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Enhancing the Visual Output of Smart Watches using Garment-Based Displays

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Abstract

In the last few years, smartwatches started to become popular. Many large-scale manufacturers have begun releasing their smartwatches. Despite this fact smartwatches still have constraints, that limit their usage. The biggest constraint of smartwatches is the small screen size, which restricts input and output capabilities. This work focuses on enhancing the output capabilities of smartwatches using garment-based displays. Current research suggests that garment-based displays will become feasible in the near future. This would enable the possibility to utilize garment-based displays as an extension for the smartwatch screen. Considering that there are many possible positions on the body for a garment-based display, we explored the users' location preferences for body-attached displays. Since a low-resolution display prototype was built to simulate a garment-based display, we also explored users' preferences for visualizing information on low-resolution displays. One common use-case for smartwatches that is limited by the screen size is the interaction with maps. As this work focuses on enhancing the output capabilities of the smartwatch, a new off-screen visualization technique using the display prototype is proposed as a way to minimize this limitation. We then implemented the off-screen visualization technique and conducted a user study in which we compared our approach to two known off-screen visualization techniques.

Kurzfassung

In den letzten Jahren sind Smartwatches immer beliebter geworden. Viele große Hersteller haben damit begonnen, ihre eigenen Smartwatches auf den Markt zu bringen. Trotz allem gibt es noch Einschränkungen bei der Nutzung von Smartwatches. Die größte Einschränkung ist hierbei die kleine Bildschirmgröße, die vor allem die Eingabe- und Ausgabefähigkeiten einschränkt. Diese Arbeit konzentriert sich darauf, die Ausgabefähigkeiten von Smartwatches mithilfe von textil-basierten Displays zu verbessern. Die aktuelle Forschung suggeriert, das textil-basierte Bildschirme in naher Zukunft realisierbar sind. Dies würde es ermöglichen, textil-basierte Bildschirme als Erweiterung für Smartwatch Displays zu verwenden. Da es viele verschiedene mögliche Positionen für textil-basierte Displays am Körper gibt, haben wir die Vorlieben von Benutzern in dieser Hinsicht untersucht. Da ein textil-basiertes Display durch einen niedrig auflösenden Display Prototypen simuliert wird, wurden auch die Vorlieben von Benutzern in Hinsicht auf die Visualisierung von Informationen auf niedrig auflösenden Displays untersucht. Ein allgemeiner Anwendungsfall von Smartwatches, der durch die geringe Bildschirmgröße eingeschränkt wird, ist die Interaktion mit Karten. Da sich diese Arbeit auf die Verbesserung der Ausgabemöglichkeiten von Smartwatches konzentriert, wird eine Off-Screen Visualisierungstechnik vorgeschlagen, die den Display-Prototypen verwendet, um diese Einschränkung zu minimieren. Diese Off-Screen Visualisierungstechnik wurde implementiert und mithilfe einer Benutzerstudie mit zwei bereits bekannten Off-Screen Visualisierungstechniken verglichen.

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1 Introduction

The first evidence of the smartwatch becoming popular was the Pebble Smartwatch. It was financed through Crowdfunding in 2012, thereby being one of the most successful crowdfunding campaigns at this time with 85.000 supporters. This large number of supporters makes it clear that there is a huge market demand for smartwatches. Therefore, many large-scale manufacturers such as Apple or Samsung recently began releasing their own smartwatches [RPP14]. Despite the popularity of smartwatches, there is still no real consensus on what their capabilities should be. The main question is if they should only be limited-function fitness devices or fully independent computing devices. This question probably originates from the fact that smartwatches are in some ways restricted in their capabilities. Constraints of smartwatches include limited battery capacity, less precise sensors and the small screen size which restricts input and output capabilities. On the other hand, the smartwatch offers advantages such as its mount location, which is an already known, standard location and also its continual connection to the skin that offers opportunities to identify the user's physical activities and location. Constraints such as limited battery capacity and less precise sensors will certainly be overcome in the near future since hardware components get smaller through advances in sensor technologies and electronics. Overcoming the small screen problem proves to be the biggest challenge. Garment-based displays could help to overcome this limitation of smartwatches. They could be utilized to extend the smartwatch screen without the user having to carry a bigger watch or additional gadgets. The current research suggests that garment-based or, in general, flexible, thin displays will become feasible in the next years. New technologies such as printed electronics offer possibilities for creating paper thin, deformable electronics made up of fabric [Ste15]. Other technologies explored for creating garment-based displays include optical fiber displays and electroluminescent displays.

