time. We pointed out that this was just an example and participants could imagine any other kind of display and use case.

The survey had a total of seven questions. The first question (Question #1) served as the basis for the ranking of the requirements. In the first question, participants had to distribute a total of 100 points among 16 given requirements for SDJ with regard to their importance. The higher the points the more important a participant rated a requirement. The requirements were derived from literature (see Section 3.1) and an interview with a goldsmith (see Section 3.2). Requirements **R15** and **R17** described in Section 3.1 were not included in the survey, because the survey was conducted before the literature reporting these requirements was published.

For the survey, we limited the number of requirements to 16, and we chose these during a focus group discussion with five HCI professionals from our research team. We restricted the requirements to 16 as being a number which we considered as manageable, considering that participants had to distribute the points among the single requirements. This resulted, e.g., in the decision to integrate only two different body locations for which previous work [PLEG13, HLSH09] reported that they are the most preferred and suitable locations for jewellery or a wearable display. We chose an aggregated assessment method because, in the first question, we did not want to investigate which requirements are important at all – we already know this from previous work – but how important a requirement is perceived when directly compared to another. We expected all of the 16 requirements to be, to some extent, important, and wanted to come up with a ranking. Therefore, we asked participants to assess the single requirements in direct comparison to each other. To cancel out sequence effects, requirements were displayed in random order.

The requirements were phrased as 16 statements. For a more generalised analysis, we assigned the statements to six categories. Categories are *Form*, *Functionality*, *Body Location*, *Customisability*, *Interaction and Display Design*, and *Context Awareness*. In the following, we list the 16 statements. References to the requirements described in the previous sections of this chapter can be found in brackets.

*Form*

**FF1** It looks good. (R6, R10, R11)

**FF2** It is small. (R10, R12)

**FF3** It is lightweight. (R10)

**FF4** It is solid. (R18)

**FF5** It is comfortable to wear. (R10)

*Functionality*

**FU6** Its battery lasts for at least 24 hours. (R8)

**FU7** It offers several functions (e.g. feedback on physical activity and reminder of regular water drinking). (R14)

*Body Location*

**BL8** It can be worn on a finger (as ring). (R1, R3, R10, R11, R16)

**BL9** It can be worn on the wrist (as bracelet or watch). (R1, R3, R10, R11, R16)

*Customisability*

**CU10** I can change its appearance (e.g. changing modules, changing colours of the jewel) (R6, R10, R13, R14)

**CU11** I can configure how the information is presented (e.g. certain light colours). (R6, R10, R13, R14)

*Interaction and Display Design*

**ID12** The functionality is integrated unobtrusively and it can be operated unobtrusively. (R10, R11)

**ID13** I can operate it quickly and with few effort. (R7, R10, R16)

**ID14** Without further knowledge, people near by cannot understand the meaning of the displayed information. (R9, R10)

*Context Awareness*

**CA15** The display adapts to my environment (e.g. brightness of the light display adapts to lighting conditions). (R5, R10)

**CA16** The display adapts to my situation (e.g. display is deactivated while driving; light display is dimmed during a meeting). (R5, R10)

In the second question we asked for further requirements for SDJ that were not included in the first question (free text). Question #3 asked for any comments on the requirements named in question #2 (free text). The other questions asked for demographic details, such as the participant's age (question #4, integer), sex (question #5, choice) and nationality (question #6, choice). Question #7 was for general comments and feedback.

#### 3.3.1.2 Participants

47 volunteers completed the online survey, of which 20 were males and 27 females. Their age varied between 20 and 48 ($M = 30.6$, $SD = 7.2$). All participants were German. Participants were acquired through public announcements in social networks and an online forum of the local university. Participants were not paid for taking part.

### 3.3.2 Results

In the following, we describe the results of the survey. The first three subsections present the results of survey question #1, the rating of requirements. Besides the overall rating, we analysed the ratings with regard to sex, and different age groups. For the analysis, we aggregated the points for each requirement. In the last subsection we report on further requirements for SDJ by summarising the results of survey questions #2, #3, and #7.

#### 3.3.2.1 Overall Rating of the Requirements

Figure 3.1 shows a bar chart that illustrates the ranking of the 16 requirements (aggregated points per requirement). Colours and patterns of the bars indicate

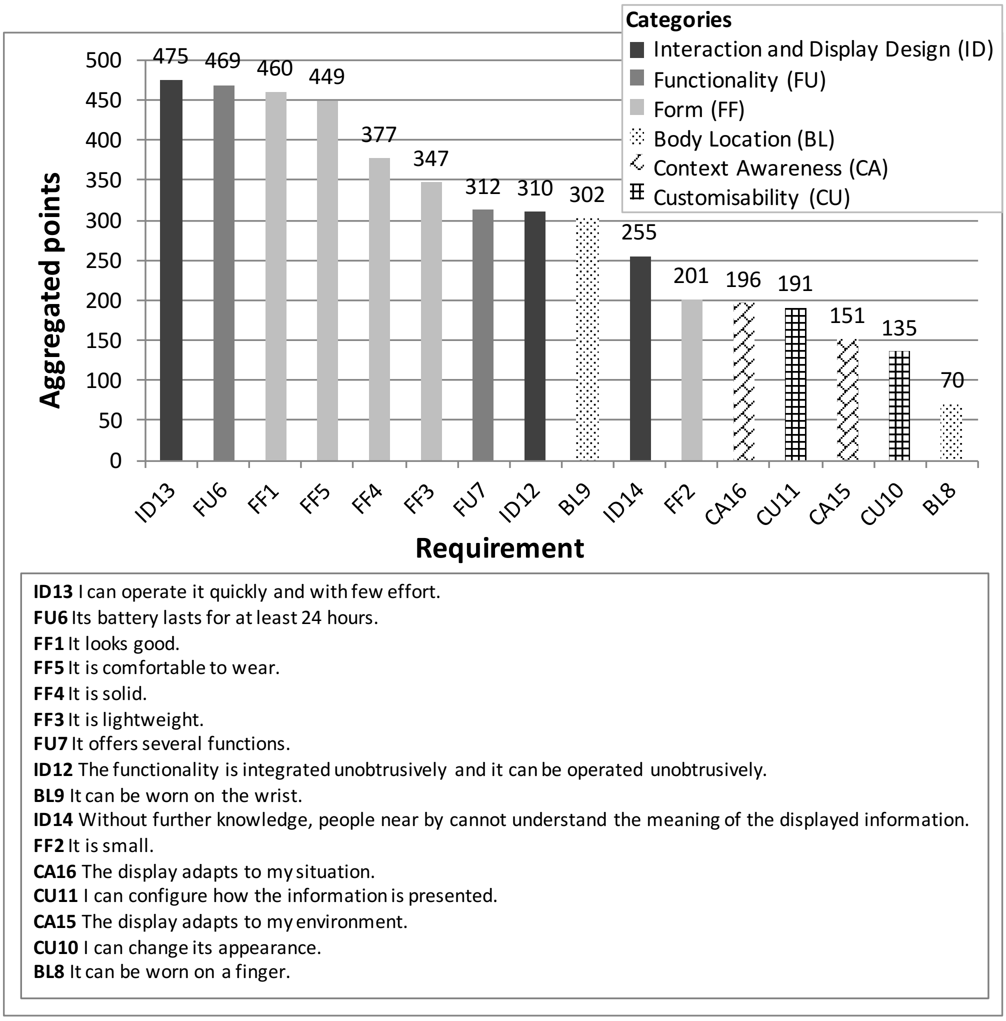



*Figure 3.1: Aggregated points of the 16 requirements in backward sorting from most to least important.*

the category a requirement is assigned to. The ranking shows that a quick operation (ID13) is the most important requirement for participants, closely followed by a long battery life (FU6). Ranks 3 to 6 are hold by requirements describing the form, which are a good appearance (FF1), wearing comfort (FF5), robustness (FF4), and a light weight (FF3). On rank 7 we find a comprehensive functionality (FU7), closely followed by an unobtrusive integration and operation of functionalites (ID12). Ranks 9 and 16 are hold by the body location requirements, which are wrist (BL9, rank 9) and finger (BL8, rank 16). Privacy concerns with regard to the displayed information (ID14) were rated less important and ranked on position 10. The requirement *small* (FF2) follows on rank 11. Context Awareness expressed by the adaption of the display to the situation (CA16, rank 12) and the environment (CA15, rank 14) were rated less important. Customisability regarding the information presentation on the jewellery (CU11, rank 13) and the jewel's visual design (CU10, rank 15) were ranked among the least important.

Figure 3.2 shows the ranking for the six categories. Displayed are the aggregated points per category, i.e., the aggregated points over all requirements in a category, divided by the number of requirements in the category. The chart shows that participants rated the three categories *Functionality* (390.5), *Form* (366.8) and *Interaction and Display Design* (346.67) distinctly more important than the other three categories *Body Location* (186), *Context Awareness* (173.5), and *Customisability* (163).

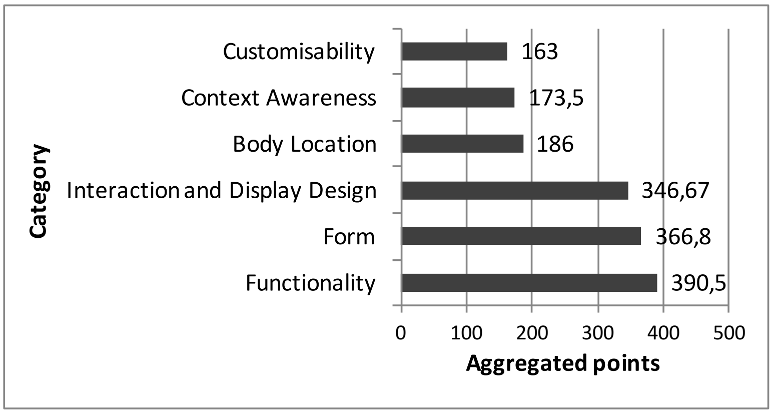
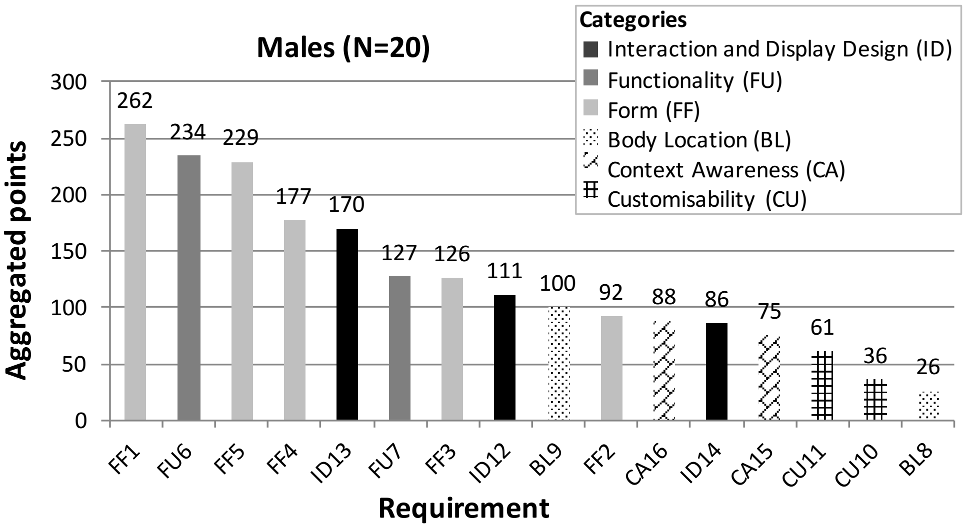



*Figure 3.2: Aggregated points for the 6 categories, divided by the number of requirements in a category*

### 3.3.2.2 Differences in the Rating between Males and Females

We found differences in the ratings of males and females. Overall, the curve of male participants runs similar to the general curve. Males rated a good appearance (FF1) as the most important requirement, and – in contrast to females – a quick operation (ID13) only on rank 5.

Figures 3.3 and 3.4 also show more distinct differences on the lower ranks: Males rated the customisability with regard to the information presentation (CU11) on rank 14, whereas females ranked this on 11. With 70 points difference between the first and the second rank, female participants rated a quick operation (ID13) distinctly more important than all other requirements. A good appearance (FF1) was – in contrast to male participants – only rated on rank 8. However, as can be seen from the data, female participants distributed the points more evenly to several requirements, than male participants. E.g., the range of points for ranks 2 to 8 is only 37 points for females, whereas for males it is 123 points. Thus, between ranks 2 to 8, female participants did not distinguish as much between the importance of the requirements as males did.

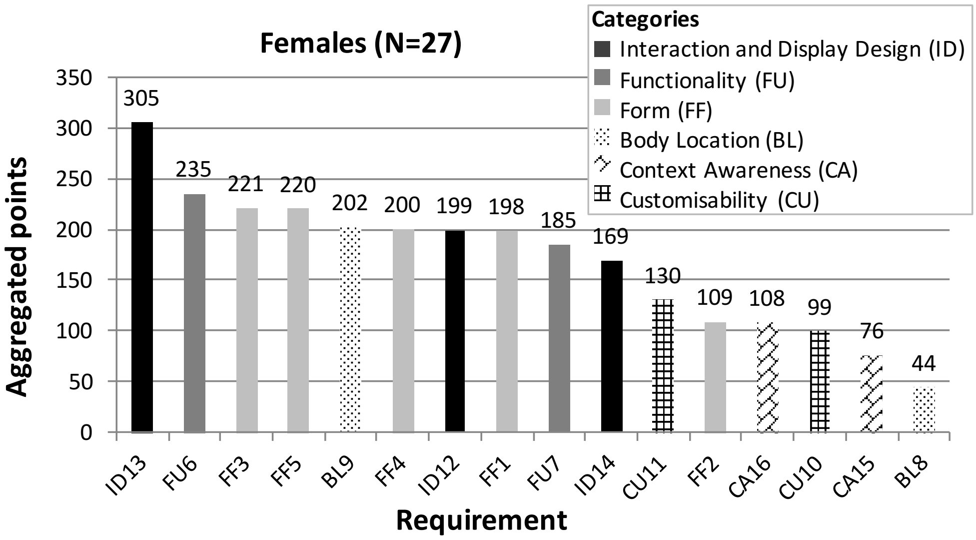



**FF1** It looks good.
**FU6** Its battery lasts for at least 24 hours.
**FF5** It is comfortable to wear.
**FF4** It is solid.
**ID13** I can operate it quickly and with few effort.
**FU7** It offers several functions.
**FF3** It is lightweight.
**ID12** The functionality is integrated unobtrusively and it can be operated unobtrusively.
**BL9** It can be worn on the wrist.
**FF2** It is small.
**CA16** The display adapts to my situation.
**ID14** Without further knowledge, people near by cannot understand the meaning of the displayed information.
**CA15** The display adapts to my environment.
**CU11** I can configure how the information is presented.
**CU10** I can change its appearance.
**BL8** It can be worn on a finger.

*Figure 3.3: Aggregated points for the 16 requirements that were distributed by male participants.*

### 3.3.2.3 Differences in the Rating between different Age Groups

Having a look at the different age groups of participants, we found a few differences. Figure 3.5 illustrates the distribution of points for three different age groups: *20-29* years (N = 22, 12 females), *30-39* years (N = 17, 10 females) and *40-49* years (N = 8, 5 females). For the *20-29* years old, the general curve fits on the whole. They consider an unobtrusive integration and operation of functionalities (ID12) more important (rank 5) than all participants together (rank 8). Also, for the *30-39* years old, the general curve fits on the whole. Older participants, i.e., the *40-49* years old, differed more from the general rating of all participants. They considered a good appearance (FF1, rank 1) and robustness (FF4, rank 2) as the two most important requirements, whereas requirements such as an unobtrusive integration and operation of functionalities (ID12, rank



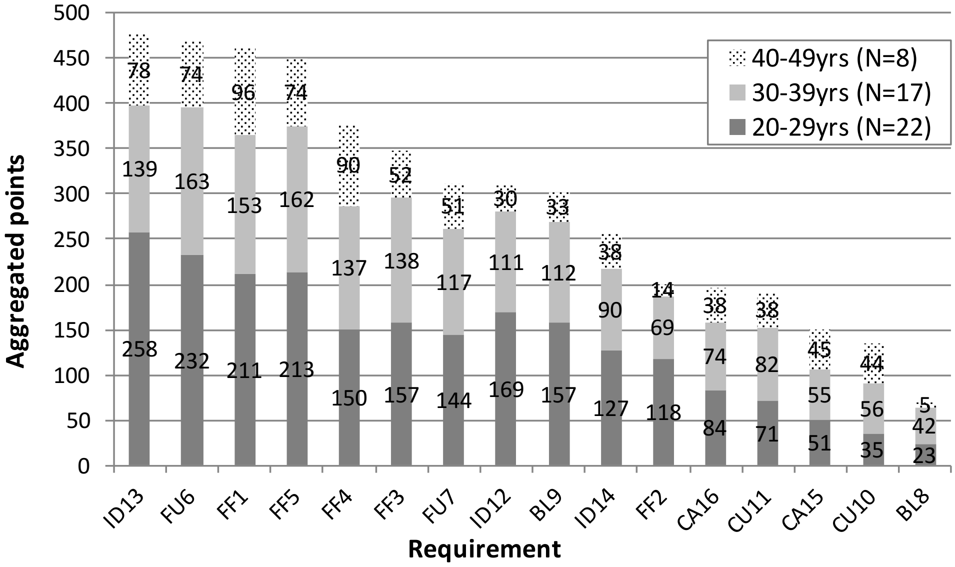

**ID13** I can operate it quickly and with few effort.
**FU6** Its battery lasts for at least 24 hours.
**FF3** It is lightweight.
**FF5** It is comfortable to wear.
**BL9** It can be worn on the wrist.
**FF4** It is solid.
**ID12** The functionality is integrated unobtrusively and it can be operated unobtrusively.
**FF1** It looks good.
**FU7** It offers several functions.
**ID14** Without further knowledge, people near by cannot understand the meaning of the displayed information.
**CU11** I can configure how the information is presented.
**FF2** It is small.
**CA16** The display adapts to my situation.
**CU10** I can change its appearance.
**CA15** The display adapts to my environment.
**BL8** It can be worn on a finger.

*Figure 3.4: Aggregated points for the 16 requirements that were distributed by female participants.*

14) and a small size (FF2, rank 15) were ranked very low. Further, they rated the customisability of the SDJ's appearance (CU10) more important (rank 9) than participants of other ages (ranks 14 and 15). With increasing age of participants, the unobtrusive integration and operation of functionalities (ID12) was ranked less important, i.e., on position 5 for the *20-29* years, position 9 for the *30-39* years, and position 14 for the *40-49* years old.

#### 3.3.2.4 Additional Requirements for Smart Digital Jewellery

In the survey, we further asked for additional requirements participants considered to be important for SDJ, besides those listed in question #1.




**ID13** I can operate it quickly and with few effort.
**FU6** Its battery lasts for at least 24 hours.
**FF1** It looks good.
**FF5** It is comfortable to wear.
**FF4** It is solid.
**FF3** It is lightweight.
**FU7** It offers several functions.
**ID12** The functionality is integrated unobtrusively and it can be operated unobtrusively.
**BL9** It can be worn on the wrist.
**ID14** Without further knowledge, people near by cannot understand the meaning of the displayed information.
**FF2** It is small.
**CA16** The display adapts to my situation.
**CU11** I can configure how the information is presented.
**CA15** The display adapts to my environment.
**CU10** I can change its appearance.
**BL8** It can be worn on a finger.

*Figure 3.5: Aggregated points for the 16 requirements pigeonholed into three different age groups:* 20-29, 30-39 *and* 40-49*.*

Participants gave a lot of answers regarding the functionality of SDJ. Many, i.e., about 20% of the statements were related to the synchronisation and networking between different pieces of SDJ, and between SDJ and other technologies, such as a smartphone, computer, TV, or scale. Also, participants named technological features such as WLAN, GPS, heart rate monitor, temperature sensor, and a watch display. Participants wanted the battery of SDJ to be charged easily and quickly, e.g., via induction. Overall, the answers show that participants wished for a multi-purpose device that serves as an everyday companion, i.e., besides supporting a healthy lifestyle, it should, e.g., remind for dates, send out a distress signal in case of emergency, and allow to control other devices in a smart home environment.

Regarding the interaction design, participants stated that they would like to have the choice for different output modalities, such as light, vibration, sound, and heat. As input concepts they named push buttons, finger gestures on the display, and pressure on the digital jewel itself. Two participants stated that a stand-by or silent mode is important.

Participants named requirements with regard to the form of SDJ. The most named requirement was that it should be waterproof. Also, participants wished for a high-quality fabrication, including a material that is suitable for allergy sufferers. For the attachment participants named the integration into glasses, and the possibility to wear it as a clip or magnet attached to the clothing. Robustness and the possibility to wear the digital jewel during sports were also mentioned.

Other requirements mentioned were a reasonable cost price, and the possibility to use SDJ even when it is not worn, e.g., by connecting it to a docking station.

### 3.3.3 Discussion

The study results show that there are differences in the perceived importance of different requirements for SDJ. We also found differences in the importance ratings, that are related to sex and age. In general, males tend to distinguish more clearly between the importance of specific requirements, whereas females tend to perceive the importance of several requirements about the same. Further, the results indicate a few differences for participants of different ages regarding the perceived importance of certain requirements.

The results of the survey show that requirements regarding the functionality, form, and interaction and display design of SDJ are very important. This includes aspects such as a long battery life, a decorative and unobtrusive appearance, and a quick operation. Requirements with regard to the body location, context awareness and customisability of SDJ are less important. These are, e.g., the location where SDJ is worn, if it adapts to the environment, or if a user can customise its appearance. With regard to the body location, participants clearly preferred the wrist to a finger.

Interestingly, today's wearable market products more and more put a focus on customisability, e.g., they offer devices in various colours, but miss general decorative requirements, such as a business-suitable look. Also, there are many devices that serve only one purpose. Our study results indicate that aspects such as a long battery life, a comprehensive functionality, a decorative appearance, wearing comfort, and weight play a much more important role for users. We assume that the extent to which the aspects that users consider to be of most importance are realised in a piece of SDJ, will influence whether a user is accepting the wearable in the long term or not.

Overall, the points were more evenly distributed for females than for males. Thus, males make a sharper distinction between the importance of single requirements than females do. The study results show that the females' preferences differ from the males' in a few factors. For females, a quick operation (ID13) was the most important requirement, and a good appearance (FF1) was the eighth most important. In contrast, males rated these requirements reversely, i.e., they ranked a quick operation (ID13) on position 5, but a good appearance (FF1) as the most important requirement. Customisability (CU10, CU11) was in general considered less important, but it was rated as more important by females than by males. This indicates, that, in case not all requirements can be satisfied equally, SDJ should be designed with a different focus on specific requirements, depending on whether the target group is male or female.

Overall, there were a few differences in the importance ratings of participants with different ages. Younger participants (*20-29* years) consider an unobtrusive integration and operation of functionalities (ID12) more important than all participants together. Older participants, i.e., the *40-49* years old, differed more from the general rating of all participants. They considered a good appearance (FF1) and robustness (FF4) as very important, whereas requirements such as an unobtrusive integration and operation of functionalities (ID12) were ranked very low. Further, they rated the customisability of the SDJ's appearance (CU10) more important (rank 9) than participants of other ages (ranks 14 and 15). With increasing age of participants, the unobtrusive integration and operation of functionalities (ID12) was ranked less important, i.e., on position 5 for the *20-29* years, position 9 for the *30-39* years, and position 14 for the *40-49* years old. This indicates, that, in case not all requirements can be satisfied equally, SDJ should be designed with a different focus on specific requirements, depending on the age of the target group. In particular, older participants between *40-49* years tend to perceive the importance of certain requirements differently than younger participants do.

Our study is limited in that only Germans participated in the survey. We assume that the results would be similar for people from other modern, western countries, but we cannot be sure. For people belonging to other cultures, that have different attitudes towards technology, fashion, clothing and items worn on the body, results could differ.

In the survey we asked participants for further requirements they consider important. Due to the study design, these additional requirements were not ranked by participants. So, we could not include the requirements that were additionally mentioned in the ranking.

## 3.4 Conclusions

In this chapter, we investigated the user requirements for SDJ. In particular, we studied the importance of certain requirements for SDJ. We presented the user requirements that we gathered from literature on wearable computing and SDJ. Further, we summarised an interview with a goldsmith in which we gained insights into the feasibility, challenges, and specific requirements on SDJ from the perspective of a goldsmith. In the last section, we presented an online survey in which we investigated the importance of certain user requirements for SDJ from the perspective of potential users.

From the interview with a goldsmith, we learned about the three major challenges for crafting SDJ: material, size, and weight. Creating SDJ appears to be less a task for a goldsmith, but realisable by factories in terms of mass-produced fashionable jewellery. The results from the requirements survey show, that overall, all requirements included in the ranking are considered important by potential users. We found differences in the perceived level of importance of certain requirements. We also found differences in the importance ratings, that are related to sex and age. In general, participants considered functionality, form, and interaction and display design as very important, whereas they found body location, context awareness and customisability less important. From the survey results, we conclude that, ideally, all requirements included in the ranking are addressed. In case not all requirements can be satisfied equally, designers of SDJ should consider the importance of certain requirements for the target group. This chapter contributes to research question Q1 with a ranked list of user requirements. This is to be seen as decision support for designers which requirements to address with which priority in case not all requirements can be satisfied equally. Thus, it helps designers of SDJ to focus on the - from a user perspective - more important aspects, before considering the less important ones. We highlight differences in the requirements for males and females, and differences in different age groups. In general, designers of SDJ should focus on the functionality, form and interaction and display design first, before considering aspects with regard to body location, context awareness, and customisability. Particularly, when designing SDJ, designers should consider the different requirement importance rankings for males and females and for certain age groups, in case not all requirements can be satisfied equally. The requirements a designer should focus on also highly depend on the use case of the digital jewel. In this study, we focused on everyday consumer products, i.e., products that are typically just worn for fun. For those, addressing highly ranked user requirements is very important with regard to the acceptance of the device. The results we presented here refer to such everyday systems and are presumably not applicable to, e.g., safety-critical or lifesaving systems.

# 4 Encoding Everyday Information by Light

Light as modality to present information relates to the requirements presented in the previous Chapter as follows. Light has aesthetic value and thus contributes to a good look (**FF1**). It allows customisation of information presentation in that it can, e.g., be varied in colour (**CU11**). Encoding information by light is abstract and thus not meaningful to bystanders if they do not know the mapping (**ID14**). For context adaptation, light can be varied in certain parameters, e.g., brightness (**CA15** and **CA16**).

Several wrist-worn devices present information visually in terms of lighting up displays, such as the activity trackers *Nike+ FuelBand* [Nik16b], *FitBit Flex* [Fit16], and *Misfit Shine* [Mis16b] (see Figure 4.1). The *Nike+ FuelBand* uses


*Figure 4.1: Activity tracking wristbands with lighting up displays. From left to right: Nike+ FuelBand, Fitbit Flex [Fit16], and Misfit Shine [Mis16b]. Image source of Nike+ FuelBand: CHIP Digital GmbH*

a point-light display to present information on a user's activity progress for the day. It consists of a row of light spots that altogether show a coloured progress indicator in a gradient from green via yellow to red. *FitBit Flex* and *Misfit Shine* display progress information via a few white-coloured light spots, either arranged in a row or in a circle. In research, wrist-worn point-light displays have been explored initially, e.g., in terms of bracelets displaying notifications [HL00], or information on social activity [WFC06] and spatial proximity [AM08] (see Chapter 2). With *ActivMON*, Burns et al. presented a watch-like device with a light spot that shows the user's and the user's friends' physical activity level. The light changes colour from red via yellow to green to indicate the user's current activity level and flashes when friends who also use *ActivMON* are physically active. A preliminary user study indicated that the device's design has to be decorative, and that the light's brightness should adapt to lighting conditions in the environment [BLB12].

Initial evaluations of lighting up bracelets seem promising and indicate that this way of information presentation on smart wrist-worn wearables should be investigated further. What is missing is a thorough investigation of wrist-worn light displays that contributes to answering the questions, if and in how far light is suitable to present information on wrist-worn SDJ. We need to investigate how wrist-worn point-light displays should present information in everyday life in an effective and pleasant way. This chapter contributes to research question Q3. We report on a user study in which we explored encodings for the presentation of everyday information on a lighting up bracelet. In the user study, we (1) investigated which kinds of light patterns users would design for different types of physical activity feedback, and (2) evaluated how the participants perceived and experienced the light patterns on a lighting up bracelet in real-life situations. On the basis of the specific use case, we propose a configuration for conveying four types of information. Further, we derived six general implications for the design of light patterns on a wrist-worn display.