This thesis explores possibilities to utilize garment-based displays as an enhancement for the visual output of smartwatches, thereby focusing on the concept of using garment-based displays as an extension of the smartwatch screen. Considering that the screen extension doesn't necessarily have to be placed right next to the smartwatch, we explore the users location preferences for body-attached displays. Since garment-based displays, are not yet commercially available, we built a low-resolution display prototype to simulate a garment-based display. Therefore, we also explore the users preferences for visualizing content on low-resolution displays. A commonly used feature on smartwatches that is limited by the small screen size is the interaction with maps. To overcome this limitation we propose an off-screen visualization technique, that utilizes an additional body-attached display. We implemented the concept and compared it to two known off-screen visualization techniques.

Outline

This thesis is structured the following way:

Chapter 2 – Background and Related Work: In this chapter the related work which serves as a basis for the thesis is discussed. Focusing on smartwatch interaction, off-screen visualization and display technology.

Chapter 3 – Designing Garment-Based Displays: In this chapter the concept of this work is described, as well as the design space of garment-based display as an enhancement for the visual output of smartwatches.

Chapter 4 – Exploring Location and Visualization Preferences: In this chapter location and visualization preferences are explored in a user study.

Chapter 5 – Implementation: This chapter describes the implementation of an off-screen visualization technique using the display prototype as well as the implementation of two other techniques, Arrows and Halos.

Chapter 6 – Evaluation - Comparing Off-Screen Visualization Approaches: In this chapter the evaluation is described. The display prototype off-screen visualization technique is compared to Arrows and Halos.

Chapter 7 – Conclusion and Future Work This chapter summarizes the results of this work and provides ideas for possible future work.

2 Background and Related Work

This chapter is divided into three topics to provide a wide-ranging overview of related work relevant for this thesis. The first section covers smartwatch interaction, thereby focusing on different input and output techniques. The second section covers different approaches for off-screen visualization. The third part focuses on display technology, especially concentrating on garment-based and low-resolution displays.

2.1 Smartwatch Interaction

To cover the whole topic of smartwatch interaction we have to discuss different input and output techniques. The current main input technique for smartwatches is touch input, which is restricted by the small screen size. Therefore, current research while focusing on enhancing touch input also focuses on exploring novel input techniques, such as gesture input. Visual output is the most widely used output technique on smartwatches, which is just like touch input restricted by the small screen size. Hence, research focuses on enhancing the visual output as well as exploring other also commonly used output techniques such as auditory and vibrational output. In the context of multimodal feedback, haptics has been shown to complement sight and sound [Cor10].

2.1.1 Touch Interaction

Most existing mobile devices have touch screens. Therefore touch is the most commonly used input technology. Since the extremely small size of the screen on devices like smartwatches hinders the touch interaction by occluding the screen during input, many new approaches have been explored to better utilize the touch screen technology.

One direction of approaches has explored the possibility to enhance touch input by combining or extending it with other input techniques. For instance Oakley et al. presented "beating gestures" a new type of multi-finger input, which is based on pairs of simultaneous or rapidly sequential touches made by the index and the middle finger of one hand. [OLIE15]. They want to minimize the need for on-screen feedback or ensure that the critical content is visible on the screen. The input technique received generally positive feedback in their conducted study regarding speed and convenience. Although users expressed some concerns regarding the unfamiliarity of the input method. Oakley et al. show some limitations to their work, regarding non-existing multi-touch screens on smartwatches, high power consumption through rapidly polling touch sensors and a need to perform further studies to establish whether a broader population of users can perform beating gestures. They also consider trying beating gestures on larger devices with graphical feedback. TapSense [HSH11] is an enhancement to touch interaction that allows touch surfaces to identify the object being used for input. Harrison et al. identify the object by its unique acoustic signature created when touching the surface. With this approach, they can use new types of finger input technologies, using the pad, tip, knuckle and nail. This could be useful to solve the small screen problem considering that for example using only the fingernail for input would prevent the finger from occluding large parts of the screen. Their study shows that the technique is extremely accurate and immediately feasible. Heo and Lee explored ForceTap [HL11] a technique combining the touch input with the tapping velocity as detected by a built-in accelerometer as an addition to a mobile devices touch screen interaction techniques. They created an algorithm that detects whether the contact with the touchscreen is a gentle tap or a strong tap. Their experiments show that ForceTap is feasible and can be learned well without visual feedback.