Our overall idea is to discreetly present information on a decorative lighting up bracelet that is already worn as a piece of jewellery. The sketch in Figure 4.2 illustrates this idea in terms of a composable silver bracelet. The single links are

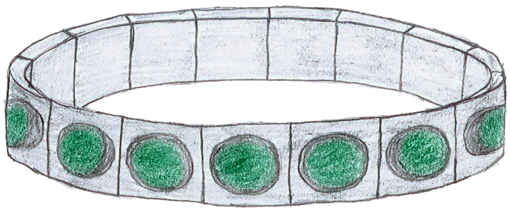


*Figure 4.2: Sketch of a composable silver bracelet whose links are studded with single light spots that appear as stones*

studded with light spots that appear as stones. On the basis of this idea, we have built a prototypical point-light bracelet to explore how information should be presented with light spots. In a user study, participants designed light patterns for a hands-on scenario: physical activity feedback. We chose this scenario as it addresses a very relevant topic in health care and is easily understandable. Physical inactivity can lead to serious illnesses and overweight [US 96]. Long sitting periods have been shown to increase the risk of diabetes and cardiovascular disease [WEA+12]. However, physical inactivity has become a normal condition for many people today, and in the long run accounts for 1 out of 10 deaths world-wide [FWS16, LSL+12].

After the design session, participants tested their light patterns on our prototype in a 3 days in situ study. Results show that participants often preferred similar light patterns for specific types of information, such as progress and challenge. Participants in general wished for a customisable bracelet in terms of design and light patterns. From our results, we derived implications for the design of light patterns on wrist-worn displays.

Parts of this chapter were published in *Jutta Fortmann, Heiko Müller, Wilko Heuten, and Susanne Boll. How to present information on wrist-worn point-light displays. In Proceedings of NordiCHI '14, pages 955–958, 2014. ACM* [FMHB14].

## 4.1 Prototype Implementation

To explore how information should be presented with light spots we built a lighting up bracelet (see Figure 4.3). We used a 25cm long digital RGB LED stripe with a waterproof casing. We curved it to the form of a bracelet and fixed it with cable fixer. The LEDs were covered with semi-transparent film to diffuse the light. In this length the bracelet provided six visible LEDs. We chose this length

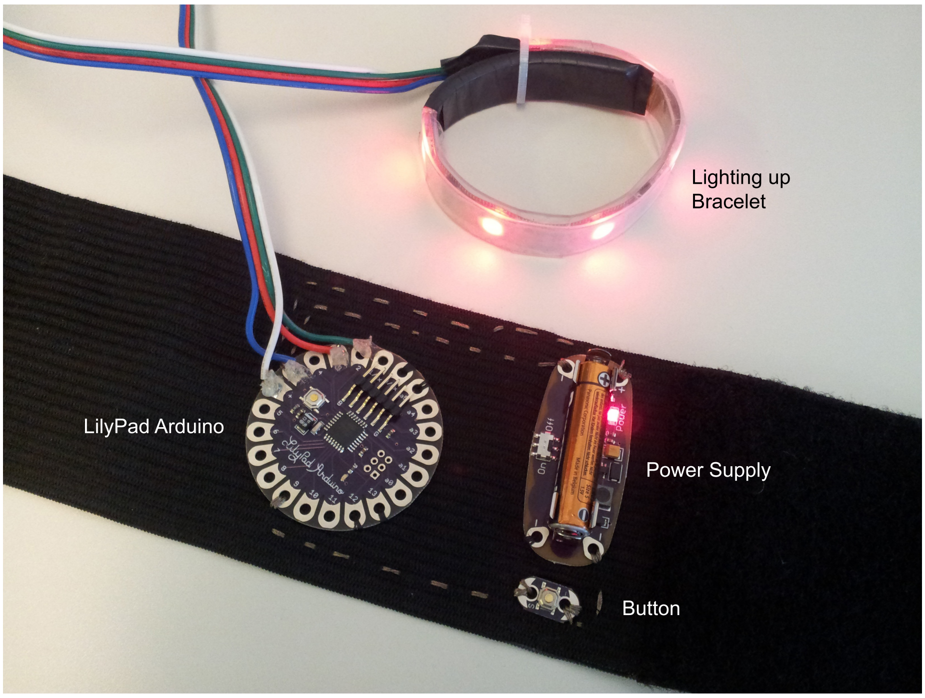



*Figure 4.3: Study prototype consisting of the lighting up bracelet and the armlet with the Arduino microcontroller, power supply, and button*

because it supports different wrist sizes. The LEDs on the bracelet were controlled by a LilyPad Arduino 328 microcontroller, which we sewed on an elastic armlet. An AAA battery provided the system with power and a LilyPad Button Board allowed the user to activate the light display. All LilyPad components were sewn on the armlet and connected by conductive thread. The armlet made it possible to keep the size of the plain bracelet minimal and to make the bracelet look as decorative and unobtrusive as possible considering its early prototype status. We connected the LilyPad microcontroller and the LED stripe with a quad cable. To program the microcontroller we used the Arduino Programming Language.

## 4.2 Design Study and Evaluation

In a user study we firstly, investigated what kinds of light patterns users would design for different types of physical activity feedback. Secondly, we evaluated how the participants perceive and experience their light patterns on the bracelet in daily life. The focus of our investigation was on user experience and everyday life suitability of the light display. We wanted to gain a deep understanding of how users experience the light patterns on the prototype in situ. Thus, we did not connect the bracelet to an activity tracker, but imitated the user's activity behaviour over the day.

### 4.2.1 Material

We used the presented bracelet prototype. The armlet was fixed on the participants' upper arm on top of their clothes and the bracelet was fixed on their wrist. The connecting cable was fixed with an elastic band.

### 4.2.2 Participants

Seven volunteers (four females) took part in the study. Their age group varied between *under 21* and *28 to 34*, whereby four participants were in the age group *21 to 27*. Participants were students at the local university (not related to the research team) and employees in a local institute. None of the participants suffered from dyschromatopsia. None of them had prior experiences in the use of the bracelet. The participants were paid 25€ each as reimbursement.

### 4.2.3 Procedure

Participants took part in individual sessions. After they had signed an informed consent and completed a demographic questionnaire they were introduced to the bracelet. In the first part of the study, we asked the participants to design light patterns for four different types of physical activity information: (1) daily progress, (2) time elapsed since the last activity, (3) trend with regard to the preceding week, and (4) challenge to move. We explained the four information types and demonstrated the available light parameters on the bracelet. We selected the light parameters according to good perceptibility, discernibility, and pleasant appearance (see Table 4.1). Additionally, we handed out a coloured print out with sketches of the light parameters. After the participants had designed light patterns using crayons and paper templates (see Figure 4.4), we demonstrated these on the bracelet. When the participants were satisfied, we interviewed them about inspirations they had with regard to the designs.

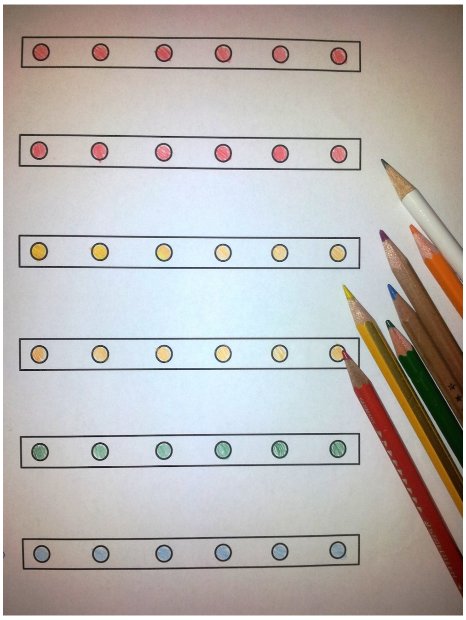


*Figure 4.4: Light patterns were designed with crayons and paper templates*

In the second study part, we programmed the bracelet with the designed patterns and explained all issues regarding the prototype use. Each participant was given a bracelet with the individual lighting designs he or she had designed in the first study part. Participants were instructed to wear the bracelet while following their daily routine. We asked them to push the button to activate the light display at least once in every new situation they get into, as long as they feel comfortable with it. After the first day of usage, participants were interviewed about their experiences in general and with regard to specific everyday situations. Inspired by Rico et al. [RB10], we defined situations by location, audience and lighting conditions. Furthermore, participants could redesign their light patterns, which we then reprogrammed on the bracelet. After two more days of usage, we repeated the interview to learn about experiences from further situations. Additionally, we asked about the overall acceptance of the bracelet and about ideas for improvements. Finally, participants rated the comfort of the bracelet using the Comfort Rating Scales (CRS) [KBSB02], which are a standardised assessment tool for wearable computers. With the CRS, cognitive and physical comfort were assessed by means of six dimensions that were rated each on a 20-point scale. The six dimensions were *Emotion*, *Attachment*, *Harm*, *Perceived change*, *Movement*, and *Anxiety*.

### 4.2.4 Information presented on the bracelet

We chose the kind of information to be presented on the bracelet according to the criterion of applicability for various use cases. We included four different, widespread, abstract classes of information and mapped these to the use case of our study, which was physical activity feedback. In the following, we list the information classes and the mapping to our use case. In brackets you find the defined levels of the corresponding information.

*Information 1: Progress display from negative to positive*
Your today's number of steps in percentage regarding your goal for today (0%, 20%, 40%, 60%, 80%, 100%)

*Information 2: Drop display from positive to negative*
Time elapsed since your last steps (0 min., 30 min., 60 min., 90 min., 120 min., more than 120 min.)

*Information 3: Trend display in relation to a neutral base*
Trend of your activity level with regard to the preceding week (distinctly worse, worse, constant, better, distinctly better)

*Information 4: Attention-Arresting display*
Challenge to move ("You should move again!", "You should really move again!")

Following the design of current wrist-worn activity trackers, Information 1, 2 and 3 were displayed on the user's demand. As Information 4 should arrest the user's attention, it was displayed automatically. With this display concept, we could investigate how users experience the light display on the one hand, when they activated the display, and on the other hand, when the display was activated automatically.

The choice of the physical activity information is particularly based on Consolvo et al.'s [CESL06] design requirement "Provide personal awareness of activity level" which can be fulfilled by the three information types *history of past behaviour*, *current status*, and *activity level performance*. We included the challenge to move as Information 4, because – in contrast to previous work – we also wanted to address the problem of irregular activity, which was highlighted by Wilmot et al. [WEA$^+$12] and Dunstan et al. [DKL$^+$12].

As the participant's actual activity was not measured during the study, we imitated the user's activity behaviour over the day. The restricted lifetime of the battery allowed for a flawless operation of at least 6 hours. Hence, we defined that one day lasted for 6 hours and distributed the single levels of the different types of Information 1 to 3 accordingly. For, e.g., Information 1 and 2, which had 6 levels each, this meant that each level could be retrieved within a time slot of one hour. The single levels of Information 4 were displayed alternately every hour, assuming that the user had not been walking within this time. This procedure ensured that the user could see all different levels within a day.

### 4.2.5 Set of light patterns

In our lab, we tested several light parameters on the bracelet with regard to good perceptibility, discernibility, and pleasant appearance. Finally, this resulted in a set of 7 colours (white, yellow, orange, red, green, blue, purple), 2 brightness levels (bright (maximum RGB value was set to 63 out of 255), dimmed (maximum RGB value was set to 13 out of 255)), 1 flashing level (rate: once every 2 seconds for a duration of 1 second), a linear colour gradient, and a linear brightness gradient choosable for each of the 7 colours. Table 4.1 shows an overview of the set of light parameters we defined. For this work, we restricted the light parameters in a way that we controlled all 6 LEDs on the bracelet uniformly. We did this because on the one hand, we wanted to narrow down the design space for the study. On the other hand, we wanted to overcome the problem of covering, in a way that information cannot be perceived because the specific LED that lights up is currently under the wearer's arm and therefore not visible.

| **Light Parameter** | **Range** | | | | | | |
|---|---|---|---|---|---|---|---|
| Colour | white | yellow | orange | red | green | blue | purple |
| Brightness | dim | | | bright | | | |
| Flashing | off | | | on | | | |
| Colour gradient | off | | | on[1] | | | |
| Brightness gradient | off | | bright to dim[2] | | dim to bright[2] | | |

[1] for each combination of colours listed above
[2] for each colour listed above

*Table 4.1: Set of light patterns for the study*

Information 1 to 3 were displayed when the user pushed the button on the armlet once, resp. twice or thrice. If he did so, the according light pattern would be displayed for 6 seconds before all lights turn off. If the parameter *flashing* was defined, it would be displayed on the bracelet as 4 flashes of 1 second each, before all lights would turn off again. Information 4 was displayed automatically and would light up in the same way as described above.

### 4.2.6 Results

We found that, in general, the lighting up bracelet was accepted in and suitable for many everyday situations. Participants often preferred similar light patterns for the same type of information. The possibility to customise the bracelet and the light patterns for the user seems worthwhile. The results indicate that the context-sensitive presentation of information is important for the acceptance of the bracelet.

#### 4.2.6.1 Design sessions

In the design sessions, participants designed a total of 28 light patterns for the four different types of physical activity information, i.e., 7 light patterns per information type. In the following, we present the results of the design sessions.

*Participants designed according to a certain principle*
Participants typically designed light patterns according to a consistent scheme. These schemes were gradients with same colours, specific colours which always represent the most positive and the most negative information, or cool colours (blue, green) which were mapped to more positive information, whereas warm colours (red, orange) were mapped to more negative information. Reasons mentioned were that schemes make it more easy to remember the encoding, can prevent confusion and allow different types of information to be easily compared to each other.

*Gradient-like patterns often chosen for Information 1-3*
Participants typically encoded the different levels of Information 1-3 with different colours, which often followed a gradient-like pattern. In the initial design, the gradient red to green respectively vice versa was chosen by 2 participants for Information 1 and by 4 participants for Information 2. 3 participants chose a slightly varied version of this gradient and included blue. P4 chose the "gradient" according to the idea of using lighter colours (white, yellow) for more positive and darker colours (orange, purple) for more negative information.

*Traffic light metaphor often mapped to rating information*
The colours red and green were preferred by many participants for negative (red) and positive (green) information. A participant said: "Colours of traffic lights are well-defined. Everyone knows their interpretation and you can find them everywhere.".

*Flashing typically used for urging or negative information*
Except for one case, flashing patterns were used only for negative or challenging information. To represent the urgent level of Information 4, 5 participants chose a red flashing pattern. For the also challenging, but less urgent level of Information 4, 3 participants chose an orange flashing pattern. 4 participants mentioned that a flashing pattern, especially in red or orange, indicates "Attention!" and shall warn of something. A participant said it reminds her of the lights at a building site.

*Clear distinction between the best and all other levels*
4 participants stated the wish for a clearly visible distinction between the most positive level of specific information and all other levels, especially with regard

to Information 1. In their designs, they tried to implement this by changing brightness, colours or using a flashing pattern only for the last level. 3 participants mentioned: "One would deserve a reward when a goal is reached."

*Interpretation of colours varied distinctly*
Besides the colours red and green, which were associated with negative or positive information without exception, other colours were interpreted differently. 2 participants associated, e.g., blue with something good, whereas 3 others interpreted it as neutral. White was either interpreted as positive or as neutral. Purple was either perceived as something negative (by 3 participants), or something neutral.

*Emphasis of neutral level as reference value*
Information 3 has the level *constant*, which represents neutral information. Participants clearly emphasised this level with specific colours like blue or purple, which they did neither map to positive nor to negative information.

#### 4.2.6.2 In-Situ Usage

In total, participants assessed 19 different situations. These included seven different locations: *at home*, *at the office*, *in the lab*, *in a lecture or seminar*, *in a canteen or bar*, *in a supermarket*, and *while driving*, as well as five different audiences: *partner or family*, *friends*, *colleagues or fellow students*, *public or strangers*, and *by oneself*, and two different lighting conditions: *bright* and *dim*. A typical situation was, e.g., *being at home with the partner or family and the light dimmed*.

*Differences in brightness were hardly observed*
No participant was able to reliably distinguish different brightness levels at daylight. Participants said, they did not recognise when the brightness of the light had changed, although they knew that they had designed it that way. This was the main reason why participants redesigned their initially chosen light patterns. Typically, they changed a brightness gradient or levels of same colours with different brightness levels into a colour gradient.

*The light of the bracelet was generally rated as being distinctly perceivable, pleasant and not disturbing*
Over all different situations, participants rated different statements with regard to the user-initiated types of information and the system-initiated types of information on a 5-point Likert scale from 1 = "I fully disagree" to 5 = "I fully agree". Participants distinctly perceived the light of the bracelet for both the user-initiated types of information and the system-initiated types of information (for both Mdn = 5; Mo = 5). Participants liked the light of the bracelet for the user-initiated types of information (Mdn = 4; Mo = 4) as well as for the system-initiated types of information (Mdn = 4; Mo = 3) . Participants perceived the light of the bracelet as undisturbing for the user-initiated types of information (Mdn = 5; Mo = 5). For the system-initiated types of information,

participants slightly varied in how disturbing they perceived the light, with an overall tendency towards feeling undisturbed (Mdn = 4; Mo = 2 and 5). Across all situations, participants found it generally pleasant to wear the bracelet with regard to both types of information (Mdn = 4; Mo = 5). To summarise, the ratings were generally high, i.e., good, and did not or only slightly vary between the two different types of information. The radar chart in Figure 4.5 illustrates how the median ratings of the different statements relate to each other.

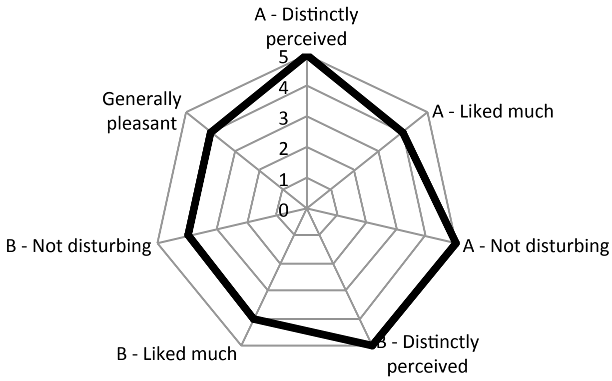



*Figure 4.5: Median values of Likert scale ratings, pigeonholed in system-initiated (*B*) and user-initiated information (*A*)*

*System-initiated information was assessed slightly worse than user-initiated information*
As Figure 4.5 shows, in general, the system-initiated information ($B$) with regard to liking and disturbance was assessed slightly worse than the user-initiated types of information ($A$).

With regard to disturbance, participants experienced particular situations (see below) in which they felt uncomfortable when the bracelet lighted up automatically and therefore, in these situations preferred the on-demand display.

*Dark environments and the presence of strangers influenced how participants experienced the light*
The few situations in which participants rated the light as disturbing were either characterised by a dimly lit environment or by the presence of strangers. A participant who was watching a film with a seminar group stated: "I didn't like it because not only me but also the others were distracted from the film when the bracelet flashed. In the dark environment it was too conspicuous.". Beyond that, a participant mentioned that she felt frustrated because – while working in the lab – she could not react to the challenge to move.

*Reactions of others had little influence on participant's feelings*
In 13 cases, participants experienced reactions from bystanders, but only in two cases this made participants feel uncomfortable. Bystanders just looked, asked with interest or joshed the participant on friendly terms. In 10 cases, participants

felt invariably after the reactions, even if they, e.g., were surrounded by strangers looking at them in a supermarket.

#### 4.2.6.3 Comfort Rating Scales

The comfort of the bracelet prototype was rated with the Comfort Rating Scales (CRS) [KBSB02]. Participants rated how they perceived each of the six dimensions *Emotion*, *Attachment*, *Harm*, *Perceived change*, *Movement*, and *Anxiety* on a 20-point scale from *low* (1) to *high* (20). The CRS were analysed individually. The lower the rating for a dimension, the more comfortable the prototype was perceived. Figure 4.6 shows the median values of the single dimensions. While *Harm*, *Perceived Change* and *Anxiety* are rated very low (for all Mdn = 1), *Emotion* (Mdn = 11), *Attachment* (Mdn = 5) and *Movement* (Mdn = 12) received higher ratings. As the reason for the perceived impact on movement, for the

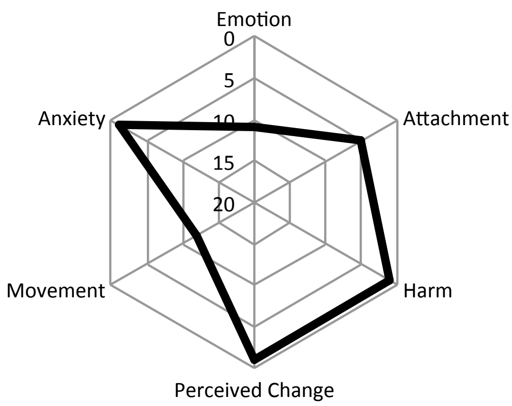



*Figure 4.6: Median values of individual ratings of the Comfort Rating Scales*

sensing of the attachment, and for the worry about their appearance (= *Emotion*), all participants gave the armlet and the cable which connected the bracelet with the LilyPad. In addition, most participants worried about that they could demolish the prototype. Several participants said that if the prototype consisted only of the bracelet without the armlet and cable, they would have rated it more positive regarding the factors *Attachment*, *Movement*, and *Emotion*. To the latter a participant added: “I worried about how I look like when I wear an armlet with protruding electronics, cables and a red light. I thought I might look like an assassin with a bomb and therefore did not wear the bracelet in public transport.”. The red light the participant was referring to was the continuously illuminated status lamp of the power supply board which was attached to the armlet (see Figure 4.3). Another participant said something similar about her stay in the concourse of an airport.

#### 4.2.6.4 Post-hoc Interviews

5 participants stated they can imagine to wear a similar bracelet in everyday life, if it was in a more sophisticated status. All participants stated that they can imagine to wear a similar bracelet if it was embedded in jewellery such as a decorative bracelet or watch. 4 participants explicitly mentioned that it shall be customisable, e.g., 2 male participants added that they want it to be made out of leather.

Participants conceived several ideas on the overall prototype design. 4 participants would like the light display to be discreetly integrated into a watch, as one of them said "A watch you take with you anyway and you also look at it regularly.". Another participant suggested to use a watch band as the display, which appears somehow like a glow stick without separated light spots. The reduction of the number of light spots was suggested by other participants as well, of who 1 preferred only one light spot, and 2 preferred two light spots. Another female participant suggested to use smaller light spots which appear like little gemstones.

Furthermore, participants mentioned to integrate other modalities for useful functional supplements. Vibration was mentioned as an appropriate modality to get the attention of the user if, e.g., the bracelet was covered by a sleeve and not visible. Finally, an additional "snooze" function was suggested. It shall allow to display the reminder to move once again after a customisable delay time for the case that Information 4 was triggered in an improper situation.

### 4.2.7 Discussion

From the study results we derived six implications for the design of light patterns to convey information on a wrist-worn display. We will summarise these in the following.

#### 1. Use a consistent pattern mapping

Participants designed light patterns for the different types of information according to a certain principle. This indicates that different light patterns for similar types of information should be designed in such a way that they follow a consistent pattern. We assume that this facilitates the learnability of the information encoding and thereby increases the acceptance of the system.

#### 2. Use colours to differentiate levels of specific information, and make the colour mapping configurable

Participants preferred different colours to differentiate between the levels of specific information. Also, they preferred a traffic light pattern to encode rating information, like Information 1-3. Thus, our results reaffirm the suggestion of Tarasewich et al. [TCXD03] to use colours to distinguish between different types or levels of information. Further, we adapt the recommendations to use the colours red, orange resp. yellow, and green for "Danger", "Caution", and "Safe" [Hel87], as well as for high priority, medium priority and low priority [TCXD03] to negative, middling, and positive information. Nevertheless, our results indicate that the colour mapping should be configurable by the user, because participants associated certain colours with different emotions and things, and would like the bracelet to fit their styles.

#### 3. Use flashing for urgent information only

Participants preferred the flashing pattern due to its attention arresting and urgent character and did not use it to encode general information. This finding fits in with the recommendation of Tarasewich et al. [TCXD03] to use flashing patterns only to arrest attention.

#### 4. Do not use brightness to encode information, but adapt brightness level to lighting conditions

Participants reported how difficult or even impossible it was for them to distinguish between different levels of brightness, when they saw them displayed temporally separated from each other in situ. As this already applied to the distinction between only two brightness levels, it became even more obvious for the brightness gradient over six levels. Therefore we recommend to not use different brightness levels presented on single light spots to distinguish between different pieces of information in mobile context. Some participants perceived the light as being too intense in dark environments and wished for a display which adjusts its brightness according to the lighting conditions in the environment.

#### 5. Clearly encode minimum and maximum levels

Participants stated that the most positive level of a progress display should stand out from all other levels, and with regard to physical activity should indicate a reward. This corresponds with the design strategy *Positive* of Consolvo et al. [CML09]. The neutral level of an information type – if existing – should be encoded clearly, too. As a clearly recognisable reference value it can help users to interpret the information more efficiently.

#### 6. Allow "invisible" mode during inappropriate moments

A context-sensitive display that adapts its display to the current situation seems promising. In an improper situation, e.g., when the user is giving a talk or just cannot react anyway, the display could switch to an "invisible" mode for not drawing unwanted attention to the user. The display of information triggered during this mode should then be postponed to a convenient moment, or be presented in another, more unobtrusive way.

From the study results, we derived a mapping of light patterns to four different types of information to be presented on a wrist-worn display, such as progress, trend and challenge (see Table 4.2). It is based on the common patterns we

| **Information Type** | **Level 1** | **Level 2** | **Level 3** | **Level 4** | **Level 5** | **Level 6** |
|---|---|---|---|---|---|---|
| 1: Progress from negative to positive | red | Colour gradient | | | | green (pulse) |
| 2: Drop from positive to negative | green | Colour gradient | | | | red |
| 3: Trend related to a neutral base | red | orange | blue | yellow | green | – |
| 4: Attention arresting | orange flash | red flash | – | – | – | – |

*Table 4.2: Proposed configuration for conveying four different types of information on a wrist-worn light display*

identified across all participants' designs and factors in the design implications described above. To emphasise the most positive level of a progress display, e.g., the accomplishment of the daily step goal, we propose a reward in terms of a pulsing pattern, which is defined by a slow and regular change between increasing and decreasing brightness. We consider a flashing pattern, that some participants suggested, to be too distractive and attention getting for a reward only. A pulse pattern like that used by Harrison et al. [HHHH12], is much more discreet.

The study is limited in that it was conducted with an early prototype and a small sample size. The proposed mapping of light patterns should be seen as an exemplary mapping. To be statistically significant, the findings would have to be verified with a larger sample. In our study, participants wore the prototype for three days. This period already captured various situations, however a longer study period would allow insights into further everyday situations that occur less frequently.

## 4.3 Conclusions

In this chapter, we report on a user study in which we explored encodings for the presentation of everyday information on a lighting up bracelet. In a user study, participants designed light patterns for a hands-on scenario, which was physical activity feedback. After the design session, participants tested their light patterns with the prototype in a 3 days field study.

We found that the bracelet was accepted in and suitable for many everyday situations. Participants often preferred similar light patterns for the same type of information. The possibility to customise the bracelet and the light patterns for the user seems worthwhile. The results indicate that the context-sensitive presentation of information is important for the acceptance of the bracelet. This chapter contributes to research question Q3 as follows: From our study results, we derived (1) an exemplary configuration for conveying four different types of information on a wrist-worn light display, such as progress, trend and challenge. We assume that this configuration can be transferred to other use cases where progress, trend and challenge play a role, e.g., fluid intake behaviour. Furthermore, we derived (2) six implications for the design of light patterns on a wrist-worn display. These can be applied to our future work and can be helpful for the design of future wrist-worn light displays. We expect wrist-worn point-light displays that consider the presented findings and implications - although preliminary - will benefit from an increased user acceptance.

In future, we need to analyse if and in how far the acceptance of the display changes if worn over a longer period of time. Furthermore, we think the context-sensitive presentation of information on wrist-worn technology is essential for their acceptance. Questions arose such as when to present a certain type of information, and how to present the information in a specific situation. Another interesting follow-up would be to investigate the pros and cons of having the users design their own feedback vs. having it preprogrammed. One participant stated: “Great, that I can pick my favourite light patterns.”, which raises questions such as whether a self-selected light pattern would be perceived more positively, or be easier to remember than a preprogrammed one.

# 5 Reminding of Recurrent Tasks: *WaterJewel* Bracelet to Support Fluid Intake

Fluid intake is essential for human health. Insufficient fluid intake can cause discomfort such as headache, lack of energy and lightheadedness [HG98]. Scientists recommend an intake of *at least* 2 litres of fluid a day [EFS11]. Accordingly, a well-known rule of thumb suggests to drink *at least* eight 8-ounce (≈ 237ml) glasses of fluid a day. However, a recent study revealed that every fourth German adult drinks less than 1.5 litres a day, and only 55% drink evenly distributed servings over the day [Tec10]. This may be because of being busy or just because of not being thirsty.