Baudisch and Chu claim that any pointing technique on the devices front will occlude content and prevent precision [BC09]. As a solution some techniques [WFB+07, BC09] have been proposed to utilize the devices back for touchscreen interaction. This completely prevents the fingers from occluding the screen while using the device. LucidTouch [WFB+07] allows the user to control a device from its backside. This is realized using pseudo-transparency meaning the user can see his hands while attempting to acquire a target from the back of the device. It supports input from all ten fingers at the same time. They don't show the users hands directly. Instead, they overlay an image of the user's hand with touch-cursor over each fingertip that can be seen in Figure 2.1. This makes it clearer visible for the user which touch cursor belongs to which finger. For the prototype, they used a camera to capture the fingers for display and to detect touch-cursor locations. To detect the points of contact with the fingers they used a touch pad and mounted it behind the display. Baudisch and Chu explore using touch on the backside of very small touch devices. They created a prototype called nanoTouch [BC09], a small screen device with the possibility to use touch input on the devices back. They also provide device concepts ranging in size from a ring to a clip-on. In contrast to LucidTouch [WFB+07], NanoTouch doesn't use a camera. NanoTouch simulates a camera based on the positions of the fingers on the touch pad and a pre-rendered image of a finger.

The approach of utilizing the devices backside is taken further by proposing transparent devices. Iwabuchi et al. present LimpiDual [IKN08] a transparent display that supports dual-sided touch input. The user can operate the device from its backside. Since the display is transparent, the user can see both the displayed content and his fingers. LimpiDual also supports interactions from multiple users. They can share the display from both sides and control objects on the screen simultaneously. Another touch enabled transparent device is tPad [HRRB+14], a transparent tablet device. Hincapié et al. explore how such transparent tablets can be used for everyday tasks like multitasking and information capture. Their results show that interactions

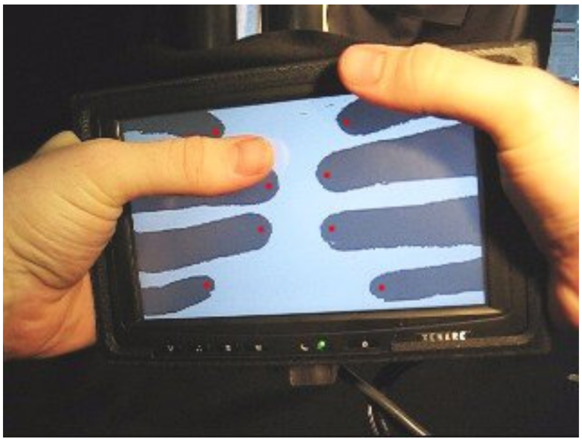


Figure 2.1: LucidTouch [WFB+07] is a pseudo-transparent device that allows the user to control the device from its backside while still being able to see his hands.

with transparent displays outperform interactions with non-transparent displays. Othani et al. compared front and back touch using transparent double-sided touch displays [OHKN11]. They came to the conclusion that users are most accurate when using both sides. Although using both sides is slower than just using the front touch, because the users could see the location and motions of their fingers on the back of the screen.

Butler, Izadi, and Hodges propose another approach to solve the occlusion problem that occurs during touch interaction with small screen devices. They investigate using touch on the space around small screen devices [BIH08]. They created SideSight, a prototype that supports virtual "multi-touch" interactions around the body of the device, in a situation where the device is located on a flat surface. They use optical sensors, which are positioned on the edges of the device to sense the presence and position of the fingers. Similarly Han, Ahn and Lee present Transture, a technique that allows to continue touch gestures beyond the screens border in the air [HAL15]. For their prototype, they used a smartwatch with a depth camera attached. They implemented three Transture examples and tested them in a user study. Thereby they observed some issues and plan to improve Transture in the future.

2.1.2 Gesture Interaction

On small screen devices, touch input occludes large parts of the screen. Therefore, gestural input has been explored as an alternative input technique. Song et al. explored "In-air Gestures" for utilizing the space around mobile devices without occluding large parts of the screen like touch input on small screens does. They propose a machine learning algorithm to recognize the gestures using only the devices camera [SSP+14]. Since cameras are nowadays available on almost every smartphone, this could be a possibility to make gesture interaction accessible to a large user base. They proposed some interaction scenarios to allow the