Solution approaches are carrying a bottle of water, checking the watch from time to time, or setting an alarm every few hours. But these approaches are not satisfactory. People easily forget to drink when they have to keep that in mind by themselves. Setting up an alarm every few hours is tedious. Besides, interval-based reminders such as alarms are often triggered only once at a certain point of time, which might be awkward and might not allow the user to go into the matter. In this case, despite the reminder signal, the user might forget the task she was reminded of because she could not react immediately. Also, reminders typically signal in an obtrusive way, such as an auditory alert, a noisy vibrating phone, or a popup window appearing on the user's screen. This forces the user to interrupt a current task immediately and shift attention to the reminder. This is unnecessarily disruptive and furthermore – in public environments – can cause discomfort by drawing unwanted attention to the user. Alarm clocks, e.g., are available in various forms and typically remind after a preset time period. *Carbodroid* [Joo] is a popular Android application which serves as a fluid intake reminder via sound or vibration. Additionally, it visualises the amount of fluid intake and the time of single servings for the day on the graphical display of a smartphone. *Ah!Qua* [Gug] is a decorative bracelet which, similarly to *Carbodroid*, vibrates in preset intervals over the day to remind its user to drink regularly. It does not provide additional information. *MyWay* [UNI] is a silicone bracelet on which a four-segment bar display and an occasionally flashing light spot both indicate the time elapsed since the user's last fluid intake within a fixed timeframe.

Integrating a fluid intake reminder into a discreet piece of SDJ seems promising. It makes a fluid intake reminder always accessible while being integrated into a decorative object. Further, by using light to display information, the reminder can be unobtrusively perceived in a user's periphery of sight, i.e., in a way the user does not have to interrupt her current task.

This chapter presents the design process and two evaluation studies of the light-based bracelet *WaterJewel*, that serves as a reminder of recurrent tasks, i.e., it promotes a healthy fluid intake behaviour. The first part of the chapter deals with the user-centred design process of the bracelet and a field experiment, in which we firstly, investigated the user experience of the bracelet, and secondly, compared it to a prevalent mobile fluid intake reminder application. From the results we gathered insights into the suitability of certain forms and appearances (research question Q2), information encoding (research question Q3) and interaction design (research question Q4) of SDJ. We found that *WaterJewel* was perceived as a decorative, discreet, and usable wearable system. Further, participants drank more in total and more regularly using the bracelet. We found a lighting up bracelet to be a suitable form for SDJ. Our results indicate usable encodings for the number of illuminated light sources as well as for a continuously illuminated light source with gradual colour changes. The second part of the chapter presents a field study in which we compared a modified version of *WaterJewel*, that adapts the lights' brightness to an ongoing calendar event, to a non-adaptive version. The aim of the study was to explore if a brightness-adaptive light display can improve user's and observer's experience. The results indicate that users and – particularly distinct – also observers experienced the adaptive bracelet more positively (research question Q3).

Parts of this work were published in *Jutta Fortmann, Vanessa Cobus, Wilko Heuten, and Susanne Boll. Waterjewel: Design and evaluation of a bracelet to promote a better drinking behaviour. In Proceedings of MUM '14, pages 58–67. ACM* [FCHB14] and in *Jutta Fortmann, Benjamin Poppinga, Wilko Heuten, and Susanne Boll. Real-life experiences with an adaptive light bracelet. In Proceedings of British HCI '15, pages 138–146. ACM* [FPHB15].

## 5.1 Design and Evaluation of *WaterJewel*

We have designed and built *WaterJewel* (see Figure 5.1), a bracelet with discreetly integrated light spots that reflect the user's actual fluid intake behaviour via abstract light signals. In a participatory design process, we created two decorative designs for a masculine and a feminine style of *WaterJewel*. In a field experiment, we explored the use of the *WaterJewel* prototypes in daily life, and compared *WaterJewel* to a prevalent mobile fluid intake reminder application.

In the following, we present the design process and implementation of *WaterJewel*, as well as the field experiment with its results.

### 5.1.1 Design

In the following, we describe the design process of *WaterJewel*. First, we present the conceptual design of *WaterJewel*, and afterwards the presentation design of two different bracelet styles (masculine and femine). From the results of a brainstorming session, we created three different presentation designs per style.

*Figure 5.1:* WaterJewel*: Single light spots on a bracelet reflect the user's daily fluid intake behaviour and thus help her to drink 2 litres in 8 evenly distributed servings over the day.*

In a user study, participants evaluated and redesigned these designs. From the results, we derived our final designs which we present at the end of this section.

#### 5.1.1.1 Conceptual Design

A wearable display is suitable to support a person's fluid intake behaviour in everyday life as it is ever-present. It needs to be aesthetic, unobtrusive, practical and convenient [KBSB02, CESL06, CML09]. A piece of jewellery is able to fulfil all of these requirements. Therefore, the discreet integration of a fluid intake display into jewellery seems promising. Having regard to the work of Tarasewich et al. [TCXD03] and Harrison et al. [HHHH12], and due to their applicability for abstract information presentation, we decided to use light spots for the information presentation. A bracelet is a common piece of jewellery, clearly visible from the wearer's viewing angle, and worn on a well suited body location for information presentation [HLSH09]. So, we integrated a light display in terms of single light spots into a bracelet.

In order to implement the requirement of supporting the user to drink 2 litres a day in 8 evenly distributed servings, we chose the following design concept: *WaterJewel* displays the amount of fluid intake for the day ("volume display"). This allows a user to reflect on the daily fluid intake and thus supports him/her in accomplishing the recommended fluid intake of 2 litres. To support the user in drinking roughly evenly distributed servings over the day, *WaterJewel* uses an ambient reminder ("reminder display"), which reminds the user to drink in an continuously perceivable and yet unobtrusive way.

The volume display consists of eight single light spots, each representing a glass of fluid of 250ml (see Figure 5.2). These add up to the daily recommendation of 2 litres. As this information does not necessarily have to be ever-present, and to ensure an unobtrusive display, the light spots light up on demand only. A drink entry is made through the long push of a button on the bracelet. This activates another light spot in the volume display. If the same button is pushed for only a short moment, all activated light spots of the volume display are illuminated for some seconds. The reminder display is represented as a central light spot

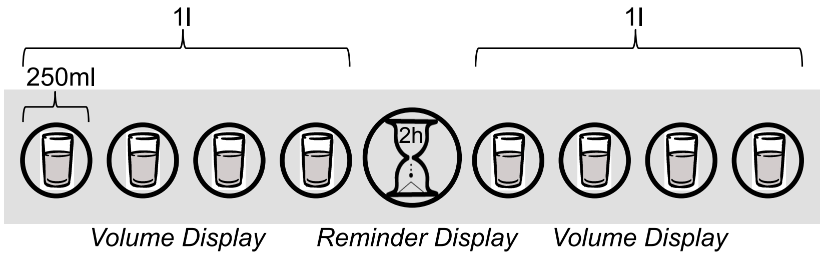



*Figure 5.2: Illustration of the display concept of* WaterJewel*: 8 light spots represent 8 glasses of fluid which add up to 2 litres. A central light spot indicates the time elapsed since the last intake.*

which indicates the time elapsed since the last intake and is always illuminated to support constant awareness of the recent fluid intake behaviour and to remind the user to drink regularly. We assume a person is awake for 16 hours a day in which s/he needs to drink two litres, i.e., 250ml every two hours. So, the reminder display needs to indicate the period between 0 and 2 hours. The reminder display is supported by a vibration display which is integrated into the inner surface of the bracelet. It will vibrate for 500ms if the user has not drunk for two hours. If the user did not react, it would vibrate again twice after one minute for 500ms each, and again for 1s after another 30 minutes. If the user still did not react, the procedure would not start again until after another two hours.

#### 5.1.1.2 Presentation Design

The conceptual design served as the basis for the presentation design. As we wanted to design a smart piece of jewellery, the bracelet design should suit the taste of potential users. Therefore, we involved users in a participatory design process.

Our initial ideas for the presentation design were inspired by current trends in jewellery design, and by a brainstorming session. During the brainstorming session, we asked six volunteers (3 females; age: M = 24, SD = 1.55), which we recruited form personal contacts and who were interested in fashion and jewellery, about the jewellery styles they preferred for themselves and for the other gender as well. We found that the preferences of male participants differed considerably from those of female participants. Women preferred charm bracelets made of metal, as well as thin and wide bangles. Men preferred wide wristbands made of rubber or leather. All in all, these findings corresponded to our trend research. As the form factor of a wearable object is critical for its acceptance [CESL06], we decided to design two different bracelet styles: femine and masculine. On the basis of the results we created sketches for three different bracelet designs per style.

Figure 5.3 shows the masculine designs, beginning with M1, a wide bracelet, e.g., made of leather, with horizontally arranged light spots. The button and the reminder display are placed centrally. The second bracelet, M2, is smaller than M1 and similar to a watch. In the middle of the bracelet is a wider central

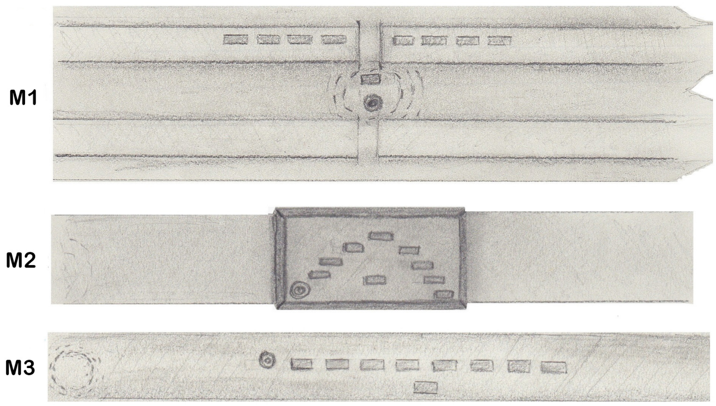



*Figure 5.3: The masculine bracelet designs looked similar to plain leather wristbands and varied in width and the orientation of light spots.*

section which could be made of metal. The light spots are arranged pyramidally on this central section. The button is, in contrast to M1, positioned next to the light spots. M3 is a small, plain and very artless bracelet, e.g., made of plastic or leather. The light spots are arranged in the same way like for M1, except for the button, which is positioned on the left of the light spots.

Figure 5.4 shows the feminine bracelet designs. The first bracelet, F1, is a charm bracelet, with each light spot and the button integrated into a charm. These charms hang on the bracelet in line. F2 is a conspicuous, wide bracelet. It consists of thin bangles coupled together at two sides so they cannot move and cover the light spots. These light spots are positioned on the uppermost bangle, also in a row. The button is arranged centrally, below the reminder display. The third design (F3) shows a wide, plain bangle. The light spots are arranged in a semi circle in the centre, similar to M2, as well as the button, which is located at

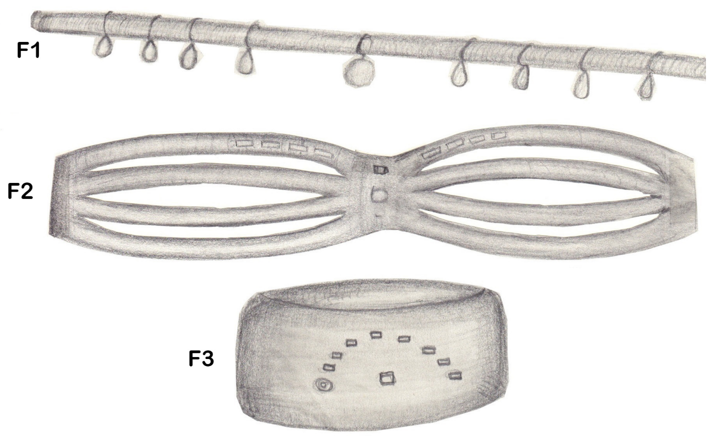



*Figure 5.4: The feminine bracelet designs included a charm bracelet, a conspicuous bracelet with several thin bangles, and a wide plain bangle.*

the left end of the semi circle. This arrangement is supposed to be reminiscent of a petrol gauge.

#### 5.1.1.3 Evaluation of the Bracelet Designs

To define a final presentation design, we evaluated the sketches of the bracelet designs in a user study with 20 participants. Participants rated the design sketches with particular regard to their aesthetics and were asked about the arrangement and colour of the light spots. During the study, participants were also encouraged to draw entirely new sketches in case they had further ideas.

##### Method

20 volunteers (10 females) took part in our study. They were recruited from the local university and personal contacts. The average age was 25.2 (SD = 3.01) for the males, and 26.4 (SD = 7.09) for the females. None of the participants suffered from dyschromatopsia. They stated their interest in jewellery as moderate to strong, i.e., on a 5-point Likert scale from 1 =“Not at all” to 5 = “Very strong”, the male participants rated the question “How strong is your interest in jewellery?” as 2.6 in average (SD = 0.97), and the females as averagely 3.7 (SD = 0.82).

None of the participants was paid for taking part in the study. Prior to the study each participant signed an informed consent. Participants took part in the study individually. Each study session included a short introduction, the completion of a demographic questionnaire, the design part, and concluded with a post-hoc interview. For the design part, participants were presented the three style-specific design sketches, and were equipped with blank paper sheets, a ruler, and coloured pencils. Participants were encouraged to comment on the sketches by naming advantages and disadvantages, to name their preferred sketch, and also to modify the sketches or to draw entirely new sketches if they had own ideas. In addition, they were asked to think and comment on the arrangement and colour of the light spots. In semi-structured interviews we asked participants to, e.g., describe their preferred jewellery styles, desired light pattern for the reminder display, and if there were colours which should be avoided in general.

### Results

The generally preferred jewellery styles of female participants were artless (9 votes) and elegant (6 votes), followed by conspicuous (2 votes), sporty, and glamorous (1 vote each). Male participants clearly preferred an artless style (9 votes), followed by sporty (4 votes), elegant, and conspicuous (1 vote each).

This distribution fits the design votes. 4 male participants preferred design M1, 3 chose M2, 2 chose M3. One participant preferred his self-drawn bracelet sketch, which was similar to M1, but more conspicuous as it winded itself round the arm (see Figure 5.5). Apart from that, this participant preferred design M1. 3 male

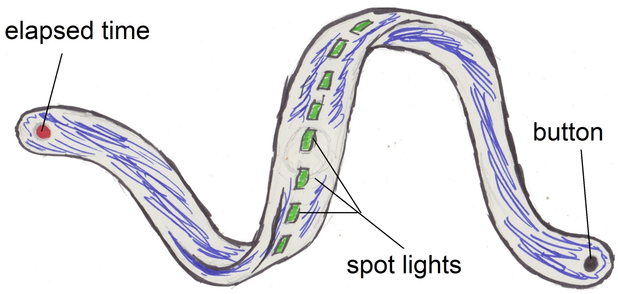



*Figure 5.5: Sketch of a bracelet that winds itself round the user's arm, designed by a male participant.*

participants who did not choose M1 said the only reason was that it was too wide. The horizontal arrangement of the light spots and the button as in M1 and M3 was positively emphasised by 8 male participants. The vote for the feminine designs was more clearly: 7 female participants preferred design F1, 2 chose F2 and one chose F3. Several female participants positively emphasised that F1 is artless and elegant at the same time, as well as narrower and more delicate than the other designs. In addition, the female participants liked the arrangement of light spots in line and appreciated the possibility of individualising the shape of the charms.

For the reminder display, all participants preferred a light pattern in terms of a colour gradient for which most of them preferred the colours green (just drank) to red (drank long ago). Regarding the colour of the volume display, 7 participants (4 males) chose blue. Other choices varied distinctly: 3 participants (2 males) chose green and 3 participants (2 males) chose red. Other colours mentioned by female participants were purple and pink, whereas these colours were explicitly mentioned as ugly by male participants. The distribution varied more for the female participants, who said that their choice reflected their favourite colour. Besides, several male participants suggested to clearly distinct the last light spot from all others to indicate the daily goal is accomplished.

The choice of the colour for the eight light spots varied distinctly and was related to the participant's favourite colours. 3 female participants preferred blue, followed by several other colours like green, red, purple or pink (1 vote each).

#### 5.1.1.4 Final Design of WaterJewel

From the study results we derived our final design for the feminine and the masculine styles of *WaterJewel* which we describe in the following.

The masculine bracelet is based on M1 but narrower, as most of the male participants preferred M1. The main point of critique of those who did not choose M1 was, that M1 was too wide. Thereby, the reminder display is arranged in line with the light spots of the volume display and the button is placed left of the light spots. The feminine bracelet is like F1, as most of the female participants preferred and fancied this design. The button is integrated into another charm arranged left of the light spots.

The first seven light spots of the volume display are coloured blue because most participants chose this colour and the last light spot is green to distinct it as the "goal accomplished" light spot. With respect to the study results, the reminder display shows a colour gradient from green to red over a period of two hours. If the user has not drunk for two hours, the reminder display will illuminate in red. If a new light spot is activated, it will be reset to green.

### 5.1.2 Prototype Implementation

According to the final design, we built two bracelet prototypes. Each bracelet (see Figure 5.6) consists of eight LEDs for the volume display, one button to activate these LEDs, one RGB-LED for the reminder display in terms of a colour gradient from red to green and vice versa, one vibration display for an additional signal and a microcontroller board to control the bracelet. Because of its simple programmability and its low weight we decided to use the *Arduino LilyPad* microcontroller board with some of its hardware components. The *LilyPad* and also a *LilyPad* battery holder for an AAA-battery were fixed on an additional armlet to keep the size of the plain bracelet minimal. The components on the armlet and on the bracelet were connected by coated wires. To hide the electronics on the armlet, we whipped the whole armlet with black felt.

*Figure 5.6: Masculine (left) and feminine prototype (right) of the WaterJewel bracelet.*

For the masculine bracelet we used eight *LilyPad* Micro LED boards with a size of 3 x 9mm and a *LilyPad* RGB-LED board with a diameter of 20mm. These LEDs were fixed on a plain leather bracelet. A *LilyPad* button board (8 x 16mm) was mounted next to the row of LEDs and allows to activate the LEDs. A *LilyPad* vibe board with a diameter of 20mm served as a vibration display and was positioned on the inner surface of the bracelet. Due to design reasons we did not use the *LilyPad* LEDs for the feminine bracelet. Instead, we used eight leaded LEDs with a diameter of 3mm, of which we bent the pins to use them as charms. Because the smallest leaded RGB-LED has a diameter of 5mm, which is too big, we used a green-red Duo-LED with a diameter of 3mm, which can display green, red, and all gradient colours. To make the LEDs look more like charms, we modelled a cover from translucent bakeable modelling clay and hot glue for each LED. A positive effect of this cover is a softer light of the LEDs. Wires and soldering joints that connected the LEDs were wrapped with black satin ribbon to make the bracelet more aesthetic. The button board was glued on the back of a decorative charm attached in line with the LEDs. The vibe board was positioned on the inner surface of the bracelet.

### 5.1.3 Evaluation

In a four-week field experiment, we explored the use of the *WaterJewel* prototypes in daily life and compared them to the fluid intake reminder application *Carbodroid* [Joo]. We chose *Carbodroid* as it is a state-of-the-art and prevalent fluid intake reminder, rated best of all currently available mobile fluid intake reminder applications in the Google Play Store[1], and because its conceptual design is similar to the one of *WaterJewel*. The intention of this experiment was to get beyond potential novelty effects that may be present in shorter field studies. We wanted to investigate the everyday suitability of *WaterJewel* and its effectiveness compared to *Carbodroid*. To assess the effectiveness, we measured how much participants would drink, how often they accomplished the daily fluid intake goal, how regularly and in which intervals they drank. To assess how usable *WaterJewel* and *Carbodroid* are, we asked participants to rate their usability after they used the systems. Participants also rated how they perceived the emotional and wearing comfort of *WaterJewel*.

**Regularity of fluid intake** To analyse how regularly participants drank, we measured the timeframe between two drink entries and calculated the standard deviation over all of these timeframes. The more the timeframe varies, the higher the standard deviation gets. Thus, the lower the standard deviation, the more regularly the participant drank.

**Interval of fluid intakes** To analyse the interval when participants drank, we measured the timeframe between two drink entries per day. We counted a value as *prior* to the reminder event when $120Min > value > 0Min$ and a value as *after* the reminder event when $value > 120Min$. For the analysis we compared *prior* with *after* counts per condition. As the recommendation is to drink *at least* 2 litres of fluid a day, we interpret *prior* counts as generally positive, because, if recurrent, they lead to more fluid intake. We interpret *after* counts as negative, because when a drink is taken after the 2 hours interval it is less likely that the user will accomplish the daily goal.

We assumed that the continuously illuminated Reminder Display of *WaterJewel* would lead to an increased and more regular fluid intake as being perceivable whenever in the user's focal or peripheral vision and showing the current fluid intake status at a glance by light colour. Further, we assumed the quick accessibility of the wrist-worn and one-button operated *WaterJewel* would lead to higher effectiveness compared to *Carbodroid*. On the basis of these assumptions we formulated our hypotheses which are:

**H1)** participants drink more with *WaterJewel* than with *Carbodroid*.

**H2)** participants more often meet the recommendation of drinking 2 litres fluid a day with *WaterJewel* than with *Carbodroid*,

**H3)** participants drink more regularly with *WaterJewel* than with *Carbodroid*, and

**H4)** participants drink more often prior to the reminder event with *WaterJewel* than with *Carbodroid*.

[1] `https://play.google.com/store`

#### 5.1.3.1 Material

For the study we used the masculine and the feminine versions of *WaterJewel*. Participants used their own Android smartphones with the installed *Carbodroid* application. *Carbodroid* reminds to drink via vibration every two hours. The main view of the application shows the app character (see screenshots shown in Figure 5.7). This character indicates the water intake of the user. It is filled with water more and more and the character's facial expression becomes happier whenever the user makes another drink entry. The user enters a glass of water by selecting the glass icon below the character. The daily fluid intake goal is set to 2000ml. Another view ("list view") shows an overview of the drinks of the day in terms of a list showing serving size and time of drinking. This view as well as the main view are always reset automatically at midnight.

Figure 5.7 shows four different types of information and how they have been displayed on *Carbodroid* and *WaterJewel* during the experiment. In the upper left the initial status is shown. *Carbodroid* shows an empty and therefore sad character. The reminder display of *WaterJewel* illuminates in red and the light spots of the volume display are deactivated. The upper right illustration shows both systems when the user has drunk his third glass of water one hour ago, that makes 750ml in total. The character is filled up with water up to his upper body and looks slightly happier. *WaterJewel* illuminates the first three light spots of the volume display in blue and the reminder display in yellow. In the lower left the goal status is shown, i.e., the user has just reached his daily fluid intake goal of two litres. *Carbodroid* shows a popup saying that one has drunk enough water for today. The character in the background looks happy and is completely filled up with water. *WaterJewel* illuminates the first seven light spots of the volume display in blue and the last light spot in green. The reminder display lights up in green. The lower right illustration shows the display of the information that the last intake was two hours ago. *Carbodroid* makes the smartphone vibrate, and *WaterJewel* illuminates the reminder display in red and, in addition, also vibrates.

#### 5.1.3.2 Participants

12 participants (6 females) volunteered to take part in the study. They were recruited from the local university, personal contacts, and through public announcements. 5 participants were students, 1 was an apprentice, 4 were (self-)employed, 1 was job-seeking, and 1 was a housewife. The participants mapped their age to the following ranges: *under 21* (N = 1), *21 to 27* (N = 6), *28 to 34* (N = 4), and *42 to 48* (N = 1). None of them suffered from dyschromatopsia, and none of them had already used neither *WaterJewel* nor *Carbodroid*. They all estimated their fluid intake about less than 2 litres of fluid a day. The participants were paid 25€ each as reimbursement.

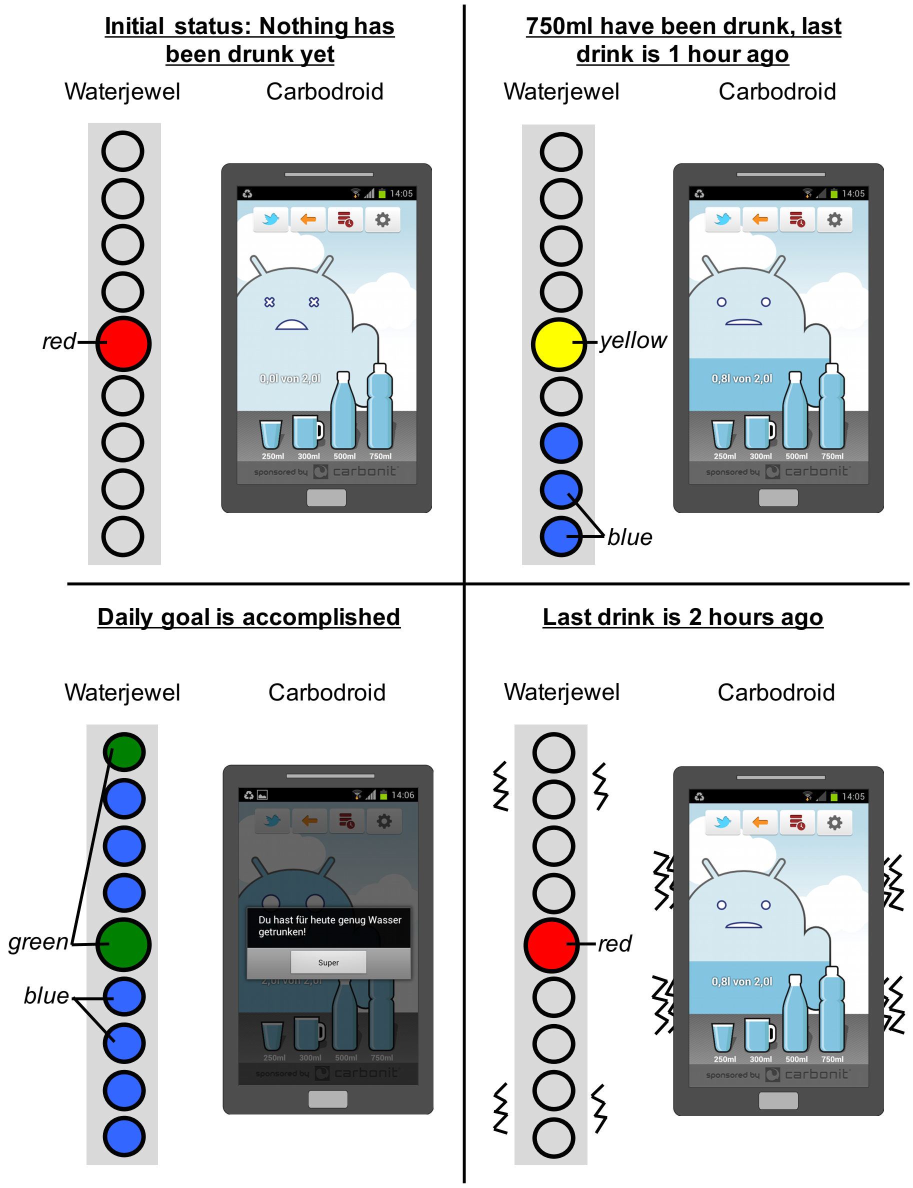



*Figure 5.7: Examples of different types of information and their display on* WaterJewel *and* Carbodroid

### 5.1.3.3 Study Design

We used a repeated measures design and alternated the order of conditions to cancel out sequence effects. The type of fluid intake reminder (*WaterJewel* or *Carbodroid*) served as independent variable. In the experimental condition, *WaterJewel* was worn on the wrist and provided feedback on the fluid intake behaviour. In the control condition, *Carbodroid* was provided on the participants' smartphones for the same purpose. The dependent variables were the fluid intake volume per day, the number of days on which at least 2 litres consumed liquid had been entered, the standard deviation of the timeframe between two drink entries (regularity of fluid intake), and the timeframe between two drink entries (interval of fluid intakes). We measured the values by logging the participants' drink entries on the corresponding device.