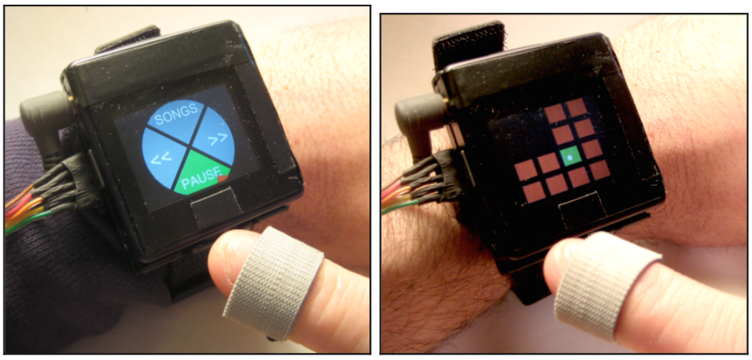


Figure 2.2: Abracadabra [HH09] is a magnetically-driven finger input technique, which supports two different input modalities. The one on the left is a one-dimensional polar input and the one on the right enables the user to use the finger as a cursor.

user to switch easily between touch and gesture interaction and also use touch and gesture interaction simultaneously. In contrast to using the devices camera for recognition Gesture Watch [KHLS07] and HoverFlow [KR09] use infrared proximity sensors to track hand gestures. GestureWatch allows users to control other devices with hand gestures, whereas HoverFlow already integrates the sensors into a mobile device. Although in GestureWatch Kim et al. provide a concept of how those sensors might be integrated into a wristwatch. Similarly to GestureWatch, ShoeSense [BMR+12] is a wearable system that allows to control other mobile devices with gestures. It consists of a depth sensor mounted on a shoe which points upward at the wearer. ShoeSense recognizes discreet hand gestures as well as large and demonstrative hand gestures. They present three sets of hand gestures that can be performed without much visual attention from others. ShoeSense could be a solution to overcome the problems of using small screen devices with touch input. Also using ShoeSense simple tasks could be carried out without reaching in your pocket for your mobile phone and without disturbing other people since discreet hand gestures are used. Their study showed promising results regarding social acceptance and gesture recognition with a rate of 94-99% even for eyes free gestures.

Many different techniques are used to recognize gestures, apart from using the camera, proximity sensors or depth sensors Harrison and Hudson present Abracadabra, a finger input technique that is magnetically-driven. They support two different input modalities that can be seen in Figure 2.2. The first one is one-dimensional polar input circumscribing the device and uses information from the sensor's two axes to calculate a bearing to the users finger. The second input modality approximates the spatial location of a user's finger by taking into account the field strength, which makes it possible to use the finger as a cursor [HH09]. Their study shows that users can achieve a high selection accuracy with their technique, even outperforming touch-based finger input in some scenarios. Gupta et al. present SoundWave a technique that uses the speaker and the microphone of devices to sense in-air gestures around the device. [GMPT12]. They generate an inaudible tone, which gets frequency-shifted when it reflects off moving objects like hands and measure this shift with the microphone to infer various gestures. Their solution only uses components that are already available in most devices which could make it easily accessible to a large number of users.

2.1.3 Other Input Techniques

Some approaches utilize the other parts of the smartwatch for input instead of the screen, meaning for example the wristband or the bezel. For instance WatchIt [PLEG13] is a prototype device that uses the wristband of the smartwatch for interaction and provides two interaction techniques for command selection and execution. Method one is rolling the finger along the watchstrap for scrolling and method two is pointing to the position on the watchstrap for pointing. For selecting items in a list, the users preferred the natural scrolling, although the pointing achieved better results. Similarly Funk et al. also propose utilizing the wristband of the smartwatch for input [FSHS14]. They propose a text entry technique using a touch-sensitive wristband. They created two keyboard layouts, a multitap layout, and a linear keyboard. Their study showed that the multitap layout outperforms the linear keyboard. In the future, they want to create a complete user interface that can be controlled with the wristband. Another approach utilizing the wristband is BandSense [AHY+15]. It is a prototype that supports pressure-sensitive multi-touch interaction on a wristband. Their system is built with two pressure-sensitive, multi-touch sensors, a micro-controller, and a pressure-sensitive multi-touch gesture recognition software. They present various applications with several input vocabularies.

In the US patent "Watch device having touch-bezel user interface" [LML+10] using the bezel of a watch for touch input is described. This is realized by putting a sensor in the bezel of the display for detecting when the bezel is touched by a user of the watch device. The sensor is described as being capable of detecting single presses, multiple presses, multiple simultaneous presses and scrolling motion presses about the bezel.

Xia et al. propose a complementary input approach, which uses the watch as a multi-degree-of-freedom mechanical interface [XLH14]. They developed a smartwatch prototype that supports continuous 2D panning and twist, as well as binary tilt and click. This input technique can be used simultaneously with physical buttons, touchscreen and voice.