Participants took part individually in the study. Each study session included a short introduction, the study itself lasting for four subsequent weeks, two post-hoc interviews, one after the first two weeks and the other on the last study day, and concluded with the completion of a System Usability Scale (SUS), an established standard questionnaire for assessing the usability of a system [Bro96]. With the SUS, participants rate 10 statements, e.g., "I thought the system was easy to use." on a 5-point Likert scale, ranging from "Strongly disagree" (1) to "Strongly agree" (5). After the experimental condition, participants also completed the Comfort Rating Scales (CRS) [KBSB02], a standard assessment tool for wearable computers, to rate the comfort of *WaterJewel*. With the CRS, cognitive and physical comfort were assessed by means of six dimensions that were rated each on a 20-point scale. The six dimensions were *Emotion*, *Attachment*, *Harm*, *Perceived change*, *Movement*, and *Anxiety*. During the introduction, the participants learned about the procedure of the study, and the operation of *Carbodroid* and *WaterJewel*. After they signed an informed consent, they assessed their personal fluid intake behaviour by means of a questionnaire. Afterwards, they were equipped with *WaterJewel*, i.e., female participants received the feminine version and male participants the masculine version of *WaterJewel*. Then, the participants engaged in their usual daily routine for two weeks. Afterwards, they exchanged *Carbodroid* for *WaterJewel* or vice versa, and continued their daily routine for another two weeks. In between, we shortly met the participants once a week to read the logged data on their bracelet or smartphone and to gain an insight into the course of the study. At the end of the second and the fourth study week, we conducted a post-hoc interview in which we asked for the situations in which the participants had worn the bracelet and carried the smartphone and where they had carried the smartphone and how visible they had worn the bracelet. On the last study day we also asked for the participants' general preference regarding *Carbodroid* and *WaterJewel* and which system supported them better in taking in fluids regularly and sufficiently.

#### 5.1.3.4 Results

Our results show that with *WaterJewel* participants drank more in total, more often accomplished the daily fluid intake goal, drank more regularly, and drank more often prior to the reminder event than with *Carbodroid*. Participants found *WaterJewel* usable, appreciated its decorative appearance, felt comfortable with it in general, and most of them preferred *WaterJewel* to *Carbodroid*.

### Quantitative Results

In total, we logged 1341 drink entries on *WaterJewel* (approx. 335.25l), and 1225 drink entries on *Carbodroid* (approx. 245l). 12 participants used *WaterJewel* for a total of 168 days and *Carbodroid* for a total of 159 days. *Carbodroid* was used for a total of 9 days less, because 4 participants did not use *Carbodroid* on single days.

**Personal fluid intake behaviour** To assess the personal fluid intake behaviour of the participants in a natural way before the study, we asked for the number of glasses (200-250ml) the participants usually drink for breakfast, lunch, dinner, and inbetween. Participants stated they drink on average 5.96 (SD = 1.94) glasses of liquid per day. If we assume that a glass contains 200-250ml, this makes approx. 1192-1490ml. With regard to the recommendation of drinking at least 2 litres a day, these values indicate that the participants had difficulties to drink sufficiently.

Before the study, we also asked the participants from which container they usually take their drinks. 3 participants named a bottle, 1 named a big glass, and another one stated a small glass. 4 participants named a big glass and a bottle, and 3 participants named a small glass and a bottle.

**Fluid intake volume per day** On average, participants made drink entries for a total of 1995.54ml per day with *WaterJewel* (SD = 11.1, Mdn = 2000, Min = 1500, Max = 2000), and for a total of 1528.7ml per day with *Carbodroid* (SD = 345.22, Mdn = 1700, Min = 400, Max = 2000). To keep the results comparable, we excluded the totalling 9 days from these calculations on which *Carbodroid* was not used. Figure 5.8 shows a bar chart for the entered fluid intake volume per day

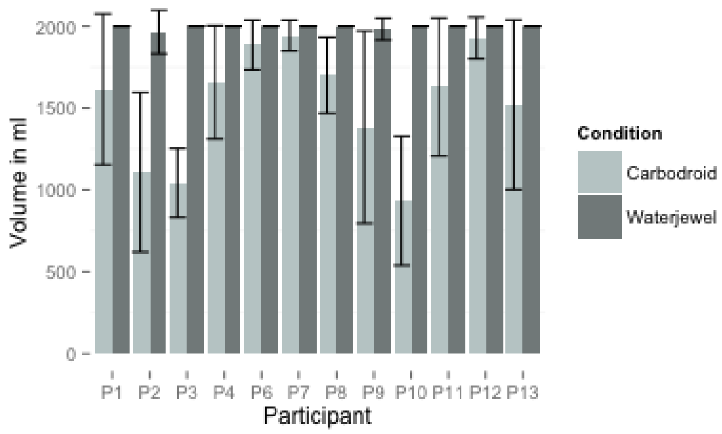



*Figure 5.8: Average entered fluid intake volume per day per participant*

per participant for *WaterJewel* and *Carbodroid*. A two-tailed t-test showed that this difference was significant ($p < 0.001$). Thus, hypothesis H1 is supported.

**Accomplishment to drink 2 litres a day** On average, the daily fluid intake goal of two litres was accomplished on 14/14 days (Mdn, Min = 13) in the experimental condition, and on 4.5/14 days (Mdn, Min = 0, Max = 10) in the control condition (see boxplots in Figure 5.9). A chi-square test showed that this difference was significant ($\chi^2 = 17.14$, df = 1, $p < 0.001$) and therefore supports hypothesis H2. When these results are interpreted it should be considered that 4 participants did not use *Carbodroid* on single days, i.e., altogether they did not use it for 9 days out of 168 days, on which these participants theoretically could have accomplished the daily goal. Participants also assessed this subjectively after the study. 6 participants thought *WaterJewel* was more successful in making them drink at least 2 litres a day, and 6 participants thought that there was no difference in their amount of drinks with regard to *WaterJewel* and *Carbodroid*.

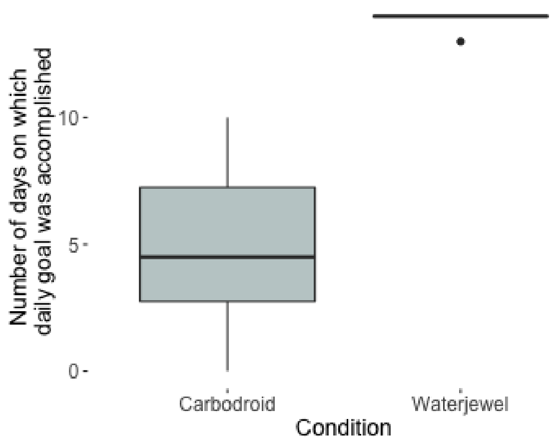



*Figure 5.9: Average number of days per participant on which at least 2 litres of consumed liquids had been entered*

**Regularity of fluid intake** On average, participants drank more regularly in the experimental condition (SD = 19.23), than in the control condition (SD = 103.53). Figure 5.10 shows the regularity of fluid intake for each participant in terms of the standard deviation for all timeframes between two drink entries. A two-tailed t-test showed that this difference was significant ($p < 0.001$). Therefore, hypothesis H3 is supported. This result is supported by the subjective assessment by the participants themselves after the study. 10 participants thought they drank more regular with *WaterJewel*, and 2 participants thought that there

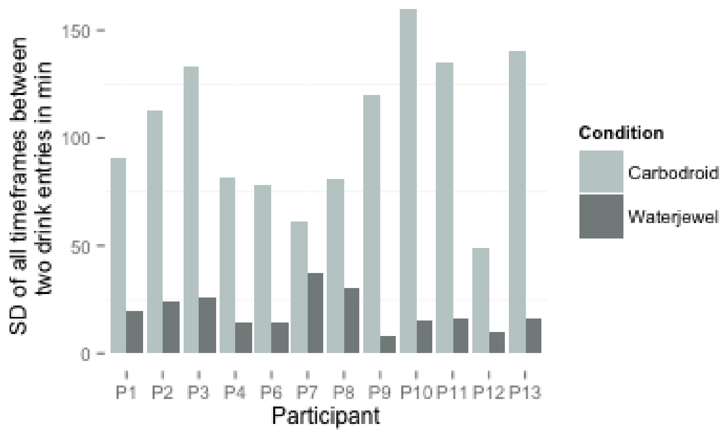



*Figure 5.10: Regularity of fluid intake per participant*

was no difference in their fluid intake regularity with regard to *WaterJewel* and *Carbodroid*.

**Interval of fluid intakes** On average, participants drank every 94.01 minutes (SD = 11.52) in the experimental condition, and every 140.03 minutes (SD = 36.74) in the control condition. A two-tailed t-test showed that this difference was significant ($p < 0.01$). With regard to the colour of the reminder display of *WaterJewel*, 94 minutes that elapsed since the last drink entry were displayed as a mid orange.

Of all the drinks participants entered in the experimental condition, they made 95.63% prior and 4.37% after the reminder event. Of all drinks they entered in

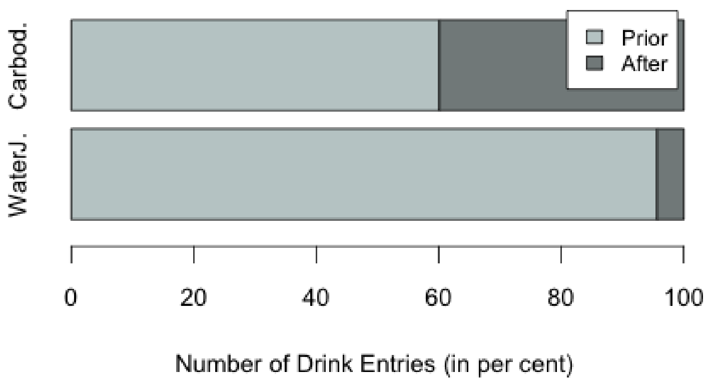
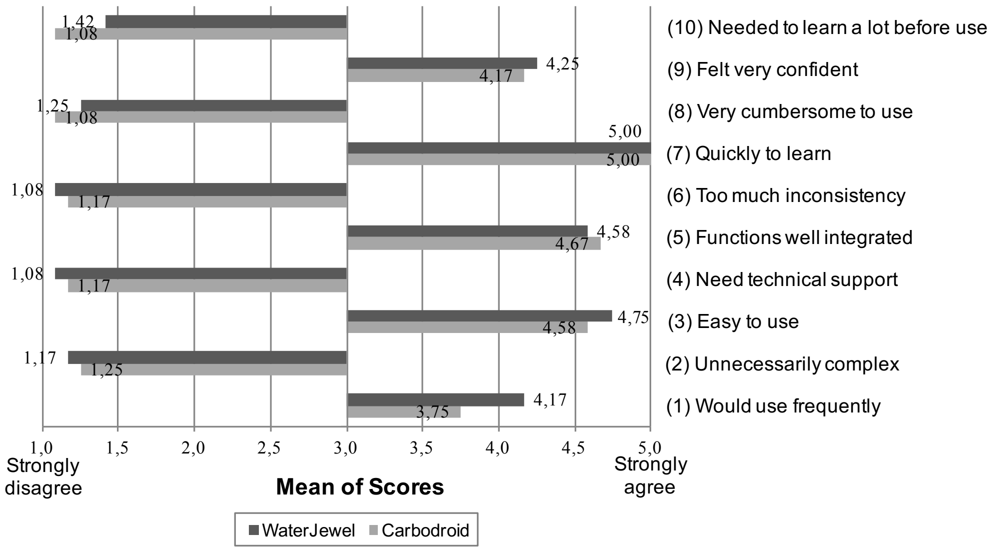



*Figure 5.11: Drink entries that were made prior and after the reminder event with* WaterJewel *(bottom) and with* Carbodroid *(top)*

the control condition, participants made 60.1% prior and 39.9% after the reminder event (see Figure 5.11). A chi-square test showed that this difference was significant ($\chi^2 = 335.35$, df $= 1$, $p < 0.001$) and therefore supports hypothesis H4.

**Usability Rating** The SUS scores were averagely 91.88 (SD = 6.84, Mdn = 93.75) for *WaterJewel* and 91.04 (SD = 5.69, Mdn = 90) for *Carbodroid*, i.e., both systems were rated as excellent in usability with only a very small difference for the benefit of *WaterJewel*. A two-tailed t-test could not show that this difference is significant ($p = 0.71$). Figure 5.12 shows the mean values over all participants for the single scores of the SUS. All scores were distinctly above-average. For the aspect frequency of use, both systems received their proportionally worst scores (*Carbodroid* 3.75, *WaterJewel* 4.17). Quick learnability received the best scores for both systems (*Carbodroid* 5, *WaterJewel* 5).




(1) I think that I would like to use this system frequently.
(2) I found the system unnecessarily complex.
(3) I thought the system was easy to use.
(4) I think that I would need the support of a technical person to be able to use this system.
(5) I found the various functions in this system were well integrated.
(6) I thought there was too much inconsistency in this system.
(7) I would imagine that most people would learn to use this system very quickly.
(8) I found the system very cumbersome to use.
(9) I felt very confident using the system.
(10) I needed to learn a lot of things before I could get going with this system.

*Figure 5.12: Diagram of mean values for the single scores of the SUS. All scores were above-average and the overall usability was rated as excellent for both systems.*

**Comfort Rating** The comfort of *WaterJewel* was rated with the CRS. Participants rated how they perceived each of the six dimensions *Emotion*, *Attachment*, *Harm*, *Perceived change*, *Movement*, and *Anxiety* on a 20-point scale from *low* (= 1) to *high* (= 20). The CRS were analysed individually. The lower the rating for a dimension, the more comfortable *WaterJewel* was perceived with regard to this dimension. Figure 5.13 illustrates the ratings of the single dimensions as boxplots. In general, the CRS received very low ratings, i.e., no major comfort issues have been identified. *Harm* and *Anxiety* were rated extremely low (for both Mdn = 1, Min = 1, Max = 4), i.e., the damage to the body and anxiety regarding safety and reliability caused by *WaterJewel*. *Emotion* (Mdn = 3, Min = 1, Max = 14), *Movement* (Mdn = 3, Min = 1, Max = 14), *Perceived Change* (Mdn = 3.5, Min = 1, Max = 16), and *Attachment* (Mdn = 5, Min = 3, Max = 18) received slightly higher ratings. *Emotion* describes how worried the user felt regarding her appearance when wearing *WaterJewel*. *Movement* assesses how *WaterJewel* affected or restricted the way the user moved. *Perceived Change* means the physical change the user felt when wearing *WaterJewel*, and *Attachment* describes how the user felt *WaterJewel* on her body.

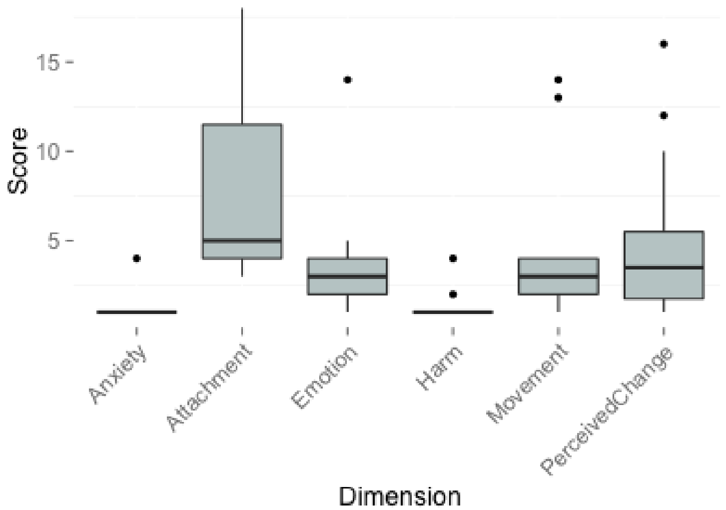



*Figure 5.13: Individual ratings of the CRS for* WaterJewel

### Qualitative Results

**Situations which participants experienced during the study** We asked the participants in which situations they carried the smartphone and wore *WaterJewel*. These situations were classified by locations, such as the office, in a lecture, the library, at home, in the street, in a medical practice, the cinema, a restaurant, at the zoo, or in the train. Participants also named various audiences, such as family and friends, colleagues, acquaintances, and public, as well as different activities they performed, such as working, meeting friends, partying, eating, watching TV, doing housework, doing handiworks, shopping, or cycling. Participants did not wear the devices during sports, or when they came in contact with water.

**Location of the participants' smartphones** During the study, participants carried their smartphones in various places. We identified two wearing patterns, i.e., participants who carried their phones directly on their body and participants who carried their phones in bags. Concretely, 7 participants (5 males) carried their smartphone either in their trousers or jacket pocket or put it on a table next to them. 5 participants (4 females) carried their smartphone either in a bag or kept it close by on the table.

**Visibility of *WaterJewel* during the study** We asked the participants how visible they had worn *WaterJewel* during the study. In general, participants wore *WaterJewel* in a clearly visible way on their wrist. Some participants mentioned that the bracelet was not visible outdoors when they wore a jacket which covered the bracelet. One participant said she intentionally covered the bracelet on the wrist during a cinema show because the bracelet's light was too bright and obtrusive. Most participants stated they hid the additional armlet under their clothes, particularly when they were in public environments. Reasons were the apparent and prototypical appearance of the technical components. Participants said they did not want to unsettle other people who might have thought they were ill or dangerous.

**Reasons for difficulties in drinking regularly and sufficiently** Participants reported they had difficulties in drinking sufficiently and regularly when they were on the way or experienced a stressful working day. This was due to the absence of drinks or because participants were short of time. With regard to *Carbodroid*, participants mentioned situations in which they forgot to carry their smartphone, were not motivated to fetch the phone from another room, in which the smartphone battery was flat, and in which the triggered vibration was inappropriate in a way that they could not react to it. Several participants reported they sometimes did not notice the vibration of the phone. Thus, they forgot to drink, or added a drink belatedly. One participant stated she had difficulties to drink regularly at school and at work, where she was not allowed to use a smartphone.

**Preference and Comfort** On the precondition that *WaterJewel* was a finished product with less prototypical appearance and all components integrated into the bracelet, 8 participants preferred *WaterJewel* to *Carbodroid*, 3 preferred *Carbodroid*, and 1 liked both systems. As the reason for the perceived impact on movement, perceived change, and for the sensing of the attachment, that participants rated using the CRS, they gave the armlet and the cable which connected the bracelet with the hardware components on the armlet. In addition, some participants stated they worried about that they could demolish the prototype. As the main reason for the perceived worry about their appearance (= *Emotion*), participants named the overall prototypical appearance of *WaterJewel*.

*Carbodroid* was experienced as easy to handle and intuitive. A participant was especially motivated by the illustration of the app character. He said he liked to fill up the character and thus drank more than usually. A female participant experienced *Carbodroid* as unnecessarily playful. As a big drawback of the application participants mentioned that *Carbodroid* reminded to drink every two hours, no matter if the user drank in the meantime. Besides, participants criticised that *Carbodroid* automatically reset all input values at midnight, no matter how the circadian rhythm of the user was.

All participants liked the appearance of *WaterJewel* in terms of a decorative bracelet and especially mentioned the advantage that it was always in the view, did not need to be fetched or could not be forgotten like a smartphone and was very intuitively to use. The green light spot of the volume display was experienced as a motivating sense of achievement. All participants commended that the reminder display allowed continuous awareness of the time elapsed since the last intake and thus helped to drink in an anticipatory way. Several participants added they would not need the additional vibration signal. E.g., a participant reported that she drank in an orange lighting phase because she knew the upcoming appointment would overlap the red lighting phase. However, one participant experienced *WaterJewel* as pushing because he felt stressed by the red light of the reminder display. Furthermore, participants appreciated that – in contrast to *Carbodroid* – the countdown for the fluid intake reminder of *WaterJewel* was reset when the user had entered a drink.

#### 5.1.3.5 Discussion

In summary, the results show that *WaterJewel* helps to improve the fluid intake behaviour with respect to the presented study conditions. *WaterJewel* performed significantly better in fluid intake volume (H1), accomplishment of the daily fluid intake goal (H2), fluid intake regularity (H3), and fluid intake interval (H4) compared to *Carbodroid*. The participants found *WaterJewel* usable, appreciated its decorative appearance, and in general felt comfortable with it due to its unobtrusive character. Most participants preferred *WaterJewel* to *Carbodroid* for daily fluid intake support.

The study revealed that *WaterJewel* in particular impressed by its convenience in terms of a wearable technology which is ever-present, unobtrusive, decorative, and integrated into an object which is often worn anyway in everyday life. Especially the reasons participants named for not performing well while using

*Carbodroid*, such as not being motivated to fetch the device, having forgotten the device, or having missed the phone's vibration, plead for the use of a wearable device with an always perceivable display, such as *WaterJewel*. A central finding was that a continuously illuminated light display such as of *WaterJewel* is well-suited to serve as a reminder in daily life, and to support drinking more regularly. Furthermore, it allowed drinking in an anticipatory way, i.e., users could plan their fluid intake and could prevent being in situations in which they need to drink but the situation does not allow them to. We found participants averagely drank when the reminder of *WaterJewel* displayed a mid-orange, i.e., they drank every 94 minutes. Overall, with *WaterJewel* they typically drank prior to the reminder event. It may thus be concluded that participants actively made use of the continuous information presentation. With regard to fluid intake reminders, the study showed these should factor in the user's circadian rhythm, his/her actual drinks and a selectable drinking unit, e.g., from different glass sizes. Reminders based on onetime signals should repeat or encourage the signal if the user does not react.

Our study results reflect the participants' fluid intake behaviour on the basis of drink entries that participants made independently. We assume, participants made the entries to the best of their knowledge, but still this cannot be guaranteed. Besides, some results have to be interpreted carefully. The measures "fluid intake regularity" and "fluid intake interval" might be influenced by belatedly added drinks in the *Carbodroid* condition, for the benefit of *WaterJewel* (see section on qualitative results). Although our study was reasonably long compared to the related work, we cannot be sure that we were successful in overcoming the novelty effect. However, a potential novelty effect would have been present for both conditions, albeit less intense in the *Carbodroid* condition because all participants were used to a smartphone. The findings from the evaluation study are based on the experiences and behaviours of a duration of two weeks. We do not know if and how experiences and behaviours do change when SDJ is worn for a longer period and becomes a natural everyday object.

The current approach is limited in that intakes have to be entered manually. Also, drinking unit and daily goal are fixed to standard values. In a practical setting, serving sizes may vary and daily goals might differ due to age, illness or physical activity. However, having a look at current developments we think that, in future, wearable activity recognition applications and physiological sensors such as sticking hydration sensors will be used to automatically detect fluid intake needs and thus make user input unnecessarily.

Our current *WaterJewel* prototypes do not yet fulfil all requirements, in particular with regard to aesthetics. Although we designed two decorative bracelets, we could not implement them with a sufficiently decorative appearance that is required for a piece of jewellery. E.g., the discreet integration of all hardware components into the bracelet itself would allow a much more convenient use in everyday life. These limitations are due to the bracelet's prototypical status.

Further, worthwhile improvements seem to be the adjustment of the display's brightness due to lighting conditions in the environment.

### 5.1.4 Conclusions

In this work, we found a lighting-up bracelet to be an effective tool to promote a better fluid intake behaviour in everyday life. We demonstrated the design process of the interactive, decorative bracelet *WaterJewel*. A four weeks field experiment showed that with *WaterJewel*, participants drank more in total, more often accomplished the daily fluid intake goal of 2 litres, drank more regularly, and drank more often prior to the reminder event than with a prevalent mobile fluid intake reminder application. Participants rated *WaterJewel* as very usable, and especially highlighted it as pleasing thanks to its form. Our results indicate that the always perceivable reminder display of *WaterJewel* enables constant awareness of the personal fluid intake behaviour. We argue that the implementation of motivational and reminder applications in terms of a presentable and always-in-the-view wearable technology is very promising. We think that such wearable technologies could be a useful complement of mobile applications or could even replace them, according to the desired information depth. Our qualitative study results provide recommendations for a suitable and appealing design of fluid intake reminders and wrist-worn light-based SDJ.

This section contributes to the thesis' research questions as follows. We found a lighting up bracelet to be a suitable form for SDJ. Our investigations showed that preferences regarding the form and appearance of a bracelet differ distinctly between females and males. Generally, users expect a high degree of customisability with regard to form and appearance (research questions Q2). Light was found to be well-suited to notify and present information on wrist-worn SDJ. Through the Volume Display, countable units could be intuitively encoded by the number of illuminated light sources. A continuously illuminated light source with gradual colour changes over an interval of two hours, i.e., the Reminder Display, increased awareness and remained unobtrusive at the same time. Further, the evaluation results showed that the brightness of a SDJ's light display should adapt to lighting conditions to ensure the user feels comfortable in various environments. That means, in dark lighting conditions, the light display should be dimmed, whereas in bright lighting conditions, the light display should be bright. Vibration used as additional signal to support the light feedback for critical information was found to be unnecessary for most participants, but did also not disturb when it was triggered (research question Q3). With regard to user input, a push button is well-suited for simple input instructions. In the evaluation study, users successfully controlled two functions by either a long or a short push on a button (research question Q4).

This work contributes to the field of wrist-worn informational displays and self-tracking technology. By means of the concrete use case of a fluid intake reminder, we have shown that its implementation in terms of wrist-worn SDJ is a promising approach to integrate wearable technology unobtrusively into everyday life. Furthermore, we have shown that this technology is usable for self-tracking in everyday life and inspired participants to perform a specific behaviour.

A fluid intake reminder is one use case for a personal everyday reminder. We assume, *WaterJewel* and similar wearables can also be appropriate for other everyday activities for which the regularity of actions is important, like being physically active, eating, or medication. Also, onetime reminders which remind of, e.g., closing the window, removing the tea bag from the water, or taking the cake out of the oven seem to be potential use cases for a continuous light-based information display, such as *WaterJewel's* reminder.

## 5.2 Enhancing Comfort through Adaptivity

From the work presented in the last section, we learned that the context in which wrist-worn light-based SDJ is worn changes the degree of comfort a wearer feels. While the information displayed on the light display is important for the users themselves, it can cause discomfort and can confuse bystanders when displayed in a conspicuous way. Consequently, the unobtrusiveness of a persuasive device has been identified as an important design goal [CML09]. However, it has not been researched yet how information should be presented on wrist-worn light-based SDJ in order to meet this design challenge. In this section, we explored the effect of the light's brightness on user and observer experience. We present a study, in which we investigated if and how wrist-worn SDJ is perceived differently when the brightness of its light display adapts to a current situation.

In the following, we give a brief introduction into related research in the field of context-aware wearable systems. Context awareness is an important feature of a wearable user interface [KS03, DSAF99, Sta01a]. Dey [Dey01] defines context as

> *"[...] any information that can be used to characterise the situation of an entity [...], that is considered relevant to the interaction between a user and an application".*

Furthermore, he defines that

> *"a system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task".*

Dey lists three categories of features that a context-aware application can support, which are:

- presentation of information and services to a user,
- automatic execution of a service for a user, and
- tagging of context to information to support later retrieval.

In his list of four ideal attributes of a wearable device, Starner [Sta01a] defines that a wearable device must observe the user's environment to provide the best cognitive support for the user. A wearable device should adapt its interaction modalities based on the user's context, and it should augment and mediate interactions with the user's environment.

In previous work, several context-aware wearable displays have been presented. Rhodes [Rho97] introduced the *Wearable Remembrance Agent*, a system with a heads-up display that provides notes to the user that might be of relevance at a certain moment. The captured context information is, e.g., the time-stamp, the user's physical location, and which persons are around. Rhodes investigated which kind of information should be presented in a specific context. Kern and Schiele [KS03] investigated whether or not to notify the user in a specific context and if so, through which modality. They classified the context according to five factors: the importance of the event that is being notified (a), the user's activity (b), the social activity (c), the social situation (d), and the location (e). They present a model to classify typical situations with regard to the interruptibility of the user and that of the environment. Also, they map these interruptibility classes to appropriate notification modalities, which are vibration, beep, ring, speech message, a watch display, and a head mounted display. With their work on speech and audio interactions, Sawhney et al. explored, in which level of detail information should be presented in a specific context [SS00].

*WaterJewel* uses light to present information. Previous work on wearable light displays found that the light's brightness has a big influence on the perceived obtrusiveness of the display [BLB12, LSHH11]. In the following study, we use the light's brightness of *WaterJewel* to regulate the obtrusiveness of the display dependent on the event the user is currently taking part in. We enable users to change the bracelet's appearance, i.e., the brightness of the Reminder LED, according to an ongoing calendar event. The ongoing calendar event defines the context to which the brightness of the light adapts. This section contributes to research question Q3 of this thesis, i.e., how information can be presented on wrist-worn SDJ. We present an adaptive version of the fluid intake reminder bracelet *WaterJewel*, that implements context awareness by connecting the LED's brightness level to calendar events. We studied how the adaptive display will change the bracelet's usability and user experience, i.e., how users and observers perceive the adaptive bracelet with regard to emotions, attractiveness, and identity in comparison to a non-adaptive version of the bracelet.

We found that participants experienced the adaptive bracelet as being significantly more *stylish*, *presentable*, and *pleasant*. Observers felt significantly happier when looking at an adaptive bracelet than when looking at a non-adaptive bracelet. Also, observers could identify significantly better with the adaptive bracelet and found it significantly more attractive than a non-adaptive bracelet.

The section is structured as follows. First, we describe the implementation of the adaptive light bracelet. We then present a field study, in which we investigated the effect of context awareness on *emotions*, *attractiveness* of the display, and *identification* with the bracelet. After discussing our findings, we conclude the section with a summary of insights and the key contributions.