Ashbrook et al. present Nenya, a new input device that is shaped like a finger ring [ABW11]. Scrolling for example through a menu can be done by twisting the ring and selections can be made by sliding the ring along the finger. Since the device has the form of a normal ring its use is socially acceptable. Even eyes-free users were able to select from eight targets using the ring.

2.1.4 Visual Output

Researchers have explored visual output techniques in the context of mobile public display systems. Najafizadeh et al. present "I like this shirt" [NKF15] tangible manifestation of the ubiquitous Like button embedded in a t-shirt. Their approach combined input and output in smart clothing. The t-shirt can be "liked" by tapping on the shoulder, and the current "like count" can be seen on a display on the front of the shirt. Their prototype shows that wearables could enrich social interaction. Falk and Björk similarly present a mobile public display that could enrich social interaction. Their prototype BubbleBadge [FB99], is based on a handheld video-game console that is placed in the proximity of the face of the user, providing information to others. This can enrich a face-to-face conversation by providing additional information without being intrusive. Pearson et al. explore the users' acceptance for using smartwatches as public displays [PRJ14]. They investigate the social acceptance and the noticeability of looking at someone else's watch. They show that glancing at someone else's watch is already a common social practice and watches are either fully or partially visible to those nearby. Alt et al. explore how mobile public display systems that change their own context fast can gather and process information about their context [ASE09]. This could be realized by using different sensors such as Bluetooth or GPS. Also, further context could be used such as the weather or the number of people close by. Context-aware mobile public displays could be used for example to show location-specific ads. Participants in their study stated that they would wear such a system displaying ads for a compensation but were concerned about other people seeing the display asking questions about the content.

Visual output has also been explored on on-body displays, which transform the human skin or other parts of the body into an interactive surface. Olberding et al. explore the design space of a display enhanced forearm [OYNS13]. Since the display of smartwatches is very small, they find it promising to extend the screen to cover the entire forearm. They focus on the hybrid nature of the forearm as a private and public display surface. Their prototype is limited since it doesn't offer a continuous display although the concept is fully transferable to such displays. Similarly Weigel et al. envision very small displays that are worn on the fingernails. [WS13]. This could be practical since humans mostly use their fingers to interact with the environment. They are currently working on a prototype that is made up of color micro-displays connected to a microcontroller that the user wears on his arm. The controller senses interaction with a microphone on each finger. External objects are recognized through RFID. On-body displays have also been explored as tools to interact with other devices. Zadow et al. present SleeD, a touch sensitive sleeve display that can be used to interact with multi-touch display walls [ZBL+14]. They created two prototypes, one based on a bendable e-ink display and the other on a conventional smartphone, both were placed on the forearm. They presented sample applications to show the concept for this type of future devices.

Roto and Oulasvirta explore the need for non-visual feedback in Mobile HCI [RO05]. In their study, they explored the deployment of attention during the loading of a web page on a mobile device. The visual attention of the user shifted away between 4 and 8 seconds. Based on their study results they recommend multimodal feedback for mobile devices.

2.1.5 Haptic Output

Different forms of Haptic Output have been explored. Mostly not specifically in context of smartwatches but for mobile devices in general. Hoggan et al. investigated the effectiveness of tactile feedback for mobile touchscreens [HBJ08]. They evaluated the effectiveness of finger-based text entry for mobile devices with touchscreens. By comparing devices with a physical keyboard, a standard touchscreen and a touchscreen with tactile feedback. Their study showed that adding tactile feedback to touchscreens improves the performance and comes close to the performance of physical keyboards. They compared two types of tactile actuators. Using specialized actuators that can provide localized feedback, further improved text entry on touchscreens opposed to a single standard actuator that vibrates the whole device. The use of tactile feedback seems to have no drawback and it could be included in all mobile devices while could benefiting fingertip interaction as well as stylus interaction.

Pfeiffer et al. investigate using electrical muscle stimulation (EMS) for feedback when performing hands-free interaction [PSAR14]. With EMS, many different feedback strengths and characteristics are possible. Since the EMS feedback system is for example placed on the forearm and the feedback is perceived at the hand, the system can be used without being visible to other people. In the future, they consider combining EMS feedback with other haptic feedback methods such as vibrations.