### 5.2.1 The Adaptive Light Bracelet

For the study, we expanded *WaterJewel* by context awareness capabilities. The *WaterJewel* bracelet was accompanied by an Android application that connects to the bracelet via Bluetooth. After an initial pairing the application automatically connects to the bracelet whenever it is in reach. This application is able to control the brightness of the Reminder LED at three different levels, which can be mapped directly to certain obtrusiveness levels as follows:

**Level #1** switched off – unobtrusive

**Level #2** low brightness – less obtrusive

**Level #3** full brightness (default) – obtrusive

Instead of using a custom user interface, we linked the application to the device's calendar. This allows users to specify the brightness (obtrusiveness) of the Reminder LED in the title of a calendar entry, e.g., *Tea-Time with Granny #2*, thereby making the bracelet adaptive to individual calendar entries. Here, a calendar event defines the context. When a new calendar event starts, the brightness of the Reminder LED is updated immediately according to the digit placed after the hash mark in the event's title. When there is no calendar event defined in the user's calendar application, the LED's brightness will be set to the default value, i.e., the brightest level.

### 5.2.2 Field Evaluation Method

The earlier study of *WaterJewel*, presented in the previous sections, and related work found that a light's brightness has a major influence on the perceived obtrusiveness of a display [BLB12, LSHH11]. However, how exactly a display should adapt brightness in practice, and how in detail an adaptation changes the human's perception of the display, remains unclear. In this study, we adopt the idea to modulate the display's brightness and study how an adaptive Reminder LED changes the overall perception of the bracelet. In detail, we investigated how users as well as observers experienced the bracelet in everyday situations in terms of perceived emotions, identification with the bracelet, and perceived attractiveness of the bracelet. We chose these measures because they are established measures to assess user experience. They are, e.g., integrated into standard questionnaires, such as the AttrakDiff [HBK03], and referred to in international standards, such as the ISO 9241-210 [ISO10], in which emotions are explicitly named as determining factor with regard to user experience. In detail, we investigate the following hypotheses:

**H1** An adaptive display positively affects the perceived *emotions* when confronted with the bracelet.

**H2** An adaptive display positively influences how people *identify* with the bracelet.

**H3** An adaptive display positively changes the perceived *attractiveness* of the bracelet.

Because our goal was to study the adaptation on a wearable device, we studied the hypotheses from two perspectives. On the one hand, we studied each hypothesis for the participants of our study, i.e., the wearers of the device, which we refer to as **H1P**, **H2P**, and **H3P**. On the other hand, we investigated the hypotheses for the external observers of the system, which we refer to as hypotheses **H1O**, **H2O**, and **H3O**.

#### 5.2.2.1 Participant Questionnaire

To measure the *emotions* (**H1P**), the *identity* (**H2P**), and the *attractiveness* (**H3P**), we decided for subjective feedback through a custom questionnaire. This questionnaire is supposed to be answered in-situ and while or just after actually using the bracelet. Therefore, it first asks for details about the situation, i.e., date, time, place, lighting conditions, and the type of persons who accompany the participant, e.g., the public, family members, or nobody. Further, the participant was asked if he or she perceived the brightness of the Reminder LED during the situation as suitable on a 7-point Likert scale, ranging from *disagree* (1) to *agree* (7). As measures for emotions, identity, and attractiveness, we integrated parts of two established standard questionnaires, i.e., Differential Emotions Scale (DES) [IDBK74] and AttrakDiff [HBK03], into the questionnaire. The part that was inspired by the DES consists of a set of 8 statements about emotions, e.g., *"I felt surprised"*, and could be rated on a 7-point Likert scale, ranging from *disagree* (1) to *agree* (7). We chose the DES because we were especially interested in the emotions perceived towards the bracelet, and the DES is a validated instrument to assess these. The AttrakDiff alone would not have covered emotions extensively. Further, the questionnaire comes with 13 contrary word pairs, e.g., *isolating/connecting*, which were taken from the AttrakDiff questionnaire and measure the hedonic quality and attractiveness of a used device. In detail, 6 of these pairs measure the *identity* (HQ-I), and 7 of these pairs measure the *attractiveness* (ATT). The attributes from the AttrakDiff are rated on a 7-point scale ranging from the first word (1) to the second word (7). A full list statements and word pairs can be found in Table 5.1.

#### 5.2.2.2 Observer Questionnaire

With the participant questionnaire we measure how an adaptive bracelet changes the emotions of a participant, i.e., the wearer of the bracelet, how he or she identifies with the bracelet, and how it attracts him or her. However, to get a holistic understanding, we also studied how these three aspects change for observers. The aspects need to be studied to provide answers to hypotheses **H1O**, **H2O**, and **H3O**. An observer is a person that stays in the proximity of the wearer by accident. The duration of an observation can vary.

Observers completed the same questionnaire as an online version with further details, such as a study participant identifier and a unique, alphanumeric nickname, which the observer could freely decide on. These values allowed mapping all questionnaire responses. Observers could be made aware of the online questionnaire through a study participant, who was wearing the bracelet. The awareness could be created using a *link card*, which is a paper card that comes with instructions, a written link as well as a QR code to the online questionnaire, and the unique, numeric identifier of the study participant who handed the card (see Figure 5.14, top).

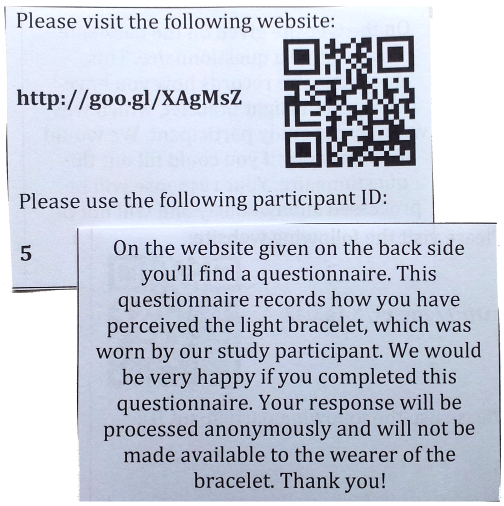



*Figure 5.14: Observers were provided with link cards that come with a link to an online questionnaire (top). These allow to capture the observer's experiences and impressions regarding the bracelet. Link cards were originally provided in German.*

#### 5.2.2.3 Design

We designed the study as a within-subjects, repeated measures experiment with two conditions. One condition is the earlier described light bracelet with adaptiveness, i.e., the brightness of the Reminder LED can be controlled. The other condition is the light bracelet without any adaptation features, i.e., the default brightness is used. We counter-balanced the conditions. Thus, half of the participants started with an adaptive, the other half with a non-adaptive bracelet.

#### 5.2.2.4 Participants

We acquired 18 participants, of which 2 stopped their participation after a few days for personal reasons. The remaining 16 participants had an average age of 26.1 years (SD = 3.79 years), ranging from 20 to 37 years. 8 of the participants were male, and 8 were female. They were recruited from the local university, and through public announcements. None of the participants was related to the research team. Participants had an average daily fluid intake of about 1.5 litres (SD = 0.50 litre), ranging from less than 1 litre to 3 litres. 12 participants reported that they wanted to increase their fluid intake, 3 were undecided, and 1 participant reported no interest in increasing fluid intake.

#### 5.2.2.5 Procedure

At the beginning of the study, participants signed an informed consent and completed a demographic questionnaire. We introduced and set up the light bracelet with the corresponding application on the participants' smartphones, and they got some time to become familiar with the system. Also, we explained how participants could specify the brightness of the Reminder LED when entering a new calendar event in their favourite calendar application.

Participants were handed 40 of the earlier described paper questionnaires and 40 of the link cards. We asked the participants to complete approximately three of the questionnaires per day and after varying situations, e.g., after a business meeting or after taking the metro. Further, we asked participants to hand out approximately three of the link cards per day. These should be handed to observers, i.e., colleagues, friends, or any other persons who experienced any kind of situation together with the study participant wearing the light bracelet.

Each participant used the light bracelet for a total of two weeks during his or her daily routine. Figure 5.15 shows a male participant wearing the light bracelet during the study. Half of the participants started with an adaptive bracelet, i.e., the brightness of the Reminder LED could be controlled. The other half started with a bracelet that had no adaptation features, i.e., the default brightness was used. After the first week, the condition changed for all participants. During the study, we conducted two interviews with each participant, one after each week.

*Figure 5.15: Male participant wearing the light bracelet during the study. On his upper arm he wears an additional armlet that contains the controlling hardware, which is whipped with black felt for decorative reasons.*

We asked for overall impressions and went through the completed questionnaires participants brought with them, so that they could elaborate on striking situations. Furthermore, participants completed the well-established System Usability Scale (SUS) after each week. After the second interview we collected all handed materials, supported participants in deleting the app that controlled the light bracelet, clarified on remaining questions, and thanked the participants. Each participant was rewarded with 25€.

### 5.2.3 Quantitative Results

In the following, we report our key quantitative findings, whereby a full representation of the results can be found in Table 5.1. For both, i.e., participants who wore the bracelet and observers, we report on changes in emotions, identity, and attractiveness. We used one-sided Wilcoxon signed rank tests for all statistical investigations, because we expected only positive effects of the context awareness.

#### 5.2.3.1 Participants

Of the 640 handed questionnaires (40 questionnaires for each of the 16 users), 416 (65%) were completed and returned. Of these, 218 were completed when using the bracelet in the control condition and 198 when using it in the exper-

| | Statement | Participant Contr. | Participant Exp. | Participant Sign. | Observer Contr. | Observer Exp. | Observer Sign. |
|---|---|---|---|---|---|---|---|
| Differential Emotion Scale | I felt happy. | 3.43 | 3.45 | n.s. | 3.62 | 4.69 | 0.01 |
| | I felt surprised. | 2.24 | 2.24 | n.s. | 4.15 | 5.31 | n.s. |
| | I was annoyed. | 2.13 | 2.13 | n.s. | 1.54 | 1.56 | n.s. |
| | I was ashamed. | 1.42 | 1.40 | n.s. | 1.15 | 1.31 | n.s. |
| | I felt guilty. | 1.26 | 1.21 | n.s. | 1.00 | 1.44 | n.s. |
| | I was feared. | 1.12 | 1.08 | n.s. | 1.00 | 1.19 | n.s. |
| | I was interested. | 3.11 | 2.82 | n.s. | 5.39 | 6.00 | n.s. |
| | I was sad. | 1.12 | 1.07 | n.s. | 1.08 | 1.31 | n.s. |
| AttrakDiff, HQ-I | isolating/connective | 4.03 | 4.13 | n.s. | 3.92 | 5.00 | 0.01 |
| | tacky/stylish | 3.17 | 3.42 | 0.05 | 2.85 | 4.00 | 0.05 |
| | cheap/premium | 3.35 | 3.43 | n.s. | 3.23 | 4.25 | 0.05 |
| | alienating/integrating | 3.99 | 4.06 | n.s. | 3.92 | 4.94 | 0.01 |
| | separates me/brings me closer | 4.01 | 4.11 | n.s. | 3.92 | 5.19 | 0.01 |
| | unpresentable/presentable | 3.48 | 3.71 | 0.05 | 3.00 | 3.75 | n.s. |
| | average | 3.67 | 3.81 | n.s. | 3.47 | 4.52 | 0.01 |
| AttrakDiff, ATT | unpleasant/pleasant | 3.38 | 3.58 | 0.05 | 3.31 | 4.44 | 0.05 |
| | ugly/attractive | 2.95 | 3.21 | n.s. | 2.85 | 3.63 | n.s. |
| | disagreeable/likeable | 3.73 | 3.90 | n.s. | 4.08 | 5.13 | 0.05 |
| | rejecting/inviting | 3.97 | 4.01 | n.s. | 3.92 | 4.75 | 0.05 |
| | bad/good | 4.11 | 4.23 | n.s. | 4.46 | 5.38 | 0.05 |
| | repelling/appealing | 3.77 | 3.86 | n.s. | 3.85 | 4.75 | 0.05 |
| | discouraging/motivating | 4.56 | 4.45 | n.s. | 4.31 | 5.38 | 0.05 |
| | average | 3.78 | 3.89 | n.s. | 3.82 | 4.77 | 0.01 |

*Table 5.1: An overview of all quantitative observations for participants and observers. Ratings on the Differential Emotion Scale were given on a 7-point Likert scale, ranging from disagree (1) to agree (7). Responses to AttrakDiff pairs ranged from the first word (1) to the second word (7).*

imental condition, in which it provided context awareness. 97 questionnaires were answered for situations in which participants were alone, 62 when they were in public among strangers, 59 when they were with friends, 57 when they were with family, 9 when they were with colleagues, 4 when supervisors were present, and in 4 cases the participants did not provide us with details about the situation. The remaining 124 questionnaires were answered in combinations of the above-mentioned situations, mostly when participants were moving in public, accompanied by family or partners. According to the free text answers about the place, most participants stated they used the bracelet at home or at work.

In the questionnaires, participants were asked to assess the appropriateness of the Reminder LED's brightness. In the control condition, i.e., without context awareness, participants rated the appropriateness with 4.82 (SD = 1.35). In contrast, participants rated the appropriateness with 5.90 (SD = 1.08) in the experimental condition, i.e., about a full step better. This difference is significant ($p < 0.01$).

We asked participants to assess their emotions in the experienced situations, using a set of statements which were inspired by the Differential Emotion Scale (DES). Overall, they mostly stated similar emotion ratings for both conditions. The most notable difference between the conditions was observed for the rated interestedness, where the control-condition was rated with 3.11 (SD = 1.48) and the experimental condition with 2.82 (SD = 1.64). However, this and none of the other emotion statements showed any statistical significance.

The questionnaires further assessed how the participants identified with the bracelet, which was measured with the HQ-I part of the AttrakDiff questionnaire. On average, the HQ-I was 3.67 (SD = 0.86) in the control condition and 3.81 (SD = 0.95) in the experimental condition (see Figure 5.16). This difference is of no statistical significance. However, we observed that participants assessed the display as being more stylish in the experimental condition (M = 3.42, SD = 1.03) than in the control condition (M = 3.17, SD = 0.99). Further, participants assessed that the experimental bracelet was more presentable (M = 3.71, SD = 1.36) than the non-adaptive bracelet (M = 3.48, SD = 1.26). Both of these observations are of statistical significance ($p < 0.05$).

As a third parameter, the questionnaire assessed the perceived attractiveness of the system, which was measured with the ATT part of the AttrakDiff questionnaire. Overall, participants tend to agree that the bracelet is similarly attractive in both conditions, i.e., experimental 3.89 (SD = 1.06), control 3.78 (SD = 1.05). In detail, we found that participants rated the experimental system as significantly ($p < 0.05$) more pleasant to use (M = 3.58, SD = 1.60) than the non-adaptive system (M = 3.38, SD = 1.64, see Figure 5.16).

After each week, participants were asked to complete a System Usability Scale (SUS) questionnaire. We observed that in the control condition the light bracelet was rated with 80.63 (SD = 13.65), whereby it was rated with 79.22 (SD = 17.74) in the experimental condition. This difference is not significant.

#### 5.2.3.2 Observers

Altogether, the study participants issued 152 link cards to observers, 82 during the experimental condition and 70 while using the bracelet in the control condition. On average, each participant issued 5.13 (SD = 2.78) link cards in the experimental and 4.34 (SD = 3.48) in the control condition. 27 observers considered the link cards and completed a total of 29 online questionnaires, which results in a 19.08 % return rate. Of these observers, 11 classified themselves as friends of the study participants, 5 as strangers, 4 as family members, 4 as colleagues, and 3 as professional superiors. 16 completed questionnaires concerned

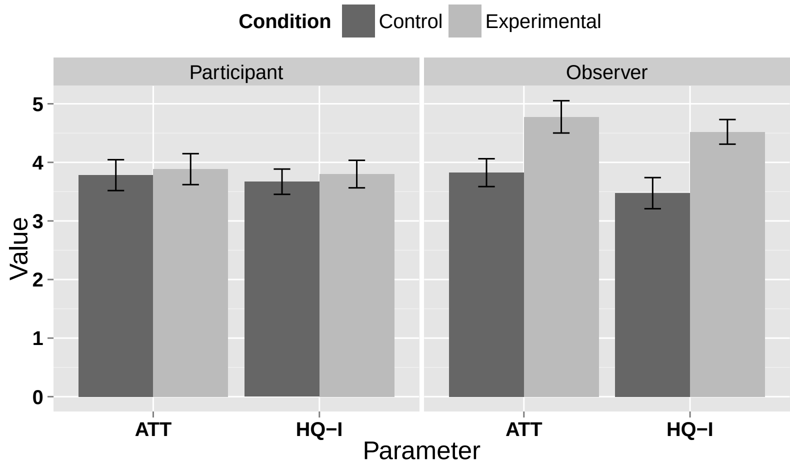



*Figure 5.16: For study participants we were unable to observe any significant differences regarding identity (HQ-I) and attractiveness (ATT). In contrast, we found significant effects for the attractiveness and identification observers perceived towards the bracelet. Error bars indicate the standard error.*

participants who were using the light bracelet in the experimental condition, 13 responses were assessing participants who used it in the control condition.

We found that observers felt significantly happier when facing an adaptive bracelet (M = 4.69, SD = 0.87) than facing the regular bracelet (M = 3.62, SD = 1.50, $p < 0.01$). Otherwise we did not observe any statistically significant changes in perceived emotions.

Regarding the identification of observers with the system, i.e., HQ-I, we observed that they overall tend to agree more in the experimental condition (M = 4.52, SD = 0.84) than in the control condition (M = 3.47, SD = 0.96, see Figure 5.16). This difference is statistically significant ($p < 0.01$). In detail, we found that observers rated the experimental system to be more connective (control 3.92, SD = 0.95; experimental 5.00, SD = 0.73; $p < 0.01$), more stylish (control 2.85, SD = 1.34; experimental 4.00, SD = 1.51; $p < 0.05$), more premium (control 3.23, SD = 1.64; experimental 4.25, SD = 1.19; $p < 0.05$), more integrating (control 3.92, SD = 0.76; experimental 4.94, SD = 0.77; $p < 0.01$), and less separating (control 3.92, SD = 1.04; experimental 5.19, SD = 0.98; $p < 0.01$).

We further found that the attractiveness (ATT) of the bracelet changes significantly, depending on whether it is adaptive or not. For the control condition observers agreed to the attractiveness with 3.82 (SD = 0.86) on average, whereby they agreed with 4.77 (SD = 1.10) in the experimental condition (see Figure 5.16). This difference is statistically significant ($p < 0.01$). In detail, the experimental condition was rated to be more pleasant (control 3.31, SD = 1.32; experimental 4.44, SD = 1.21, $p < 0.05$), likeable (control 4.08, SD = 1.32; experimental 5.13, SD = 1.45, $p < 0.05$), inviting (control 3.92, SD = 0.95; experimental 4.75, SD = 1.39, $p < 0.05$), good (control 4.46, SD = 1.20; experimental 5.38, SD = 1.26, $p < 0.05$), appealing (control 3.85, SD = 0.90; experimental 4.75, SD = 1.24, $p < 0.05$), and motivating (control 4.31, SD = 0.75; experimental 5.38, SD = 1.54, $p < 0.05$).

### 5.2.4 Qualitative Results

In the following we describe the qualitative insights that we gained from the interviews with the participants. For the analysis, interview notes were coded jointly by the interviewer and the study director.

#### 5.2.4.1 Overall Impressions

Overall, most participants liked the idea and the concept of the bracelets. Several participants mentioned they received positive feedback from friends, who said they would also like to use the bracelet as a fluid intake reminder. In general, ten participants would like to use the bracelet in future, with some saying it would have to be more sophisticated (P11, P03), more compact (P02) and pretty (P06). Four participants said they would not need it because they found they already drink enough. Two participants would prefer an app to a bracelet. Three participants stated they found the app annoying in the way that they had to check if the Bluetooth connection was available once in a while and in that they had to interact with the phone to, e.g., enter dates. Five participants mentioned they would have preferred to regulate the display's brightness directly with a button on the bracelet instead of with the app.

When we asked the participants for situations in which they would not wear the bracelet, they named various situations for different reasons. They stated situations in which the bracelet could be damaged, such as during sport activities, housework, in bed or when sweating due to hot temperatures. They also named situations such as festive occasions, burials, being onstage, at work and in a job interview, because in these situations the bracelet would not match the clothes and appearance. With regard to the condition in which the bracelet was not adaptive, a participant mentioned he felt uncomfortable wearing the bracelet at the dentist because it lighted brightly. Regarding the same condition, another participant reported that a lecturer wanted him to remove the bracelet during a talk.

#### 5.2.4.2 Perception of the Different Brightness Levels

Most of the participants said they in general appreciated the mapping of the different obtrusiveness levels to the different brightness levels. But, the preferences for particular brightness levels varied. In situations in which the brightness level was set to the brightest level #3, some participants complained about the light being too bright, in particular in dimmed or dark environments. Participant P06 explicitly said that he did not like that he could not switch off the display during the non-adaptive condition. However, with respect to brightness level #1, which meant the light was off, two participants said they did use it very rarely or never at all, because they disliked that the bracelet did not provide any feedback. Participant P10 found that brightness level #2 was the best choice in many cases. Another participant said he would be fine with brightness level #3 only. Two participants wished for one or to more levels, e.g., between brightness level #1 and #2 (P08).

#### 5.2.4.3 Perceived Difference Between the Conditions

Nine participants stated they did not consciously perceive a difference in the bracelet's display between the first and the second study week. Five participants said they consciously perceived a difference and appreciated that the brightness of the display could be adapted in the experimental condition. In the experimental condition two participants mentioned that, after a while, they got used to the bracelet and did not notice that they were wearing it.

#### 5.2.4.4 Impact on Fluid Intake Behaviour

After the study, 10 participants stated they drank more during the study than before. Two participants said they drank much more consciously. Another two participants felt confirmed by the bracelet in that it showed them they drink enough. During the study, situations occurred in which participants did not feel the display to be necessary. For example, a participant reported that during lunch he did not need the display because he drank anyway. However, fluid intake behaviour was not tracked in the study because it was not in the focus of this research. Effects on fluid intake behaviour have been investigated in previous work [FCHB14].

### 5.2.5 Discussion

The results show that participants, who wore the bracelet, and observers differed in their perception of the adaptive bracelet. Overall, participants rated the adaptive and the non-adaptive bracelet similarly. In the three ratings *stylish*, *presentable* and *pleasant* they rated the adaptive bracelet slightly higher. The ratings of observers were more marked. They rated the adaptive bracelet more positively than the non-adaptive bracelet in many aspects. Observers felt happier when facing an adaptive bracelet. In general, they could identify significantly better with the adaptive bracelet and found it to be significantly more attractive than the non-adaptive bracelet.

#### 5.2.5.1 Adaptation in General

Overall, participants liked the idea and concept of the bracelets. In general, they appreciated the mapping of obtrusiveness levels to brightness levels, but their preferences for particular brightness levels varied. Some participants reported that in the beginning they could hardly estimate how they should adjust the brightness levels, but after experiencing the light in situ it was much easier.

Five participants wished for a manual regulation of the bracelet's brightness directly on the bracelet. This shows that it is important that the device can be adapted to different contexts, but the adaptation does not necessarily need to happen automatically. During the study, situations occurred in which participants felt that the display of information was not necessary, e.g., while having lunch. This indicates that adaptation should not only be considered in terms of the presentation design, but also in terms of the information content that is presented. This implication fits in well with Starner's fourth ideal attribute of a wearable device: "Augment and mediate interactions with the user's environment" [Sta01a].

#### 5.2.5.2 Emotional Responses

We recorded the emotional responses to the bracelet from participants, i.e., wearers, and from observers, who were confronted with the participants and the bracelet in various situations. Our observations indicate that context awareness and the related brightness adaptation do not change the emotional responses significantly. Therefore, we have to reject **H1P** and **H1O**, and cannot argue that an adaptive light display improves perceived emotions for wearers or observers.

In the interviews, five participants said they appreciated that the brightness of the display could be adapted in the experimental condition. This indicates a positive emotional change towards the adaptive bracelet from the subjective view of at least five participants. We suppose that the set of statements we used according to the DES could be the reason for why the emotion ratings differed from the personal statements of participants. Of the eight emotions asked for, six were phrased negatively and only two positively, and the emotions were very hard. When comparing user interfaces that differ only slightly in particular aspects, the emotions asked for might not change significantly. Also, assessing the DES-oriented emotions in general might be difficult when evaluating a product because they focus on emotions we typically do not connect to products, such as being "feared" or "sad". Other emotions are not covered at all, e.g., the emotion described by "I appreciate that.", which participants stated in the interviews, cannot be mapped to one of the emotions we asked for in the DES-oriented questionnaire.

#### 5.2.5.3 Identification with and Attractiveness of the Bracelet

The issued questionnaire comes with a section to measure to what extent participants identify with the system. Further, another section measures the perceived attractiveness of the system while being worn by participants. Both sections were taken from the popular and established AttrakDiff questionnaire [HBK03]. Our findings indicate that there are no measurable significant differences in the identification with and attractiveness of the system, therefore we have to reject **H2P** and **H3P**.

Nevertheless, 5 of 16 study participants stated that they clearly noticed the difference between the default brightness and adapted brightness. Consensus was that the adaptation is highly appreciated and valued, particularly for sensitive situations, where the default brightness could be perceived as disturbing or distracting. The quantitative results indicate that participants found the adaptive bracelet significantly more stylish and more presentable. Therefore, we suggest to further research the effect of adaptation on the perceived attractiveness and identity.

#### 5.2.5.4 Observers' Perception of the Bracelet

In the study we investigated the bracelet from two perspectives: participants, who were actual wearers, and observers. We did this because earlier work in related fields showed that the perception of and reaction to wearable, interactive devices might differ significantly between these two groups.

We also asked observers to assess their identification with and the attractiveness of the bracelet with the same questionnaire that we handed over to study participants. Our results indicate that observers can identify with the bracelet significantly better in the experimental condition, i.e., when the bracelet is adaptive. Further, we found that an adaptive bracelet was assessed to be significantly more attractive to the observers. Consequently, we have to accept hypotheses **H2O** and **H3O**.

Overall, we can support the finding that wearers and observers of a device can get a different impression from a wearable device. On average, we did not observe a significant difference in HQ-I, i.e., identity, or ATT, i.e., attractiveness, for participants. However, we did find a significant difference for observers ($p < 0.01$). While the ratings between observers and participants are similar for the control condition, the observers seem to perceive the adaptation in a much more intense way, leading to a significant change in the perceived attractiveness and identity (see Figure 5.16).

We have the impression that observers are much more sensitive to minor changes, like the adaptation of an LED's brightness. We further think that their feelings and insights notably contribute to the overall acceptance and success of wearable technology, and that this aspect has been under-evaluated in the last few years. In fact, few details are known how exactly the observers' impressions drive their reactions, and how these reactions influence and change the participants' feelings. We therefore suggest that observers and the observer's perspective should become an essential aspect of future design processes and research.

### 5.2.6 Conclusions

In this section, we presented a field study of an adaptive light bracelet that serves as a fluid intake reminder. The study elaborated on the aspect, that users perceived the lights' brightness as too obtrusive in certain situations, which was learned from previous studies. In the study, 16 participants wore the bracelet in their everyday life for a total of two weeks each. In one week the bracelet adapted the brightness of the light according to an ongoing event. In the other week the bracelet did not provide adaptiveness and always presented the light in the same brightness level.

Our results show that overall, participants liked the bracelets and the possibility to adapt the light's brightness. We found participants did not significantly perceive the adaptive bracelet differently with regard to *emotions*, *attractiveness* and *identification*, apart from single ratings, i.e., they experienced the adaptive bracelet as being significantly more *stylish*, *presentable* and *pleasant*. The ratings of observers were more marked. They felt significantly happier when facing the adaptive bracelet, could in general identify significantly better with it and found it to be in general significantly more attractive than the non-adaptive bracelet.

The research presented in this section contributes to the thesis' research question Q3, i.e., how information can be presented on wrist-worn SDJ. From the study results we conclude, that, in general, integrating context awareness into wrist-worn light-based SDJ is a promising way to improve emotions towards SDJ, perceived *attractiveness* of SDJ, and *identification* with it. The adaptation of the lights' brightness level to user-preset values has shown to be experienced as positive by participants and in particular by observers. The results indicate that a sensible context adaptation could, e.g., be that during formal or business occasions the light is subtle (dimmed), whereas in private or public environments, the light is more conspicuous (bright). Our results will inspire designers and developers of wrist-worn light-based SDJ and - if implemented - will add to a higher acceptance of SDJ by users and observers. We assume, users will feel more comfortable using light-based SDJ in everyday life, observers will be less confused and less distracted, and that finally, this will increase the time lapse for which people use SDJ.

Social acceptability is a critical issue for wearable objects. People identify with things they were close to their body. Besides, many users care about how they appeal to observers, and the behaviour of observers towards the user influences the user's comfort. A wearable user interface that is not accepted by people in proximity is unlikely to be worn. From our experiences we conclude, that it is worthwhile to include observers in the design process and evaluation of wearable user interfaces because they can have different experiences than the actual users. Considering both, the user and observer perspectives, is particularly important when designing wearable interfaces as they are pervasive and thus influence all people in proximity.

In future work, it is worthwhile to integrate another button on the bracelet that allows to manually regulate the light's brightness, independently from the automatic brightness adaptation. To be able to improve automatic brightness adaptation, it is needed to investigate in which situations users tend to manually regulate the brightness, e.g., by measuring lighting conditions and location information. Furthermore, it would be interesting to investigate how the brightness level should adapt when it depends on both, lighting conditions as well as calendar events. Further, user input should be reduced in that calendar event titles are searched for certain keywords, so that the brightness level mapping can happen automatically.

## 5.3 Summary

In this chapter we presented our investigations on the design and performance of a fluid intake reminder bracelet named *WaterJewel*. In the first section, we described the design process of the bracelet and a field evaluation in which we explored the use of *WaterJewel* in daily life, and compared it to a prevalent mobile fluid intake reminder application. From the results, we gathered insights into the suitability of certain forms and appearances (research question Q2), information encoding (research question Q3) and interaction design of SDJ (research question Q4). We found that WaterJewel impressed as decorative, discreet, and practical SDJ, of which users expect a high order of customisability. Also, participants drank more in total and more regularly using the bracelet. Our results indicate that light is well-suited to present information on wrist-worn SDJ. A continuously perceivable light display enabled constant information awareness. A progress display in form of single light sources successfully conveyed countable units. With regard to user input, a push button was found to be well-suited for simple input instructions. Further, we found that the context in which wrist-worn, light-based SDJ is worn changes the degree of comfort a wearer feels, and that brightness has a major influence on the perceived obtrusiveness of a light display. Hence, in the second section, we explored if a lighting-up bracelet such as *WaterJewel* that changes its brightness according to the context of use does have an effect on user and observer experience in comparison to a non-adaptive version of the bracelet. The results indicate that users and – particularly distinct – also observers experienced the adaptive bracelet more positively (research question Q3). We conclude, that, in general, integrating context awareness into wrist-worn light displays by adapting brightness is a promising way to improve user and observer experiences. Overall, the results from the field studies presented in this chapter indicate that a sensible context adaptation could, e.g., be that during formal or business occasions the light is subtle (dimmed), whereas in private or public environments, the light is more conspicuous (bright). Further, the light should be dimmed in dark lighting conditions and bright in bright lighting conditions. If two conditions conflict, priority should be given to the less obtrusive choice. E.g., during a formal occasion with bright lighting conditions, the display's light should be dimmed. During a private cinema visit in dark lighting conditions, the display's light should be dimmed.

# 6 Enhancing Functionality with a Multi-Purpose Bracelet

Often, people demand for more than one application (see Section 3.3), e.g., they would like to be reminded about appointments, contact someone and at the same time keep track of their physical activity level. Three different pieces of *SDJ* could solve their needs. However, this solution would result in an unmanageable amount of objects that need to be carried. Also, the space on a human's body is limited, and aesthetical and comfort issues might conflict with wearing several objects at the same time. Multi-purpose *SDJ* could be a solution. While researchers proposed several concepts for single-purpose *SDJ* [WFC06, AM08, KG06], multi-purpose *SDJ* is underexplored. Xu et al. explored how multi-purpose smartwatches could display information on, e.g., time keeping, messaging, phone calls, calendar reminders, and fitness tracking through simple light spots and backlit icons [XL15] (see Chapter 2). Wrist-worn multi-purpose devices, such as smartwatches[1] and smartbands[2] have become popular. Typically these devices include small screens and offer features such as, e.g., notification, displaying text messages, reminder, alarm clock, and fitness tracking. However, besides their wearability, they have not much in common with *SDJ*, but are more a small wrist-worn and screen-based computer. With regard to the increased demand for multi-purpose devices, we need to explore the design of *SDJ* that integrates various features. So far, we lack an understanding of how to design multi-purpose *SDJ*.

Having a look at the jewellery market, we see modular, customisable bracelets are in vogue. The so-called charm bracelets consist of single links that are hooked on each other[3], hooked on a bracelet[4], or threaded on a bracelet[5] (see Figure 6.1). The modular concept of these bracelets allows customisation through the integration of miscellaneous elements.

In this chapter, we investigated how a smart digital multi-purpose bracelet should be designed in order to be attractive, functional, easily comprehensible, and easy to manage. This includes its appearance, functionality, information presentation, and interaction design. This chapter contributes to research questions Q2, Q3 and Q4 of this thesis from the perspective of multi-purpose SDJ. We present the requirements analysis for, the participatory design and the implementation of a modular multi-purpose bracelet that implements the applications non-verbal communication, reminder, and pedometer in form of "Tangible Apps". We present the *TangibleApps bracelet*, a proof of concept that illustrates how to integrate several applications into a single, decorative piece of jewellery (see Figure 6.2). We evaluated the bracelet prototype in a lab study with 20 participants

[1] http://www.sonymobile.com/de/products/smartwear/smartwatch-3-swr50/
[2] http://www.microsoft.com/microsoft-band/
[3] http://www.nomination.uk/composable_bracelet
[4] http://www.thomassabo.com/GB/en_GB/charmclub/charm-club
[5] http://www.pandora.net/de-de/explore/products/bracelets

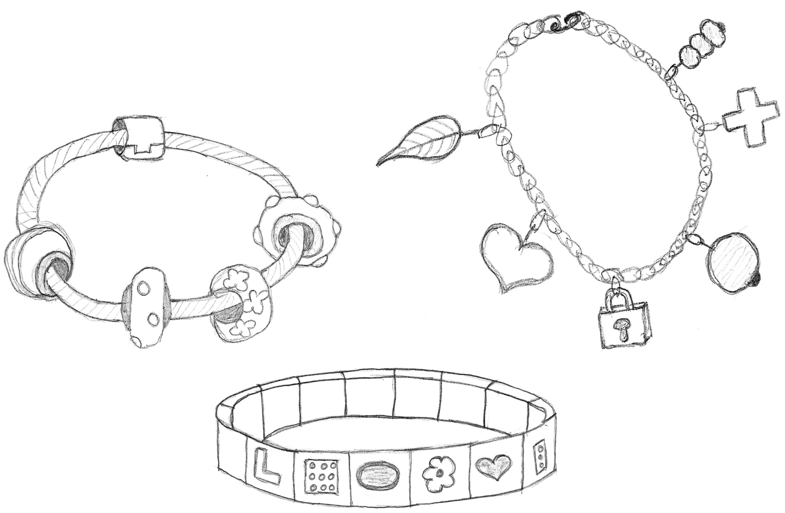


*Figure 6.1: Charm bracelet concepts. From left to right: Links are threaded on a bracelet, hooked on each other, or hooked on a bracelet.*

and assessed user experience and usability. We show, participants experienced the *TangibleApps bracelet* very positively, and could easily comprehend and handle several applications on a single piece of jewellery. Participants appreciated the seamless integration of applications and digital components into a decorative piece of jewellery and were highly willing to use the *TangibleApps bracelet* if it was refined into a product. From the design process and study results we derived design recommendations for the form and appearance (research question Q2), light-based output (research question Q3), and input (research question Q4) on multi-purpose SDJ.

The chapter is structured as follows. After presenting the requirements analysis, we describe the design and implementation of the *TangibleApps bracelet*. We then present a lab study, in which we investigated the bracelet's user experience and usability. After discussing our findings, we conclude with a summary of insights and the key contributions.

Parts of this chapter were published in *Jutta Fortmann, Erika Root, Wilko Heuten, and Susanne Boll. Tangible Apps Bracelet: Designing Modular Wrist-Worn Digital Jewellery for Multiple Purposes. In Proceedings of DIS '16, pages 841–852. ACM* [FRBH16].

## 6.1 Context of Use and Requirements Analysis

To define the context of use and gather the requirements for a modular multi-purpose bracelet, we had a look at general requirements that we gathered from

*Figure 6.2: The TangibleApps bracelet consists of single elements - each offering a specific application - that are attached to a charm bracelet. Information is presented discreetly through light and vibration.*

literature. These are described in Chapter 3. Further, we conducted interviews with jewellers and potential users that we describe in the following. All statements reflect the views of Europeans.

### 6.1.1 Interviews with Jewellers

Within semi-structured interviews, we interviewed three jewellers about the target group of bracelets, their expectations towards jewellery, and general trends in jewellery design. The jewellers were working in different, randomly chosen local jewellery shops. They were interviewed individually in their shops. Interviews lasted about 15 to 20 minutes each. During the interviews, the interviewer took notes on the responses. For analysis, interview notes were coded and summarised according to the interview questions.

We found that the target group for bracelets is in general 70% females and 30% males with an age between approximately 20 to 50 years. Modular bracelets are generally only worn by women between 20 to 35 years. Customers expect jewellery to last for life and to be wearable at any occasion. It should be made of high-quality materials. Younger women like eye-catching designs and prefer silver and red gold, whereas older women prefer classical designs made of yellow gold or white gold. Men prefer bracelets made from leather or high-grade steel.

In general, jewellery with many gemstones and made of red gold has been a trend for a couple of years. Modular bracelets have been a long-lasting trend.

### 6.1.2 Interviews with Potential Users

On the basis of the statements of the jewellers, we selected participants from the target group for semi-structured interviews. We interviewed 12 persons. 9 females and 3 males between 17-47 years (M = 28.8, SD = 9.7) volunteered for the interviews. They were recruited from the local university and through public announcements. Participants were not paid for taking part. The interviews were conducted in individual sessions and lasted for about 30 to 40 minutes each. We asked participants about their interest in jewellery, and their expectations on the design and applications of a modular bracelet. To give them an idea on modular bracelet designs, we showed them pictures of current products. We motivated the integration of electronics in a way that they may not change the appearance of the piece of jewellery. We asked participants to imagine the bracelets could, e.g., flash, vibrate or play sounds and that technically everything was possible. We audio-recorded participants' responses. For analysis, the recorded material was transcribed, coded, and summarised according to the interview questions.

We found that none of the participants owned a digital bracelet. 6 out of 9 female participants owned a modular bracelet, but none of the male participants. All participants stated that they wear jewellery for adornment reasons. In some cases participants received a piece of jewellery as a gift and therefore attached emotional value to it. Participants preferred a total of 3-6 applications per bracelet. The most preferred applications were non-verbal communication (N = 12), reminder (N = 8), and pedometer (N = 7). An element should represent an application (N = 12). Female participants preferred elements to be threaded on a string and moveable (N = 10). In contrast, male participants preferred the elements to be hooked on each other, so they have a fixed arrangement (N = 3). Elements should be distinguished by motif, colour, and shape. Female participants emphasised the importance of different element designs because, only when looking different, they could satisfy the passion for collecting that many women tend to. Input should be made via a push button on an element. Gestures were considered to be too susceptible to misentries and too silly when performed. The preferred output modalities were light (N = 11), vibration (N = 10) and sound (N = 10), whereas for sound participants were concerned about that it could disturb in certain situations, and only considered it to display very important information. The colour of the light should be customisable, e.g., regarding the communication application, each contact could be indicated through a certain light colour. An invisible mode should be offered to deactivate all displays of the bracelet for a certain period. In general, information should be displayed discreetly and the display should not draw the attention of persons in proximity to itself. Participants preferred to decide about the applications of an element when purchased. A single element could either offer various output modalities or each element could implement a specific output modality. The configuration could be done by means of a smartphone application. All participants stated they would wear a modular digital bracelet and would appreciate its additional value compared to an ordinary bracelet. The appearance of the bracelet would be the determining factor.

## 6.2 Design

In the following, we list the conceptual design decisions that we derived from the results of the interviews and the requirements analysis.

#### Functionality

- Bracelet offers between 3 to 6 applications
- Implemented applications are non-verbal communication, reminder, and pedometer
- Non-verbal communication application allows the contact making between user and specific persons through simple predefined messages like "I am thinking of you."
- Reminder application allows to set reminders for and be informed about preset events
- Pedometer application allows to display the user's current physical activity status

#### Appearance

- An application is implemented by an element
- Elements are threaded on a string

#### General Use, Information Presentation and Interaction

- Bracelet can easily be put on and off
- Bracelet switches off when not worn
- Information is displayed discreetly
- Bracelet offers an invisible mode that deactivates all displays on the bracelet
- Input is made through the push of a button, e.g., for making contact
- Light and vibration are used for output, e.g., to make the user aware of someone making contact

On the basis of the conceptual design decisions, we developed designs for a modular multi-purpose digital bracelet. To stimulate the design process with the experiences and viewpoints of both, HCI researchers and potential users, we conducted a quick and dirty prototyping workshop [IDE02] with participants from both groups. In a quick and dirty prototyping workshop, participants use all kind of everyday materials to built Lo-Fi prototypes, possible shapes or interactions. The materials include, e.g., paper, chenille wire, modelling material, handicraft materials, LEGO bricks, cable fixer, toothpicks, straws and sponges (see Figure 6.3).

*Figure 6.3: During the quick and dirty prototyping workshop. Various materials were provided to build Lo-Fi prototypes.*

### 6.2.1 Participants

The workshop was conducted in Oldenburg, Germany. Six participants volunteered for the workshop. These included three potential users, i.e., female university students between 21 to 26 years, and three HCI researchers from our lab (2 males) with an overall HCI working experience of three to six years and experience in wearable computing. None of the participants was paid for participation.

### 6.2.2 Procedure

During the workshop, the study director and a second researcher of the research team were in attendance. After participants introduced themselves, the study director presented the idea of a modular digital bracelet and the conceptual design decisions that should serve as the basis for the designs created during the workshop. The study director explained the three applications non-verbal communication, reminder, and pedometer. She also described the preferred input and output modalities and overall form of the bracelet. The study director also asked if participants wanted to add anything. Then, she introduced the quick and dirty prototyping method. After the introduction, participants were asked to split into groups as they wanted. We had one group of three (two female students, one male HCI researcher) and three single persons. We asked participants to consider the conceptual design decisions when building prototypes. During the workshop, participants communicated and discussed ideas. After the prototyping session, participants explained their prototypes. Further, the study director presented a Lo-Fi prototype that was created by the research team before the study and collected feedback from the participants. During the workshop, both, the study director and the second researcher took notes on the participants' discussions and explanations. For analysis, the study director and the researcher coded the notes jointly.

### 6.2.3 Results

During the prototyping workshop, four different prototype designs were created and one design from the research team was presented and discussed. All designs implemented the concept of "Tangible Apps", i.e., an application (app) is implemented by a (tangible) element.

#### 6.2.3.1 Design Concept A

Design concept A (see Figure 6.4) was created by a female HCI researcher and consists of three single straps that form the bracelet. The basic bracelet consists of one strap that includes a core element which can vibrate and offers a button to (de-)activate the invisible mode. This element is arranged next to the clasp. Further straps can be added and threaded in the core element. Each strap re-

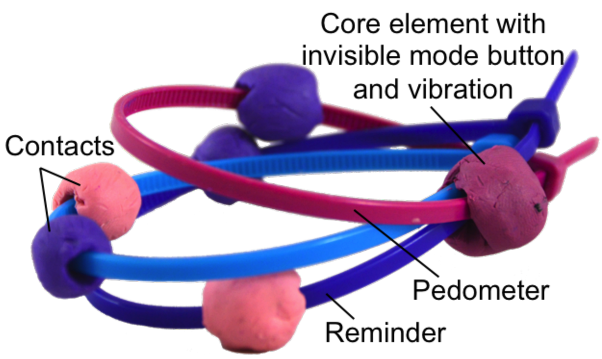



*Figure 6.4: Design Concept A*

alises an application. The maximum number of applications is limited to three. With regard to the non-verbal communication application, an element on the associated strap represents a certain contact, whereas elements are distinguished by colour and shape. When someone is making contact the associated element lights up. Additionally, the core element vibrates to indicate the contacting. To initiate a contact making, the user can push the associated element like a button. On the reminder strap, each element represents a reminder for a certain event. The associated element lights up to indicate that a reminder event is due. To display their daily activity progress, the user pushes the element on the pedometer strap. The whole pedometer strap lights up in a colour of the gradient red (little progress) to green (big progress), until the user pushes the element again. Steps are not counted by the bracelet itself, but, e.g., by an external pedometer clip or a smartphone application. The reason given was that pedometers attached to the wrist do not measure adequately. Straps in different colours should be offered for customisation. With an associated smartphone application light colours could be configured and calendar events could automatically be read and mapped to reminder elements.

#### 6.2.3.2 Design Concept B

In design concept B (see Figure 6.5), which was created by two female students and a male HCI researcher, elements have different shapes to identify certain contacts, e.g., a heart and a star. To initiate a contact making, the user can push a transparent button on the associated element. If someone is making contact, the associated element lights up and the light shines through the button. The colour of the light does not encode information, but should be configurable. As with design A, an additional vibration signal should be triggered to indicate the contacting. The reminder element is completely transparent and flashes when an event is due. Through a push button on top the user can deactivate the flashing when she took notice of it. The pedometer consists of two elements that are linked through a hanging chain. When the user pushes a button on one of the pedometer elements, the chain lights up in a colour of the gradient red (little progress) to green (big progress) to show the activity progress. A button is integrated into the

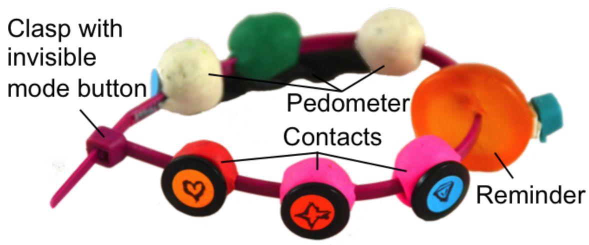



*Figure 6.5: Design Concept B*

clasp of the bracelet to (de-)activate the invisible mode. Apart from functional elements, decorative elements can be attached to the bracelet.

#### 6.2.3.3 Design Concept C

Design concept C (see Figure 6.6) was created by a male HCI researcher. All elements have a very similar look and texture, can light up and additionally also vibrate. Contact elements consist of a circular area that flashes when the user is being contacted. Contacts are distinguished by the colour of the flashing light. An option would be to provide contact elements with differently shaped areas, not only circles, to simplify the mapping. The creator of this design also introduced the idea to integrate a picture of a contact person in some kind of hinged amulet. Though, it might be inconvenient that the amulet has to be opened before the user knows who has contacted her. In contrast, if no shutter would cover the picture, this might be discomforting. Each element has a button on the side that faces the

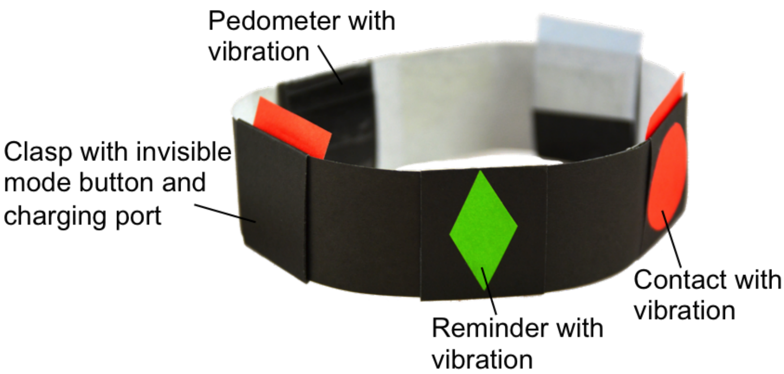



*Figure 6.6: Design Concept C*

hand like with common watches. To initiate a contact making, the user can push the button on the associated element. A reminder element consists of an area that is shaped as an icon that the user associates with the reminder event, e.g., a leaf illuminated in green reminds to water the plants. Either reminder elements could come with lighting areas in different shapes or the icon of the element could be exchangeable. Besides many predefined shapes, individual shapes that can be designed freely are desirable. Like with the display of contact making, the lighting area on a reminder element flashes when a reminder event is due. The pedometer element consists of a vertical row of LEDs that light up in the style of a battery charge condition display. It shows the daily activity progress by the number of illuminated LEDs. The more LEDs are illuminated, the more active the user was. The clasp controls the power supply. When it is opened, the bracelet is switched off. Integrated into the clasp is a port to charge the bracelet, e.g., via USB. An invisible mode button on the clasp allows to switch off all the bracelet's displays.

#### 6.2.3.4 Design Concept D

The female creator of design concept D (see Figure 6.7) emphasised that aesthetics is the most important design criteria. All elements have the same shape and are from one colour family. They are distinguished by patterns on their surface, such as triangles or lines. Each element has a discreet push button that is slightly risen and coloured like the element. To initiate a contact making, the user pushes the button on the associated contact element. If someone is making contact, small appliqués on the associated element light up and the bracelet vibrates. When an event is due, LEDs integrated into the reminder element light up, but not the whole element. All elements light up in the same colour, also elements from different applications. The pedometer element continuously displays the number of steps. If a user pushes the LEDs on an element, the light will turn off. The

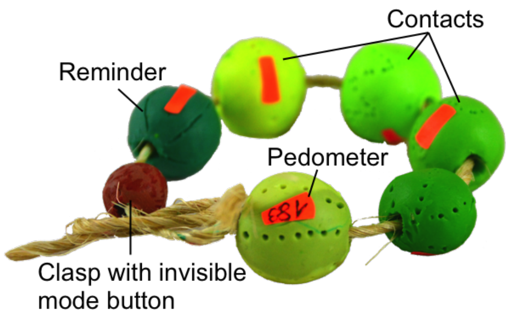



*Figure 6.7: Design Concept D*

bracelet should allow a maximum of six elements. As with designs A and B, the clasp of the bracelet includes a button to (de-)activate the invisible mode. The creator of design D preferred to configure the bracelet by a smartphone application rather than by a computer.

#### 6.2.3.5 Design Concept E

Design concept E (see Figure 6.8) was created from a member of the research team and discussed within the workshop. Elements are threaded on a silver string. A core element controls all other elements and is equipped with a button to (de-)activate the invisible mode. The button is hidden under small gemstones. Contact elements can have different shapes, e.g., a heart, whose border lights up when the user is being contacted. Additionally, the core element vibrates to indicate the contacting. Each element has a button on the side. The user can initiate a contact making by pushing the button on the associated element. An-

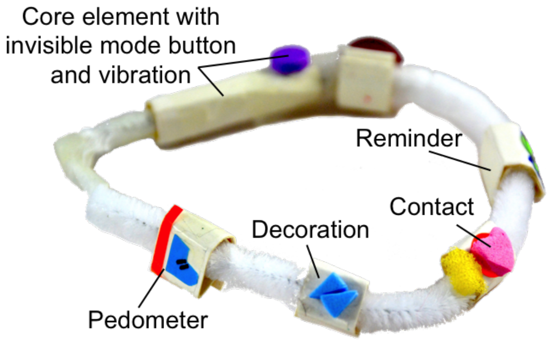



*Figure 6.8: Design Concept E*

other element with a specific shape implements the reminder application. When a reminder event is due, a flashing light discreetly shines through the shape of the reminder element. The colour of the flashing light can be configured by the user, e.g., by a smartphone application. The pedometer element is shaped like a shoe. A light on the left border lights up in red (little progress), yellow (middle progress) or green (big progress) to indicate the user's activity progress. Like with Design C, the bracelet's clasp controls the power supply. Decorative elements complete the bracelet. Workshop participants criticised that only the borders of elements light up, because that would be too unobtrusive. The idea of a core element that acts as a controller was welcomed, as well as the appearance of the design.

## 6.3 Final Design Concept

From the results of the prototyping workshop we derived the final concept of the modular digital bracelet (see Figure 6.9). The majority of designs implemented the idea of one string on which elements can be threaded (B-E). This concept is the basis of our design. Elements implement the applications non-verbal communication, reminder, and pedometer. They can have different shapes to be distinguishable and to be part of a collection. Their shape can indicate a certain application, certain contacts or reminder events (A-C,E). A core element included in a clasp controls all other elements. It includes the general hardware, such as microcontroller and battery, as well as a vibration motor and an invisible mode button (A-E). The clasp controls the power supply (C,E). Elements exist for each application resp. each contact person (A-C,E), but also decorative only elements can be used. Elements are threaded on a string with a railing system for that they are horizontally moveable on the string, but in a fixed vertical position. Thus, the user does not need to turn an element to see its display. Each element has LEDs included which indicate notifications and status information, such as an

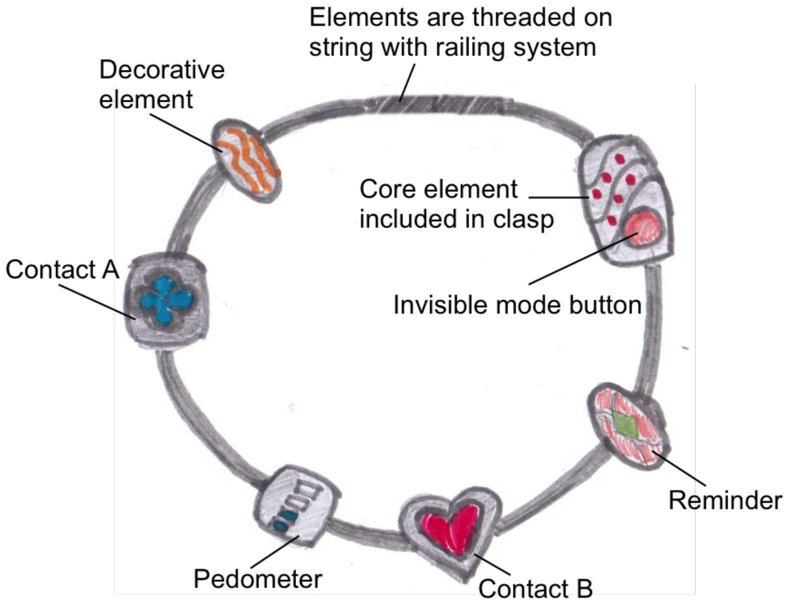



*Figure 6.9: Final design concept of the modular smart digital bracelet. A core element controls all other elements, that implement the applications non-verbal communication, reminder, and pedometer in form of tangible apps. Information is displayed through light and vibration. Input is done through the push of a button on an element.*

incoming contact making, a due reminder event, or the physical activity progress (A-E). Vibration signals are used to confirm an input and to notify of an incoming contact making (A,B,D,E). They are emitted from the core element only (A,E). Because the bracelet hangs loosely around the user's wrist, it can turn and elements change their position in relation to the wrist. This makes it nearly impossible for the user to map detected vibration signals on specific locations to specific elements. Therefore, the bracelet has one universal vibration motor. Each element consists of a push button that is hidden within the element and can be activated through a push on the LEDs or appliqués (A,B,D,E). The concept provides a smartphone application that allows to configure the bracelet via bluetooth, that is, e.g., the mapping of applications to elements, light colour of LEDs, vibration signals, reminder events, and offers further features with regard to the apps on the bracelet (A,D,E). In the following, we describe the handling of the bracelet's applications. As our research focussed on the bracelet rather than the smartphone application, we do not detail the smartphone application.

### 6.3.1 Non-verbal communication

The bracelet can contain several elements that represent specific contacts. The user can initiate a contact making by pushing the button on the associated element (A-E). The input is confirmed by a short vibration signal. On the bracelet of the person who was contacted, the associated element lights up (A-E) and three short vibration signals are emitted (A,B,D,E). The light remains illuminated until the contacted user pushes the button on the associated element. If the contacted user does not react within an hour, the light will switch off automatically. The contact making is processed by the associated smartphone application and communicated via mobile network. With the application, the user can also configure contact elements and light colours.

### 6.3.2 Reminder

The bracelet can contain several elements that represent single reminders. When a reminder event is due, the associated element flashes (C,E) in a *bright flash* pattern, i.e., the light turns on and its brightness very quickly increases and decreases three times, before it turns off and the next flash follows after half a second [HHHH12]. The element flashes for 20 seconds, because this was found to be the maximum reaction time to a light display on the wrist [HLSH09]. If the user wants to turn off the flashing within this period, she pushes the button on the element. If the user does not react, the element will flash again for 20 seconds after 5 minutes. If the user still does not react, the element will remain illuminated continuously for another hour. If the reminder is set up for a recurrent event that recurs within this period, the element will start the flashing procedure immediately when the next event is due. With the smartphone application the user can configure the reminders, and customise light colours.