The Tickler is a wearable tactile display that creates natural-feeling stroking sensations [KR15]. The feedback is very different from the usual vibrotactile stimulation that is typically used in tactile devices. The Tickler could be integrated into watch straps and other wearable devices since the design is simple and could be readily miniaturized. It presents a new technique to create tactile devices that can interact with humans in a natural and comfortable way.

Wilson investigated the use of thermal stimulation as feedback for mobile devices in his Ph.D. thesis [Wil13]. Since audio and vibrotactile feedback are not always usable or desirable, thermal feedback provides an interesting alternative. Since every object in our environment has a current temperature and a rate of thermal conductivity thermal feedback is a natural way to provide feedback. It has been used in Virtual Reality but is less established in HCI. Wilson concludes that thermal feedback is a promising means of conveying information especially indoors, where the identification achieved higher rates than outdoors. It can provide a unique form of tactile feedback.

2.1.6 Other Output Techniques

Aside from visual output and haptic output, other output techniques have been explored. Two examples for this are auditory and gestural output.

EarPod is an eye-free menu technique using touch input and reactive auditory feedback [ZDC+07]. EarPod gives the user auditory feedback that is directly linked to the touch input. The EarPod uses a circular iPod-like touchpad. By sliding the thumb, items can be discovered and selected by lifting the thumb. When sliding the menu titles are played out loud and when moving the finger faster partial playback of audio is caused.

Roudaut et al. propose using spatial gestures not only for input but also for output [RRS+13]. They propose a gesture output which moves the user's finger in a gesture that the user then recognizes. To realize this they built a long range (4cm) and a short range prototype (1cm). The devices have an actuated transparent foil overlaid onto their touchscreens which actuates the user's fingers. In the future, they want to investigate how to combine gesture output with spatial input and visual output.

2.2 Off-Screen Visualization

Many approaches are already known for visualizing content that doesn't fit on small screens – so called off-screen visualizations. These techniques point users in the direction of objects located off the screen. The following section provides an overview of different Off-Screen Visualization techniques.

Baudisch and Rosenholtz present an off-screen visualization technique called "Halo". Halo surrounds off-screen objects with large enough rings to reach the border of the display window enabling users to infer the location of the off-screen object at the center of the ring [BR03]. Compared to an arrow based visualization (see Figure 2.3) technique in their study Halo proves to be significantly faster, although there were no significant differences in error rate. Similarly Zellweger et al. developed a technique called City Lights [ZMG+03]. They use points, lines, and/or 2D objects along the window, to show information such as direction and distance. An example of CityLights use can be seen in Figure 2.4. Using lines they also convey information about the size of the off-screen object, by making the line equally long as the width or the height of the corresponding object. They found out that the user experience is generally positive since points and lights don't distract from the view and only minimal training is required. However, the Halo [BR03] seemed to improve the performance of the users on small mobile devices and for map based tasks.

Gustafson et al. propose an off screen-visualization technique called "Wedge" [GBGI08]. They use acute isosceles triangles (Wedges) to point users in the direction of off-screen content. The technique can be seen in Figure 2.5. The tip of the triangle is the location of the off-screen object

Figure 2.3: A comparison of the Halo and Arrow visualization techniques [BR03]. The arrows on the left point to POIs located off-screen and display the distance to them. The Halos on the right are located around the POIs, the distance can be inferred by the size of the Halo visible on the display.

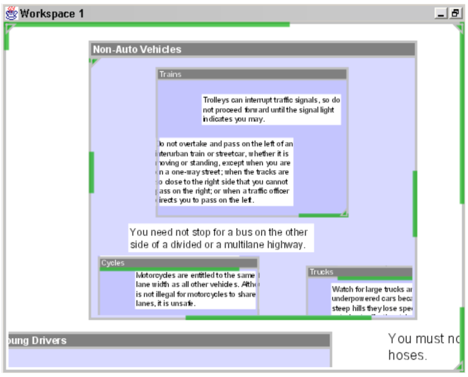


Figure 2.4: City Lights [ZMG$^+$03] with lines along the borders of the windows to point the user in the direction of off-screen objects. The length of the line corresponds to the length or width of the object located off-screen.

and the "legs" located on the screen point towards the target. The Wedges programmatically avoid overlaps. They show that their Wedge technique proves to be significantly more accurate than the use of Halos [BR03].