### 6.3.3 Pedometer

The bracelet can contain an element that represents a pedometer. The measurement of steps is outsourced to an external pedometer, e.g., a clip or a smartphone application. The element displays the daily activity progress by four bars in tiers, which light up according to the progress. The more steps the user has taken, the more bars light up (C). This concept is based on a battery charge condition display. A bar represents 25% of the daily goal. To activate the display, the user pushes the lights, and the display will be illuminated for a few seconds (A,B). Daily goal, reset time and light colour can be configured by the smartphone application. Initially, the display will be reset at midnight and the light colour is blue, because blue has a calming effect and is not perceived as evaluative.

## 6.4 Prototype Implementation

In the following, we describe the implementation of the final design concept in the form of a runnable, wearable prototype. To keep the implementation incomplex, we simplified the design concept and fixed the elements. Also, as a smartphone application for configuration was not necessary for the evaluation, we only focussed on the implementation of the bracelet.

*Figure 6.10: Left: Prototype of the TangibleApps bracelet. Elements are made up of modeling material that diffuses the light of underneath mounted LEDs. LEDs are glued on push buttons. Elements are kneaded into shapes and garnished with acrylic paint and appliqués. Silver wire is wrapped around copper wires to form the bracelet and enhance a jewellery look. Right: User pushes an element to make an input.*

The prototype (see Figure 6.10) consists of a reminder element, a non-verbal communication element, a pedometer element, and a core element. The elements are fixed on a string that was made of silver wire. The core element is mounted next to a magnetic clasp. We mounted a *LilyPad Arduino 328 Main Board*, an *Adafruit Micro LiPo w/MicroUSB charger*, and a *LiPo battery 3.7V 400mAh* to an additional armlet to keep the size of the bracelet minimal and thus keep it closer to the design concept. We connected the components on the armlet and on the bracelet with enamelled copper wires coated with a shrink tubing. To protect and hide the electronics on the armlet, and to increase wearing comfort, we whipped it with black felt. The silvery magnetic clasp controls the power supply. For the bracelet, we used the smallest electronic components we could find and handle. The core element consists of a *Shaftless Vibration Motor* (10x2.0mm), and a *Mini Pushbutton Switch - SMD* (6.4x5.5mm). The reminder and non-verbal communication element both consist of an *Adafruit NeoPixel WS2812 5050 RGB LED* (5x5mm), and a *Mini Pushbutton Switch - SMD* (6.4x5.5mm). The buttons are mounted beneath the LED on the non-verbal communication element, and on the left side of the reminder element. The pedometer element consists of four blue *1.900mcd WEABL02-C1S LEDs* (1.8mm), and a *Mini Pushbutton Switch - SMD* (6.4x5.5mm) mounted beneath. We slotted a dropping resistor in ahead the vibration motor, push buttons, and blue LEDs.

To form the elements we kneaded white modeling clay into different shapes, such as a heart (contact element), oval (reminder), and rectangle (pedometer), and formed it around the electronic components. We painted the elements with black and silver acrylic paint and garnished them with little decorative stones. We wrapped silver wire around the copper wires to form the bracelet and enhance a jewellery look.

### 6.4.1 Scenario

The prototype was programmed in the Arduino Programming Language. We implemented a scenario machine prototype, i.e., the prototype can only be used along a predefined scenario [RC02]. We chose a scenario machine prototype, because of time limitations on the one hand, and on the other hand, because it was sufficient for our evaluation goals. The scenario covers all applications and important interactions:

After the bracelet is put on, it switches on and confirms this by vibrating for 200ms. Then, two LEDs of the pedometer light up blue. After 45s, a third LED on the pedometer lights up and simulates that the user has been physically active in the meantime. When the user pushes the button on the pedometer element, the LEDs turn off. Afterwards, an incoming contact making is initialised by three short vibration signals and a red LED on the non-verbal communication element. Through a push on the button of the element, the LED turns off. The user pushes the button again to recontact the person. A short vibration signal confirms the input. After that, the bracelet simulates that a reminder event is due. Therefore, the LED on the reminder element flashes green in a *bright flash* pattern for 20s. To simulate that the user has not recognised the flashing, it starts again after a short time and remains illuminated after the flashing as long as the user pushes the button on the element to turn the light off. The light would remain illuminated for another hour if the user did not react. To better illustrate the effect of the invisible mode, in the end, all LEDs that had been illuminated during the scenario light up. Because the user takes part in a notional meeting, she activates the invisible mode by pushing the button on the core element. A short vibration signal confirms the input and all LEDs switch off. After the “meeting”, she pushes the button again: the invisible mode is deactivated and all LEDs light up again.

## 6.5 Evaluation

Using the scenario machine prototype, we conducted a lab study to investigate user experience and usability of the *TangibleApps bracelet*.

### 6.5.1 Material

For the study we used the *TangibleApps bracelet* prototype. To measure usability and user experience, we used two established standard questionnaires, i.e., the System Usability Scale (SUS) [Bro96] and the AttrakDiff [HBK03]. With the SUS, participants rate 10 statements, e.g., "I thought the system was easy to use." on a 5-point Likert scale, ranging from "Strongly disagree" (1) to "Strongly agree" (5). With the AttrakDiff, hedonic and pragmatic dimensions of user experience are studied with 21 seven-point semantic differentials, e.g., "connective" (3) to "isolating" (-3).

### 6.5.2 Participants

20 volunteers took part in the study, which we conducted in Oldenburg, Germany. We chose only female participants with a general interest in jewellery, because the target group of modular bracelets is preponderantly female, hence, the design of the *TangibleApps bracelet* caters for females. They were recruited from personal contacts and included 11 university students, a pupil, 3 management assistants, a shop assistant, an executive secretary, a dental assistant, a social pedagogue, and a media operator. Their age varied between 19 and 29 years (M = 24.1, SD = 3.2). We focussed on the age group 20 to 35 as this was defined as the primary target group for modular bracelets from the context of use analysis. Six participants owned a modular bracelet, e.g., a *Pandora* bracelet, and one of the participants a digital activity tracker wristband. Participants were not paid for taking part.

### 6.5.3 Procedure

Participants took part in individual sessions which lasted about 45 minutes. After they had signed an informed consent, we asked questions on previous experiences with modular and digital bracelets. We briefly explained the single applications of the *TangibleApps bracelet* and its overall concept, including the idea of an associated smartphone application. We also showed a sketch of the design concept (see Figure 6.9) to illustrate the appearance. Afterwards, we asked participants to name a contact person for the non-verbal communication element, so they could identify better with it. We helped participants to put on the armlet on their upper arm and the bracelet on their wrist. Then, the scenario started. We led participants through the scenario while we asked questions on the concept and implementation of the single applications according to a guided interview. We also asked questions on their understanding of the light encodings and vibration signals. For some questions, participants had to give ratings on 5-point Likert scales (1 to 5; from 1 = most negative or disagreement to 5 = most positive or agreement). After leading through the scenario, we conducted a post-test interview in which we asked for the overall experience with the *TangibleApps bracelet* and general feedback. Finally, participants completed SUS and AttrakDiff questionnaires.

### 6.5.4 Results

In the following, we report the results of the lab study. For the analysis, we coded the interview notes and evaluated the SUS and AttrakDiff responses. For the 5-point ratings, we calculated the mean value of a rating over all participants. Overall, the *TangibleApps bracelet* was perceived very positively, easy to interact with, and received very good usability and user experience ratings.

#### 6.5.4.1 Applications

In the following, we report the findings on the applications of the *TangibleApps bracelet*.

##### Pedometer

After we explained that the pedometer element shows the progress in relation to a preset daily activity goal, 18 participants were able to correctly name the displayed progress level, which was 75%, i.e., three illuminated LEDs. On a 5-point scale from 1 ("disagree") to 5 ("agree") participants scored the statement "The pedometer display is intuitive and I understand it." with 4.4 (SD = 0.66). 3 participants would prefer the display – if dimmed and more decent – to be continuously illuminated, whereas the other 17 preferred to control the display, e.g., by deactivating it in certain situations. All participants would intuitively deactivate the display by a button. After they had searched for a button on the outer side of the element without success, they pushed the lights on the element. Participants liked this light-button concept very much. A participant noted she would like an additional vibration signal when another progress level is reached, for that she can perceive her activity status without focussing the display. Another participant said she experienced the blue LEDs that simulate a filling up as very motivating, and – in contrast to traffic light colours – as calm and relaxing. Overall, participants rated the implementation of the pedometer application as intuitive (M = 4.5, SD = 0.67).

### Non-Verbal Communication

Participants found the vibration feedback that indicated an incoming contact making pleasant (M = 4.8, SD = 0.68). In combination with the illuminated light on the element, all participants mapped the vibration to a contact making and could correctly map it to the contact person they specified in the beginning. All participants intuitively pushed the button on the element once to switch off the light. To indicate a contact making, 7 participants intuitively pushed the button twice or thrice, whereas the other 13 participants pushed the button once again, which complied with the implemented concept. When asked, participants rated the implemented input method to initiate a contact making, i.e., pushing the button once again, as suitable and intuitive (M = 4.8, SD = 0.43). All participants perceived the vibration feedback after the user pushed the button to recontact the person as helpful and well-suited (M = 5.0, SD = 0.0). Further, some participants found it useful to enhance the concept by enabling urgency levels of a message, and different preset messages. A user could, e.g., push the button once, twice or thrice to indicate a certain message or urgency level. Overall, participants rated the implementation of the non-verbal communication application as intuitive (M = 4.9, SD = 0.3).

### Reminder

Participants liked the *bright flash* pattern that indicated a reminder event and found it suitable (M = 4.9, SD = 0.48). A participant explicitly stated that she recognised the flashing, but did not feel disturbed by it and could easily continue talking to the experimenter. 19 participants experienced the duration of the flashing pattern as ideal, considering that it will recur after a short time if the user does not react in the first time. One participant experienced the duration as too short. 14 participants agreed that the flashing pattern is sufficient to gain the user's attention, whereas 6 participants did not agree. The main reason for their disagreement was that they feared they could miss the light, and therefore would like to receive an additional signal, e.g., in terms of vibration. Overall, 11 participants considered an additional vibration signal as helpful. 19 participants appreciated that the light on the reminder element remains continuously illuminated if the user does not react to the recurring feedback signal. In general, the feedback via the *bright flash* light pattern was thought to be good (M = 4.5, SD = 0.67) and the implementation of the reminder application was rated as intuitive (M = 4.8, SD = 0.43).

### Invisible Mode

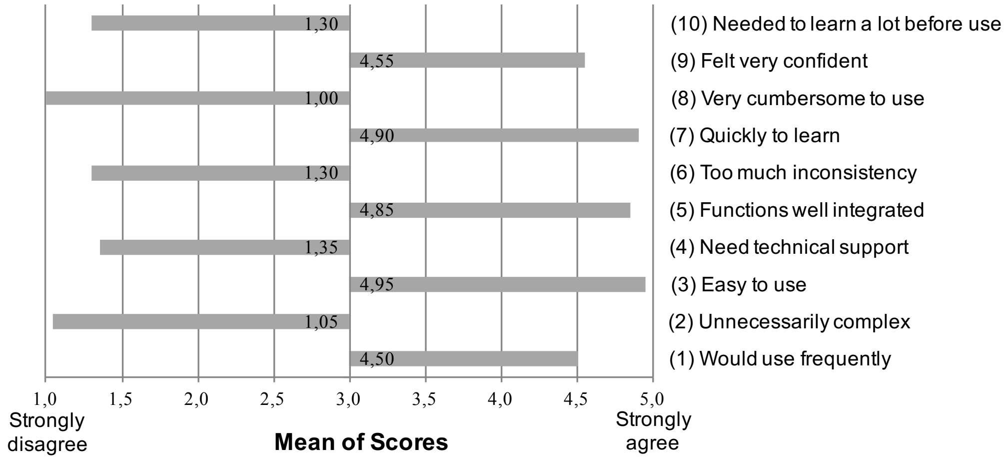
All participants found the invisible mode a useful feature. All participants intuitively pushed the button on the core element to switch on the invisible mode. Their rating confirmed that this concept was intuitive (M = 5.0, SD = 0.0). All participants considered the vibration feedback that the invisible mode is switched on necessary (M = 5.0, SD = 0.0). All participants wanted to be always in control about the deactivation of the invisible mode, in that they can manually deactivate it, e.g., by another push on the button. In addition to this, 5 participants liked the idea that the invisible mode is automatically deactivated after their working day in case they forget to do this.

#### 6.5.4.2 Overall Experience

Overall, all participants liked the input concept and found it intuitive and easy. They rated the overall interaction with the *TangibleApps bracelet* as very good (M = 4.9, SD = 0.36), and liked that all inputs on the bracelet are made by pushing a button, and no other input techniques. A participant stated that buttons should be either located on top of the elements or face the user's hand as this would simplify the input. In general, participants liked the idea to configure the bracelet by a smartphone application, which allows to keep the interaction with the bracelet itself very simple. They agreed that the outputs satisfy their information needs (M = 4.6, SD = 0.58), except for little extensions as described above. Overall, the comprehensibility of all displays was rated as good (M = 4.8, SD = 0.54). Participants were aware of the vibration as a feedback for the activation of the bracelet, but did not feel disturbed by it. They rated the vibration feedback as very good (M = 5.0, SD = 0.22) and helpful (M = 4.7, SD = 0.57). All participants stated that a feedback signal is needed to know if the bracelet is working. In addition to light, all but one participant preferred vibration over other modalities, because it is very discreet and can be perceived without looking at the bracelet. Participants welcomed that the bracelet is switched off when put off, instead of set to a standby mode. They valued the bracelet as an individual, personal item with a high order of customisability. Participants rated the appearance of the *TangibleApps bracelet* as very good (M = 4.8, S 0.54), on the assumption that the system is implemented as described in the design concept, i.e., with a railing system, and that it looks like a real piece of jewellery. The wearing comfort was rated as good and comfortable while walking (M = 4.7, SD = 0.48). 17 participants would like to use the *TangibleApps bracelet* if it was refined into a product. Reasons for abominations were a lack of technical interest, or that there was no need felt for the applications provided. Further, some participants mentioned that the bracelet should be waterproof and easy cleanable.

##### Usability

The SUS score for the *TangibleApps bracelet* was very high (M = 94.75, SD = 3.62, Mdn = 95). Hence, the usability of the *TangibleApps bracelet* was rated as excellent. Figure 6.11 shows the mean values over all participants for the single scores of the SUS. All scores were distinctly above-average.




(1) I think that I would like to use this system frequently.
(2) I found the system unnecessarily complex.
(3) I thought the system was easy to use.
(4) I think that I would need the support of a technical person to be able to use this system.
(5) I found the various functions in this system were well integrated.
(6) I thought there was too much inconsistency in this system.
(7) I would imagine that most people would learn to use this system very quickly.
(8) I found the system very cumbersome to use.
(9) I felt very confident using the system.
(10) I needed to learn a lot of things before I could get going with this system.

*Figure 6.11: Diagram of mean values for the single scores of the SUS. All scores were above-average and the overall usability was rated as excellent.*

### Attractiveness, Hedonic and Pragmatic Quality

Overall, the scores of the AttrakDiff were high, i.e., the overall user experience of the *TangibleApps bracelet* was rated as very good. In all four dimensions, the *TangibleApps bracelet* was rated as optimal, with best ratings in attractiveness (ATT; M = 2.48, SD = 0.4) and hedonic quality - identity (HQ-I; M = 2.31, SD = 0.61), and slightly weaker ratings in pragmatic quality (PQ; M = 2.1, SD = 0.44) and hedonic quality - stimulation (HQ-S; M = 2.01, SD = 0.57). Figure 6.12 shows a diagram of the mean values. Overall, the results show that the *TangibleApps bracelet* optimally assists users, they can identify with it and it stimulates and motivates them.

Figure 6.13 illustrates the mean values for the single word-pairs of the AttrakDiff. Overall, it shows that all single ratings were above-average, except for *technical-human*, i.e., the *TangibleApps bracelet* was rated as slightly more technical than human. This single rating induces the slightly weaker rating in pragmatic quality. In the hedonic quality - stimulating dimension the diagram

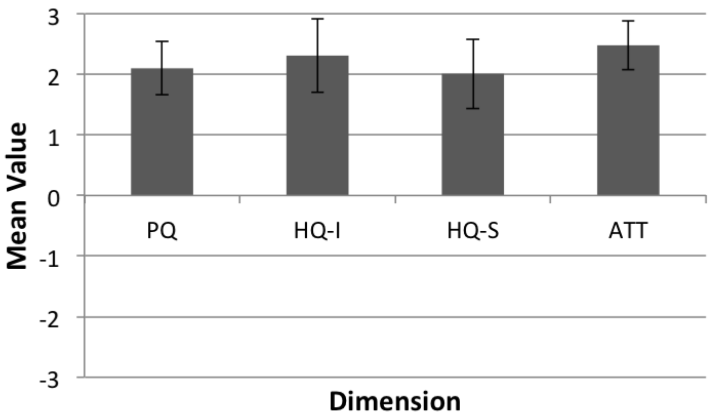



*Figure 6.12: Diagram of mean values of the AttrakDiff. The TangibleApps bracelet received optimal ratings in all dimensions.*

shows positive instead of very positive ratings for the word-pairs *cautious-bold* and *undemanding-challenging*. However, these differences are not prominent.

### 6.5.5 Discussion

In summary, the results of the lab study show that the *TangibleApps bracelet* was perceived very positively, easy to interact with, and received very good usability and user experience ratings. We found that it optimally assists the users, that users identify with it and are motivated and stimulated by it. Also, participants found it very attractive. They appreciated the seamless integration of applications and digital components into a piece of jewellery and were highly willing to use the *TangibleApps bracelet* if it was refined into a product. Further, participants could easily comprehend and handle the several applications on the *TangibleApps bracelet*. We found small standard deviations for all ratings, i.e., the specific ratings during the interviews, the SUS, and the AttrakDiff. This indicates, that participants concurred in their assessment, and strengthens the results.

The study revealed, that the combination of light and vibration as output modalities is very usable and highly preferred. With the reminder element, we found that for a bracelet, light only is not sufficient to gain the user's attention. While light is generally suitable to present information in a decent and encrypted way on a piece of jewellery, vibration signals should be added to notify of urgent information, and are useful to confirm user input in cases where the input would not be observable otherwise.

The study showed that it does not make sense to search for an all-fitting design of the bracelet in terms of, e.g., its colours and the shapes of elements. As it is seen

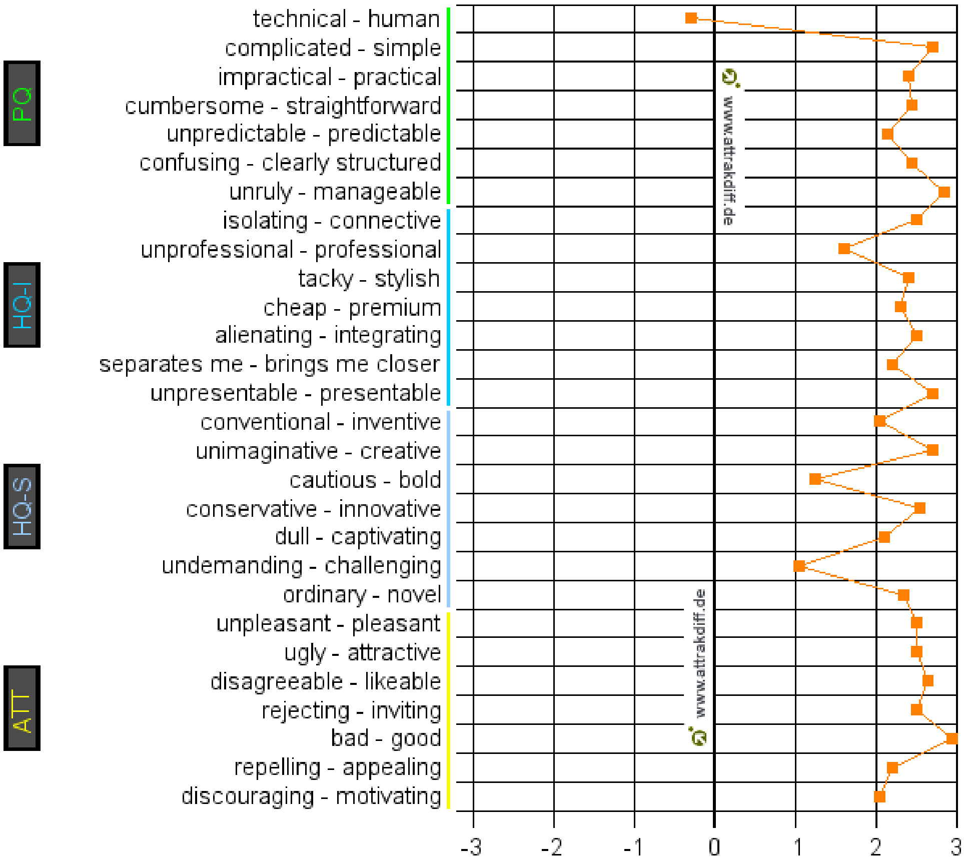



*Figure 6.13: Diagram of mean values for the single word-pairs of the AttrakDiff. All single ratings were above-average, except for* technical-human*.*

as a piece of jewellery, people want to make it individual. For *SDJ*, this means it needs to offer a high order of customisability. This includes the appearance of the hard components, e.g., elements, as well as the colour of the lights integrated. In addition, there should be a couple of applications users can choose from. Also, the final design of the *TangibleApps bracelet* is influenced by current jewellery trends in Europe. Thus, the results regarding the appearance of the bracelet, e.g., that elements are threaded on a string, are to be seen on a more conceptual level, as they might change over the next years and might differ between cultures.

Overall, participants appreciated the simple information display on and easy interaction with the bracelet itself. Particularly for a wearable, almost always observable display, the purposely limiting of information is pleasant and helps to counter information overflow. Further, low-resolution, i.e., point light displays can be discreetly integrated into a piece of jewellery without interfering with the jewellery's appearance. The study results suggest that directly on *SDJ* information should only be presented in a limited way and only basic interaction should be offered. For applications that need a more detailed view and complex interaction, either they might not be suitable to run on *SDJ* at all, or an associated smartphone application could be offered. However, designers should keep in mind, that *SDJ* is classified as a wearable computer, and as such, it should not distract a user from her primary task and be accessible quickly and with little effort [Man98, Sta01a]. The implementation of complex display and interaction concepts into *SDJ* contradicts these requirements, as well as our study results, and therefore should be avoided.

#### 6.5.5.1 Lessons Learned

In the following list, we summarise the lessons learned for the design of multi-purpose smart digital bracelets.

##### Appearance and Functionality (Research Question Q2)

- Bracelet is seen as an individual, personal item that needs to offer a high order of customisability (appearance of bracelet and elements, choice of applications)
- Several applications should be offered; popular are non-verbal communication, reminder, and pedometer
- Three different applications could easily be handled on a single piece of *SDJ*

##### Information Presentation and Interaction (Research Questions Q3, Q4)

- Vibration and light in combination are well suited and liked to present information and give feedback
- Light generally suits to notify and to present information
- Vibration suits to confirm user input and to gain the user's attention for important information
- Information presentation should be limited
- Complexity of interaction should be kept low: Only a push button for all inputs was highly appreciated
- Push buttons should be placed in a way they are easily accessible for the spare hand
- Bracelet needs an invisible mode; user has to be in control about its (de-)activation
- Bracelet should switch off automatically when put off
- Feedback that digital piece of jewellery is switched on is mandatory

## 6.6 Conclusions

In this chapter, we investigated how a smart digital multi-purpose bracelet should be designed in order to be attractive, functional, easily comprehensible, and easy to manage. Thus, this chapter contributes to the research questions Q2, Q3, and Q4 from the perspective of multi-purpose SDJ. On the basis of a participatory design process we designed and built a modular bracelet that integrates multiple applications in form of single elements that we call *Tangible Apps*. In a lab study with 20 participants, we evaluated the *TangibleApps bracelet* as a proof-of-concept implementation and assessed its user experience and usability. From the design process and study results we derived concrete implications for designing the form and appearance (research question Q2), light-based output (research question Q3) and input on multi-purpose SDJ (research question Q4).

We identified an appropriate design concept for a modular multi-purpose bracelet. We found that it should consist of single elements that implement different applications and can be threaded on a string. Applications and appearance of the elements and the bracelet need to be customisable to form an individual piece of jewellery. Simple output and input techniques such as light combined with vibration, and push buttons turned out to be effective and appreciated. The results of a lab study showed that the *TangibleApps bracelet* was perceived very positively, easy to interact with, and received very good usability and user experience ratings. We found that it optimally assists the users, that users identify with it and are motivated and stimulated by it. Also, participants found it very attractive. They appreciated the seamless integration of applications and digital components into a piece of jewellery and were highly willing to use the *TangibleApps bracelet* if it was refined into a product. Further, our results show that users could easily comprehend and handle several applications on a single piece of jewellery.

Overall, from this research we conclude that multi-purpose *SDJ* is desired, and implementable in form of a attractive, functional, and usable modular bracelet. From our study results we derived suggestions for the design of multi-purpose *SDJ*. Hopefully, these will inspire and help designers of *SDJ* and - if implemented - lead to highly accepted wearable devices.

A worthwhile next step would be to conduct a field study to see how the *TangibleApps bracelet* performs and is experienced in real-life environments. From the field study, we expect to learn about how environmental conditions influence the usage, usability and user experience of the digital bracelet. The insights would help to further improve the design of multi-purpose bracelets. To do this, we need to extend and refine the prototype. The joint work with a jewellery designer would help to enhance the appearance of the prototype. Furthermore, an interesting follow-up would be to investigate how to enable switching between different pieces of jewellery. Because people like to change their pieces of jewellery every now and then, we need to find how the applications of one piece can be transferred to other pieces, and how the interaction concept could be transferred to different jewellery forms, e.g., a ring.

# 7 Conclusions

In this chapter we highlight the contributions of the work presented in this thesis to the research questions that we described in the introduction. First, we summarise the contributions and the expected impact of the research presented in this thesis. Then, we provide detailed answers to the research questions. Afterwards, we expand on the design recommendations for SDJ that we derived from our research. Further, we reflect on the methods we used for investigating our research questions. We close the chapter with directions for future work, and final considerations on applying SDJ.

## 7.1 Summary

In this thesis, we presented the results of our research on the design of SDJ from a human-centred perspective. We investigated four research questions addressing the user requirements for, and the form and appearance, information presentation, and interaction concept of wrist-worn SDJ. The research conducted followed a design-led approach in which several wrist-worn SDJ prototypes were developed and evaluated with potential users. The prototypes are physical representations of the investigated concepts. The results provide a deep understanding of the human-centred design and evaluation of wrist-worn SDJ for several use cases. From the exploration of the research prototypes under consideration of the four research questions, we derived a catalogue of 15 concrete design recommendations for wrist-worn light-based SDJ. These address the appearance, information presentation, and interaction concept of SDJ, and will be presented in this chapter. Further, we reflect on the applicability of a variety of human-centred prototyping and evaluation methods that we used during the research process.

Overall, we found bracelets to be a suitable form for SDJ. Simple output and input methods allow an uncomplicated interaction with SDJ as a wearable object that is used in many different and changing environments. We found light in combination with vibration is well-suited to present information on wrist-worn SDJ in a discreet way. Our results show that light patterns should be designed according to specific rules to ensure good understanding and good user experience. We found that push buttons are sufficient for many simple applications, can be operated one-handed, and can easily be integrated into a piece of SDJ without interfering with its adorning appearance. In general, wrist-worn SDJ is suited for simple, single- and multi-purpose applications.

Our contributions support designers of wearable technology and SDJ in particular to create wearables with a good user experience. We expect the mature implementation of SDJ to lead to an opening up of a large share of the market that is still untapped [Was15]. Further, we assume that the long-term acceptance of wearables implementing the design recommendations presented in this thesis will increase. The reflection on the methods we used for prototyping and evaluating SDJ supports researchers in choosing appropriate methods for their related research and identifies potential areas for future work.

## 7.2 Contributions to the Research Questions

In the following we present our contributions to the research questions.

### 7.2.1 Q1: What are the user requirements for wrist-worn SDJ?

To identify the user requirements we thoroughly examined the related work. Further, we interviewed a goldsmith on the requirements, feasibility and challenges of SDJ. Moreover, we conducted an online survey to investigate the relevance of certain requirements.

From the literature analysis we gathered an overview of the requirements for SDJ. These requirements were mainly gathered from literature on wearable computing, as there is only very few literature on SDJ in particular. The requirements were complemented with further requirements we gathered from the interview with a goldsmith (Section 3.2). From an online survey (Section 3.3), we found that users perceive certain requirements differently important. In general, participants considered requirements addressing functionality, form, and interaction and display design as very important, whereas they found those related to body location, context awareness and customisability less important. For single requirements, we found differences in the ratings between different age groups as well as between males and females. We contribute with a ranked list of user requirements. It will help designers of SDJ to focus on the - from a user perspective - more important aspects, before considering the less important ones.