Irani, Gutwin and Yang propose four design goals for selecting off-screen targets: "off-screen object awareness" meaning users should be easily aware of the presence of the off-screen objects, "minimal navigation" meaning users should not have to put more effort in navigating to the off-screen objects than to on-screen objects, "context visibility" meaning users should still be able to make use of the environment surrounding the target and "full-scale view" meaning users should be able to decide if the potential targets are important.[IGY06]. Based on these design principles they developed a technique called "hop" "combining Halo [BR03], a proxy technique to bring targets close to the user's cursor and a teleportation mechanism to transport

Figure 2.5: Wedge [GBGI08] uses acute isosceles triangles to point users in the direction of off-screen content, whereby the tip of the triangles is the location of the off-screen object and the "legs" are located on the screen and point towards the target.

the user to the location and context of the target" Their results underscore the usefulness of halos and proxies and show that they can be successfully combined. [IGY06].

Burigat compared Halos[BR03], CityLights[ZMG$^+$03] and Arrows. Their study shows that Arrow and Halo based techniques don't differ much for simple spatial tasks such as finding the closest off-screen object. [BCG06] For tasks where the cognitive demand for the user is higher, the used visualization technique can make a huge difference. Their findings show that Arrow based techniques outperform Halos, especially with many off-screen objects present. Similarly Henze et al. compared three different off-screen visualization techniques by publishing a game in the Android Market [HPB10]. They compared Halos [BR03], stretched arrows and scaled arrows. Their study shows that scaled arrows are more suitable for a larger amount of objects and Halos for a smaller amount of objects. Their results are particularly relevant for systems with a high interactivity since their study analyzed the effect of the off-screen visualization if the user dynamically interacts with the objects.

Schinke et al. explore the visualization of off-screen objects in mobile augmented reality [SHB10]. They created a visualization of nearby Points of Interests based on off-screen visualization techniques for mobile Augmented Reality. They use arrows that are directly embedded in the augmented reality scene to point the user in the direction of the POI. This proved to be faster and more precise than the current mostly used solution of showing a mini-map to provide an overview of POIs that are close by.

Henze and Boll evaluate the use of off-screen visualization techniques for Magic Lens and Dynamic Peephole Interfaces [HB10]. Since map navigation on small screen devices is often limited using a magic lens to interacting with physical objects has been proposed as a solution.

Figure 2.6: Sparkle [MLHB14] is an ambient light display which uses light patterns to point the user to the location of off-screen POIs.

Another approach is the dynamic peephole interface in which a device is moved across a virtual surface. They show that using off-screen visualization improves the users performance for both approaches.

Müller et al. present Sparkle [MLHB14] an ambient light display for dynamic off-screen points of interest (POIs) embedded within a tablet computer. They compared their off-screen visualization technique to arrows. The Sparkle prototype can be seen in Figure 2.6. Sparkle uses light patterns to show different off-screen POIs according to their previously defined encodings of off-screen POIs. The distance of a POI is indicated through the brightness of the light, the brighter the light, the nearer the POI. The direction is projected orthogonally. Their study suggests that Sparkle is competitive to other off-screen visualization techniques.

2.3 Display Technology

Cochrane et al. provide an overview about different technologies used in the production of textile-based flexible displays and screens. [CMKK11]. They discuss Optical Fiber Displays, LED, and Electro -luminescent Displays as possible technologies for garment-based displays. Since Optical fibers have a good size and are flexible, they can be shaped using textile processes like weaving. They were developed as a waveguide to transmit light between two ends of a fiber. They mostly consist of a transparent core which is covered by a cladding material that has a lower refractive index. Optical fibers work with any light source and color and could therefore be used in many different ways.
LEDs can be used to build garment-based flexible displays by utilizing flexible connectors which are available on the market. Advantages of LEDs are also the low-cost and the small size.
OLEDS are solid-state devices composed of thin films of organic molecules. They create light when electricity is applied. In contrast to LEDS, OLEDs are solvent processable and have a lower power consumption. Also, the organic layers are thinner, lighter and more flexible. One

problem of OLEDs is the the lifetime of the emissive polymer layers since it differs for different colors.
Electro-luminescent light emitting textiles are also like OLEDs composed of a conductive substrate, an electro-luminescent compound, and a conductive transparent electrode. In contrast to the OLED compound, the electro-luminescent compound is more stable to oxygen and water and total encapsulation is not necessary. Another technology is thin-film electroluminescence (TFEL). Olberding et al. propose using it to digitally fabricate customized flexible displays [OWS14]. Their approach enables non-experts to print flexible, interactive displays in custom 2D shapes, which can be rolled, bent and folded to create 3D shapes.