### 7.2.2 Q2: Which form and appearance support a comfortable wearing experience?

Research question Q2 was investigated through a combination of design workshops and evaluation studies that we conducted with regard to the single-purpose *WaterJewel* bracelet (Chapter 5) and the multi-purpose *TangibleApps bracelet* (Chapter 6).

Overall, we found bracelets to be a very suitable form for SDJ as they give reasonable room to integrate actuators and sensors while still allowing a discreet and decorative appearance. Further, their form leaves scope for the implementation of various jewellery designs. We found that design preferences are influenced by jewellery trends, but also individual and very different between males and females. The studies showed that users expect SDJ to offer a high order of customisability with regard to various designs, shapes, and colours. Particularly for multi-purpose SDJ we found the design of a modular bracelet that consists of tangible elements, each representing a single application, to be a suitable concept. Further, element shapes, as well as element and light colours turned out as helpful design characteristics to support the mapping to, e.g., applications and contacts. The findings incorporate into two concrete design recommendations for the form and appearance of SDJ, which we expand in the following section.

### 7.2.3 Q3: How can information be presented on wrist-worn SDJ?

The research presented in this thesis focussed on light as a modality to present information on SDJ. We investigated research question Q3 by, first, involving users in designing light patterns for a bracelet (Chapter 4), and second, evaluating light patterns implemented in concrete SDJ prototypes, which were the *WaterJewel* bracelet (Chapter 5) and the *TangibleApps bracelet* (Chapter 6).

Overall, from our studies, we conclude that light is well-suited to notify and to present information on wrist-worn SDJ. Further, vibration was found to serve as a useful, supporting modality, especially to confirm user input, to emphasise important notifications, and to gain the user's attention immediately when needed. On the basis of the specific use case physical activity feedback, we proposed an example configuration for conveying four types of information by light. From our studies, we derived eight concrete recommendations for the design of light patterns for wrist-worn SDJ. We describe these in detail in the following section.

### 7.2.4 Q4: Which interaction design is suitable for wrist-worn SDJ?

Research question Q4 focussed on the interaction with wrist-worn SDJ from a user perspective. To answer the question on how to design the interaction in a way that it leads to good user experience, we involved potential users in both, the design and the evaluation of concrete SDJ prototypes, which were the *WaterJewel* bracelet (Chapter 5) and the *TangibleApps bracelet* (Chapter 6).

In general, we found simple input methods, such as a push button, to be very usable for wrist-worn SDJ. Push buttons are sufficient for many simple applications, can be operated one-handed, and can easily be integrated into a piece of SDJ without interfering with its adorning appearance. As perceptible components, they allow a quick, intuitive, and "eyes-free" operation. From our studies, we conclude that a push button is easily usable to control two to three different input instructions. The number of enabled input instructions should be as low as needed to keep the interaction simple. However, if more than three input instructions are needed, another button, or further concepts could be used, e.g., turning and squeezing an element of a bracelet. We derived a total of five recommendations for the interaction design for SDJ that we describe in detail in the next section.

## 7.3 Design Recommendations

On the basis of a series of developed prototypes and user studies presented in this thesis, we derived a catalogue of 15 design recommendations for SDJ that contribute to answering research questions Q2, Q3 and Q4. These are described in the following. The requirements presented in Chapter 3 exist side by side with the design recommendations presented in this chapter. The requirements serve as the basis for the overall concept of SDJ and the concrete SDJ prototypes created during our research. They are phrased on a high level. The design recommendations go a step further and provide concrete, detailed ideas on how to implement specific requirements. E.g., design recommendation 14 “For simple input a push button is well-suited”, provides advice on how to implement the requirement of a quick operation with few effort (**ID13**, see Chapter 3.3.1.1).

### 7.3.1 Form and Appearance (Research Question Q2)

#### 1. Offer a high order of customisability

Design preferences are individual and those of males differ considerably from those of females. Form and appearance are influenced by jewellery trends. There is no “one-fits-all” design. Like jewellery, SDJ should be offered in various visual designs, shapes, and colours. This also refers to the display design, e.g., light colours of light-based SDJ should be customisable for decorative aspects. Besides, the arm on which a piece of SDJ is worn and the SDJ’s orientation towards the user can vary. The form and appearance of a piece of SDJ should support this wearing freedom, and SDJ should allow the user to configure orientation of input and output components.

#### 2. Give form a meaning

The form of elements of a piece of SDJ can suggest certain information in an intuitive way. E.g., a contact can be represented by a specific colour, and a reminder event can be presented by a specific shape. In our studies, participants often had strong associations with specific shapes and colours regarding certain information. If it fits to the jewellery design, different shapes and colours should be offered to allow encoding information in an intuitive way, such as specific contacts, or reminder events. As users associate different information with certain shapes and colours, what is an intuitive mapping for one user can be unclear to another. Thus, mappings must be configurable. For multi-purpose SDJ, we highly recommend to transfer information on, e.g, applications, contacts, or reminders, by shapes and colours as this facilitates the mapping and keeps the more complex multi-purpose SDJ usable.

### 7.3.2 Information Presentation by Light (Research Question Q3)

#### 3. Use consistent pattern mapping

A consistent scheme in the mapping of light patterns to specific information was felt intuitive. It allows easy recognition, can prevent confusion and allows different types of information to be easily compared to each other. Consistent schemes can, e.g., be gradients with same colours, or specific colours that are always mapped to negative resp. positive information.

#### 4. Use colours to differentiate levels

A certain number of light colours, i.e., in our studies we tested seven different colours, can be well-perceived and distinguished. Colours were found to be easily comprehensible for differentiating the levels or the assessment of specific information. As the traffic light pattern, i.e., green – positive/inoffensive, yellow – middling/neutral, red – negative/attention, is equally-understood among a huge number of users, it should be set as the default configuration for presenting rating information.

#### 5. Make colour mapping configurable

While some colours were frequently mapped to positive and negative information, such as red for negative and green for positive information, in general the interpretation of and the preferences for colours varies distinctly among users. Also, for privacy reasons users might want to change colour mappings every now and then. Thus, users should be enabled to customise colour mapping.

#### 6. Use flashing exclusively for urgent and important information

As flashing patterns are very distracting and attention grabbing, they should exclusively be used to encode important and urgent information, if at all. A wearable object that flashes does not only grab the attention of its wearer, but also of persons in proximity. Thus, a user should be in full control about flashing patterns, i.e., be allowed to customise and to deactivate them.

#### 7. Adapt brightness to environmental characteristics and context

From our studies presented in Chapters 4 and 5, we found different brightness levels to be hardly distinguishable or not at all if consciously looked at. Thus, brightness levels should not be used to encode information. Our studies showed that adapting the lights' brightness to the context of the user increases user and observer comfort. The light's brightness level should adapt to lighting conditions and context to increase its visibility and unobtrusiveness, e.g., in dark environments the light should dim, whereas in bright environments it should be bright. A sensible social context adaptation could be, e.g., that during formal or business occasions the light is subtle (dimmed), whereas in private or public environments, the light could be more conspicuous (bright). If lighting conditions and social context conflict, priority should be given to the less obtrusive choice (dimmed).

### 8. Provide clearly discernible levels according to the user's needs

If a certain level of an information type is of great significance for the user, encode this level in a way that it is clearly discernible. E.g., gradients are well-suited to present progress information, but it is hard to estimate when exactly the start and end colours of the gradient are reached. If a certain level of an information type is of great significance for the user, than he or she should be able to clearly identify this level. A gradient pattern used to present progress information by a single light source could, e.g., be complemented by a flashing or pulsing pattern, according to its level of importance, when the level of interest is reached.

### 9. Map quantities to number of illuminated light sources

From the research presented in Chapters 5 and 6, we found that the number of illuminated light sources can convey information in an intuitive and quickly perceivable way. We recommend to encode countable units or percentage values by the number of illuminated light sources. The more light sources are used for encoding, the more detailed the information can be presented. If only one light source is available, we recommend to use a gradient instead.

### 10. Increase awareness by continuously illuminated light source

In the research presented in Chapter 5, we investigated a bracelet with a continuously illuminated light source. We found a continuously illuminated light source with gradual light colour changes to increase awareness for specific information. As the gradual light colour changed so slowly that single steps were not perceivable, it remained unobtrusive, and because of its ambient appearance, could be perceived in a concurrent way. This makes a continuously illuminated light source with gradual light colour changes a well-suited design to increase awareness for specific information on wrist-worn SDJ.

### 7.3.3 Interaction Design (Research Question Q4)

#### 11. Enable automatic switch on and off

SDJ does not need to run when the user is not wearing it, particularly with regard to battery life which is crucial for wearable technology. A smart and intuitive way to implement this is by automatically switching off a piece of SDJ when it is taken off. This can be done by, e.g., connecting the power supply to the clasp (see Chapter 6). This implementation would at the same time realise automatic switch on if the piece of SDJ is put on. For this implementation, it has to be ensured, that application data is still accessible after the piece of SDJ is put on again, e.g., by regular automatic data storage.

#### 12. Allow invisible mode

Our studies clearly showed that light-based SDJ must provide the feature to be "invisible" during specific moments, in which the presence of illuminated light sources is not desired at all. These could be inappropriate moments, such as, e.g., during a business meeting or a visit to the doctor's. Thus, SDJ should provide an invisible mode that can be activated during certain moments. For the implementation, some aspects have to be considered. The piece of SDJ must clearly provide its current visibility status at any time. The activation of the invisible mode should not happen accidentally, i.e., the input method should prevent misentries. A possible implementation could, e.g., be a latch switch with a stronger mechanic resistance. It could clearly communicate the current visibility status by its physical position and would less likely be set accidentally. A challenge is to make sure the piece of SDJ is not accidentally left in invisible mode because the user forgot to deactivate the invisible mode again. E.g., an automatic timer that is set for the invisible mode when it is activated might solve this problem, but it involves the danger of an unwanted – because too-early – deactivation of the invisible mode.

#### 13. Place I/O components close to the application controlled

For SDJ that offers several applications, placing input and output components close to the application that is controlled eases mapping and makes the interaction intuitive. E.g., for a modular bracelet where single elements are allocated to certain applications, this can be implemented by placing I/O components allocated to an application directly on the corresponding element. The TangibleApps bracelet implements this concept (see Chapter 6).

#### 14. For simple input a push button is well-suited

In our studies we investigated push buttons as input components for several bracelets. We found push buttons to be well-suited for SDJ that requires simple input. The interaction with push buttons is easy, well-known, can be done with one hand, and push buttons can be discreetly integrated into SDJ. Further, the manual interaction of pushing a button fits well to jewellery as being a tangible object. From our studies we conclude, that push buttons are well-suited for wrist-worn SDJ and easily usable to control two to three different input instructions. These can be implemented as, e.g, (1) a short push, (2) a long push, and (3) a double-push of a button. For multi-purpose SDJ, a button can be allocated to each application (see also recommendation 13). However, we did not investigate how this scales. We do not recommend to use more complex implementations, such as combinations of short and long pushes or triple-pushes, as our study results indicated that these are too complicated to perform on a wrist-worn wearable and thus, take too long and are too susceptible to faults.

15. Ensure accessibility by spare hand

Wrist-worn SDJ might not have a default orientation towards the user. It could, e.g., be worn on the left or the right arm, and in different orientations. This must be considered when designing input components. Manually operated input components should be placed in a way they are easily accessible for the spare hand while the piece of SDJ is worn. This involves that a piece of SDJ can be operated one-handed.

## 7.4 Reflection on Methods Used

In this section we reflect on the HCI methods we used during our research process and assess their applicability for researching SDJ.

### 7.4.1 System Usability Scale

Created in 1986 by John Brooke, the System Usability Scale (SUS) [Bro96] is an established standard questionnaire for assessing the overall usability of a system. After having used the system, participants rate 10 statements on 5-point Likert scales. The ratings result in an overall score that expresses the usability of the system researched. The SUS is meant as a tool to assess the overall usability of a system rather than to reveal concrete usability issues. Originally, it was developed for assessing integrated office systems running on mid-range and mainframe systems.

In the research presented in this thesis, we used the SUS in two studies. These were firstly, a field experiment in which we used the SUS to measure the usability of the WaterJewel bracelet and a mobile fluid intake reminder application (see Chapter 5), and secondly, a lab study in which we used the SUS to assess the usability of the TangibleApps bracelet (see Chapter 6). Thus, we used the SUS to assess early wearable SDJ prototypes as well as a mobile application. For both kinds of systems the SUS proved to be a useful and suitable tool to quickly assess their overall usability. The statements of the questionnaire fitted to the early physical prototypes as well as to the mobile application that we investigated, and participants found it easy to complete the SUS questionnaires. We did neither find any signs for user errors that might occur due to the alternation of positive and negative statements, nor did we have problems in scoring the questionnaires as addressed by Brooke [Bro13].

The SUS was designed at a time in which wearable technology was uncommon and in a very early stage of development. It does not particularly address critical aspects of wearable technology, such as concurrent use and changing environmental conditions. To improve the SUS with regard to its validity for wearable technology, its statements should be examined thoroughly and may be adapted for a "wearable version" of the SUS. E.g., the SUS statement number 9 could be specified in a way like "9. I felt very confident using the system *in presence of others*." and "9. I felt very confident using the system *in public environments*.". The third statement may be specified in ways like "3. I thought the system was easy to use *while moving*." and "3. I thought the system was easy to use *while following another task*.". We clearly state that, at this point, these adaptations are initial suggestions that require further research.

### 7.4.2 AttrakDiff

The AttrakDiff questionnaire was developed by Hassenzahl et al. [HBK03] to assess the perceived hedonic and pragmatic quality of interactive products. Besides considering aspects associated with usability, it factors in aspects associated with the user experience of a product, such as joy of use, and positive attitude towards a product. Having been presented in 2000 at first, since 2003, a refined version of the questionnaire is being used. To assess a product, participants rate 21 contrary word pairs each on a 7-point scale after having used the product.

In the research presented in this thesis, we used the AttrakDiff questionnaire in one study, and used parts of it as a basis for a customised questionnaire in another study. In a field experiment we used parts of the AttrakDiff questionnaire addressing *hedonic quality - identification* and *attractiveness* to assess these aspects for the original WaterJewel bracelet and a brightness-adaptive version of WaterJewel (see Chapter 5). The reason for using only parts of the AttrakDiff was that we wanted to compare two versions of a prototype, that differed only slightly in the display of information. The two versions did neither differ in functionality nor in form. Thus, we did not expect many of the aspects assessed by the AttrakDiff as meaningful, in particular those addressing *pragmatic quality* and *hedonic quality - stimulation*. Therefore, we decided to use only items assigned to *hedonic quality - identification* and *attractiveness*. In another study, we used the complete AttrakDiff to assess the pragmatic and hedonic quality of the TangibleApps bracelet (see Chapter 6). In both cases, subject of the study was an early wearable SDJ prototype.

In general, there is a clear need for standardised tools to assess the user experience of an interactive system. Standardised tools ensure a certain level of quality in research as they are thoroughly designed and validated tools. Further, study results are directly comparable if the same tools are used. Also, each time standardised tools are used, they are subject to criticism by the research community. This constant testing helps to develop tools further, as it will either reinforce a tool or stimulate discussions on the need for improvements or new tools. As a standardised tool, the AttrakDiff is greatly appreciated. However, through our studies we encountered some issues. Participants had difficulties interpreting some of the word pairs and were not sure how to map them to the system to be evaluated. We assume that the very brief wording of the AttrakDiff makes it difficult for participants to get the meaning of the items and also to map it to a system. In comparison, the SUS consists of whole sentences that clearly describe the aspect that is to be rated. Further, the SUS sentences are all phrased from a first-person perspective, e.g., "I think that I would like to use the system frequently.". It is conjecturable that both, using whole sentences, as well as phrasing in the first-person perspective, improves understanding and makes it easier to give subjective feedback. This assumption is affirmed by the fact that we did not observe any participants having difficulties in understanding the SUS.

Furthermore, we consider some AttrakDiff ratings as not meaningful for assessing early physical prototypes. Early physical prototypes often lack in a sophisticated design and technical components often remain visible. When rating specific word pairs, such as *technical - human*, *unprofessional - professional*, or *ugly - attractive*, participants might be influenced by the prototypical look and feel of the system. E.g., participants in our study rated the TangibleApps bracelet as more *technical* than *human* (see Chapter 6). The prototype used for the study was in an early stage of development, i.e., despite that we hid the electronic components as best we could, there was still a visible cable going from the bracelet to the armlet. We assume that the rating was influenced by the system's prototypical status. Thus, this rating is less meaningful, because – of course – we did not want to evaluate the prototype as being a finished product, but rather its conceptual design. Besides, letting participants imagine the prototype to be in a more sophisticated status while rating does not really help because than the rating becomes speculative.

### 7.4.3 Comfort Rating Scales

The Comfort Rating Scales (CRS) were introduced by James Knight et al. in 2002 [KBSB02]. They describe a comfort assessment tool for wearable computers by which cognitive and physical comfort are assessed by means of six dimensions that are rated each on a 21-point scale. The six dimensions are *Emotion*, *Attachment*, *Harm*, *Perceived change*, *Movement*, and *Anxiety*. The CRS allow to assess the comfort of a system per dimension, and to compare single dimensions across different systems or conditions. Participants complete the CRS after using the to-be-tested system. The lower the score, the better the level of comfort was perceived.

In the research presented in this thesis, the CRS were used in two field studies to measure the comfort of firstly, the point-light bracelet (see Chapter 4) after it had been used for three days, and secondly, the WaterJewel bracelet after it had been used for two weeks (see Chapter 5). Thus, subject of the study was an early wearable SDJ prototype in both cases. Participants had no problems understanding and completing the CRS. However, overall, we do not recommend to use the CRS for assessing early wearable prototypes, because we found the results to be too much influenced by an early prototype status. In both studies, participants rated the dimensions *Emotion*, *Movement*, and *Attachment* slightly higher than the other dimensions. In the WaterJewel study, this also applied to the dimension *Perceived change*. In the interviews, they gave the armlet and the cable that connected the bracelet with the hardware components on the armlet as the reason for the perceived impact on movement, perceived change, and for the sensing of the attachment. Further, participants named the overall prototypical appearance of the WaterJewel bracelet as the main reason for the perceived worry about their appearance (*Emotion*). Thus, the prototypical look and feel of the tested prototypes definitely influenced participants' ratings. Despite that we clearly explained that the prototypes should be seen as research prototypes and not finished products, and that the armlet and cable were just a workaround to keep the plain bracelet small and to enhance its look, participants were influenced by the prototypical status in their ratings. Consequently, we did not use the CRS in further studies and do not recommend to use them for assessing early prototypes.

### 7.4.4 Field User Studies

For the research presented in this thesis, we conducted three field studies in which we evaluated three different SDJ prototypes. These were the point-light bracelet (see Chapter 4), the original WaterJewel bracelet, and the adaptive WaterJewel bracelet (see Chapter 5). In general, we found the field studies to be very useful in that they offered insights into the usage of the prototypes in real-life conditions. Several issues participants reported only became explorable because participants experienced specific situations in specific environments with specific audiences. E.g., a participant using the original WaterJewel bracelet in a cinema reported that she intentionally covered the bracelet during the show because she felt the light was too bright and obtrusive. In the same study, a participant explained she drank when the Reminder Display was illuminated in orange, because she knew the upcoming appointment would overlap the red lighting phase, so that she would not have been able to drink for a too long time. These real-life experiences provided valuable insights into the interaction with the tested system and pointed to critical design aspects.

Evaluating early wearable prototypes in field studies is very challenging. Wearable prototypes are placed a great strain on when worn in everyday life. They must be robust enough to stand the evaluation period. This involves functionality as well as physical construction. Especially for SDJ prototypes this is challenging, because besides being functional, they also have to be comfortable, and appealing, so that participants are willing to wear them in daily life. We made the experience, that we always had to come to a compromise between robustness and wearing comfort and appeal. The basic constructional design for all our prototypes was a rather small and discreet bracelet being the visible part of the prototype, requiring an additional armlet carrying all the bigger electronics, which was hidden under the wearer's clothes if possible. This compromise enabled us to create discreet bracelets that were close to the conceptual designs and thus easier to communicate to study participants. With this constructional design, there was a clear differentiation between the actual bracelet as the subject of the study, and the technical attachment that was needed only to run the bracelet. Nevertheless, we found some participants could hardly tune out the armlet and the cable going there from the bracelet, and gave feedback such as "I found the cable disturbing.".

Through our studies, the most frequent problem were solder joints that broke during daily use. Also, situations occurred when the friction on clothes caused stationary charge of electricity, that lead to malfunctions. We reduced these errors by covering the electronics on the armlet with felt. Further, we found participants need very clear instructions on how to use the wearable prototypes in specific real-life situations. Especially for worn prototypes this is critical as they are inevitably involved in all the wearer's activities. E.g., participants have to be instructed on how to deal with the prototype regarding sports, wash, housework, sleep, travelling, charging, damage, and how they can identify whether the prototype is working or not and how to react if it is not.

Overall, for getting early feedback on SDJ concepts, evaluating early prototypes in situ can offer valuable insights. Despite the challenges and the effort, we highly encourage other researchers to involve field studies when researching wearable technology.

### 7.4.5 Lab User Study

Besides field studies, we also did a lab study in which we evaluated the TangibleApps bracelet (see Chapter 6). In general, prototypes used for lab studies do not need to be as robust as when tested in the field. Thus, lab studies are an easier way to evaluate early wearable prototypes. The lab study we conducted provided meaningful insights into the design of and interaction with the TangibleApps bracelet. It allowed us to evaluate the concept of the TangibleApps bracelet and the user experience towards the TangibleApps bracelet prototype under specific lab conditions. However, this study setup did not allow to gain any insights on the usage of the system under real-world conditions. We could only test the scenarios that we chose for the lab study, and did this under lab conditions. Particularly for wearable technology, which is highly woven into everyday life, studying it under real-life conditions is important. Consequently, for wearable technology we consider lab studies as a useful supplement to field studies, but see the bigger value in field studies.

### 7.4.6 Individual Sketching Sessions

In the course of two studies, we conducted individual design sessions in which participants designed light patterns for a point-light bracelet (see Chapter 4), and a presentation design for the WaterJewel bracelet (see Chapter 5). Therefore, participants were provided with paper templates and sketches, and could use crayons and paper to modify these and to visualise their own ideas.

We found the sketching sessions to be an easy way for participants to express their thoughts and ideas on a system's design. Further, the feedback from the participants was richer and more detailed, in comparison to the feedback gathered through, e.g., interviews or questionnaires, where participants could only phrase their thoughts but not sketch them. In the study in which participants designed light patterns for a bracelet, we presented the patterns on a working prototype immediately after the design. This procedure turned out to be helpful as it enabled participants to get a realistic impression of how the light patterns were represented by an LED-based prototype.

A limitation of this method is that the outcome depends on the ability of the participants to draw, design, and be creative. Some participants had inhibitions to draw freehand sketches. They felt more comfortable commenting on and modifying the templates we provided. Further, like for all participatory design methods, participants are influenced by things they already know when sketching and rarely come up with something all-new. Nevertheless, participatory methods enrich the design process in that they enable to include the ideas of persons with different experiences and view points into the design of a system. Thus, designs can be created that could not have been created by a single person alone.

### 7.4.7 Lo-Fi Prototyping Workshop

For designing the TangibleApps bracelet, we conducted a quick and dirty prototyping workshop (see Chapter 6). In a quick and dirty prototyping workshop, participants use various everyday materials to build Lo-Fi prototypes, shapes, and to visualise interactions. The materials can include, e.g., paper, chenille wire, modelling material, handicraft materials, cable fixer, sponges, straws and more [IDE02]. Lo-Fi prototyping workshops are typically used to create early designs not influenced by technological boundaries, to stimulate creativity, and to get early feedback on possible design solutions before these are implemented.

During the crafting session, we observed that typically, participants started with an initial idea that they extended and refined while crafting. In small teams they discussed their designs already while building and immediately tried to find solutions for problems that they revealed during the crafting process. E.g., some participants built a prototype and, when looking and interacting with their result, found that the interaction they envisioned would not work properly, or that they missed some important aspect. During the workshop, we also observed that participants from one team asked questions on the design of another team and got into discussions. Thus, the crafting process by itself stimulated an analysis and led to serious discussions on the crafted objects while they were still being built. Our experiences square with the view of Kettley, who argued that crafting as a creative process leads to products with more authenticity [Ket07].

In the beginning, some participants were sceptical about the method and it took them a few minutes to become familiar with the task and the materials provided. However, after a familiarisation phase, we found also these participants were crafting with zeal. Overall, participants liked to craft by hand and to be able to actually touch their designs. They valued the three-dimensional objects they created as a medium to illustrate their ideas to others. From our observations of the participants' behaviour and from the richness of the results, we experienced the crafting workshop not only as an easier method for the participants, but also as a method that stimulated more serious discussions, in comparison to the sketching design sessions. However, Lo-Fi prototyping workshops are a participatory design method, and as such, the limitations for the sketching sessions described above also apply there. Further, this method is limited in that the variety of results depends on the materials provided. Also, while watching and talking to other participants within group sessions can stimulate the design process, it might also influence the results in a way that they become more similar and thus represent more some kind of group solution than individual solutions.

## 7.5 Future Work

While conducting the research of this thesis, we identified a number of open questions that should be considered in future work.

### 7.5.1 Applying Design Recommendations to Sophisticated Smart Digital Jewellery

In this thesis, we gave recommendations for the design of SDJ, that we derived from a number of user studies with early SDJ prototypes. The next step should be to apply the design recommendations to a high-fidelity, appealing piece of SDJ, to then test it with potential users in the field. To ensure the creation of a high-fidelity piece of SDJ, jewellery designers, artisans, and wearable computing design and development specialists should be included in the development process. Afterwards, it is necessary to evaluate the high-fidelity SDJ prototype with users in the field over a longer period. The focus of the study should be on usability, user experience, and further qualitative insights on the usage of the SDJ prototype and how well it blends in with real-life situations and environments. This should include experiences and reactions of observers towards the piece of SDJ. The results of the study would help to validate and to refine the design recommendations.

### 7.5.2 Usage of Several Different Pieces of Smart Digital Jewellery

We know that people like to wear not only one particular, but several different pieces of jewellery (e.g., [PLEG13]). Further, people like to change their pieces of jewellery every now and then. Future work needs to investigate how to enable switching between different pieces of SDJ. Open questions are, how the features of one piece of SDJ can retain on other pieces of SDJ, i.e., be transferred, and how the interaction concept could be transferred to different forms, e.g., from a bracelet to a ring. Further, if several pieces of SDJ are worn at the same time, it needs to be investigated how these could corporate and complement each other.

### 7.5.3 Single- vs. Multi-Purpose Smart Digital Jewellery

In the research presented in this thesis, we investigated both, single-purpose, and multi-purpose SDJ. Among current wearable products, we also find both, single-purpose, as well as multi-purpose devices. In our studies, some participants stated they clearly preferred single-purpose over multi-purpose wearables. However, we do not now how this scales. We would like to see future work investigating if and in how far single- or multi-purpose is better suited for SDJ, or if both approaches are desired and suitable. Besides surveys, research should include user studies to investigate in how far single- or multi-purpose SDJ performs better in real-life situations in terms of usability, user experience, and integration into everyday life.

### 7.5.4 Natural Interaction With Smart Digital Jewellery

Further, in this work, we researched common input methods for physical interactive systems, such as pushing a button. Having a look at how people deal with jewellery, we find behaviour such as turning a ring on a finger, opening and closing the clasp of a bracelet, or turning and shuffling around the charms of a bracelet. Future work should investigate in how far such natural behaviour towards jewellery is suited to operate SDJ, which further interactions such approaches enable, and if such approaches can improve the user experience of SDJ.

## 7.6 Concluding Remark

Traditional jewellery shall last for life. In particular, when made by a goldsmith, jewellery is often worn for many years, even decades. This is due to the fact that such jewellery is expensive, unique, and often has emotional value for the holder. In contrast, fashionable jewellery is cheaper, produced in quantity, and trend-oriented, and therefore typically worn for only a few years or months. Technology evolves rapidly, and what is state of the art today is likely to become obsolete within the next years. So, for SDJ this might either mean that SDJ only addresses fashionable jewellery which has a short life span anyway, or that the technology used is that simple that it will probably last for longer, at least from the technological progress point of view (compare Versteeg et al. [VvdHH16]). However, questions arise on how to deal with issues, such as, when the technology is faulty, particularly when the piece of jewellery has emotional value for the holder. It could have psychological consequences that go beyond the worry for a "defective device". In our view, the concept of a precious life companion does not apply well to SDJ. Instead, we see great potential for SDJ that is applied to fashionable jewellery which is worn for one or a few years.

# Figures

# Tables

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