Many use cases have been explored for flexible textile-based displays. Burstyn et al. present DisplaySkin, a flexible, large 320-degree cylindrical display used as a pose-aware wristband [BSV15]. DisplaySkin tries to make information for the user easily accessible by placing it in view, independent of the user's body pose. This is accomplished by creating a kinematic model of a user's arm. The prototype was made with an electrophoretic display with a resolution of 354x944 pixels, which was put in a frame and molded into a cylindrical shape. Their results suggest that DisplaySkin is less interruptive than other non-pose-aware wrist-mounted displays when attending to a primary pointing task. Amiraslanov et al. propose a structure based on the elecro-luminescent phenomenon for flexible textile based screens meant for easy prototyping [ACCL]. They demonstrate the screens in three different scenarios, on a window, a bottle, and a gymnastics mat. Similarly Flexkit [HBB+13] is a development platform for rapid prototyping with flexible displays. This should make it possible design applications for flexible displays without knowledge in embedded hardware systems and the corresponding programming. Flexkit makes it easy to design and iterate with electrophoretic displays since it mirrors a laptop's display.

When building a garment-based display the size and the resolution of the display have to be considered. Lischke et al. explored the impact of display size on item search performance and task load [LMW+15]. They didn't find a large impact of the screen size on the task completion time and the perceived task load. Screen sizes up to four monitors with a size of 269.2 x 67.3 cm proved to have benefits. Their study showed that larger screens with a high-resolution can support working with large datasets, especially to discover similarities and trends. Low-resolution displays have been explored in the context of media façades. Hoggenmueller et al. present an approach for prototyping and pretesting hybrid media façades [HW15]. They create multidimensional information layers by using a combination of low-resolution light-emitting diodes (LED) and front projected high-resolution content. They developed a purpose built toolkit, which is composed of off-the-shelf hardware and software components, to empower designers and architects to explore novel media façade types.

Grubert et al. present MultiFi an interactive system that combines the strengths of multiple displays and overcomes the seams of mobile interaction with widgets distributed over multiple devices [GHQS15]. Their prototype consists of two smartphones, one simulating a next generation smartwatch, it can be seen in Figure 2.7. On the arm clipboard, extended screen

Figure 2.7: MultiFi [GHQS15] combines the strength of using multiple displays by using widgets distributed over multiple devices.

space for low fidelity widgets can be seen Spatial pointing enables switching to the high fidelity widget on a handheld, which offers more detailed information. They demonstrate that using Head-Mounted-Displays and smartwatches together can outperform using only a single wearable device.

3 Designing Garment-Based Displays

As previously mentioned in the related work (Chapter 2), visual output is the most commonly used output technology for smartwatches. Since the small display limits the visual output, we focus on overcoming this limitation. In this chapter, we provide a concept for enhancing the visual output of smartwatches using garment-based displays as well as an in-depth analysis of the design space.

3.1 Design Space for Garment-Based Displays

Garment-based displays or, in general, body-attached displays offer many opportunities for enhancing the visual output of smartwatches. Not only for personal use but also for use as public displays. Different questions we have to consider when building such as system, as well as concerns and limitations, are discussed in the following

3.1.1 Location on the User‘s Body

Choosing the proper location for the garment-based display on the user's body is dependent on many factors. First a decision has to be made about the usage of the display. Mainly if it should be utilized for personal or public use. This decision has a big influence on the possible position of the display. A display for public use should be placed on the users body in such a way that it is easily visible to other people. Possible locations for the display are also dependent on the desired size of the display. Since the desired size for a public display would probably be relatively large, possible locations could be the back or the chest or maybe even the back of the head. A private display has other implications on the location. It should be placed in such a way that it is easily visible to the user himself. Considering that a display for private use might offer sensitive information, it should possibly also not be easily visible to others. Possible locations could be a standard location like the forearm or different locations such as the thighs.

3.1.2 Resolution of the Display

Current prototypes of garment-based displays mostly have a rather low-resolution. This provides some constraints for the possible enhancement of the visible output of smartwatches since only a small amount of content can be displayed. However, this also challenges to carefully consider what to display. This could lead to showing only the most important content. High-resolution garment-based displays would make it possible to show more detailed information. This would make it an option to display all content that is too small on the smartwatch screen on a larger garment-based display. Examples for such content could be photos or large amounts of text. Altogether there are use-cases for low-resolution as well as for high-resolution garment-based displays.

3.1.3 Display Size and Form Factor

The display size and form factor just like the location highly depend on the use of the display as a private or public display. Another factor is the location itself which limits the size and form factor of the display. A public display as discussed previously might be placed on the chest or back. At this location, a bigger sized display would be possible. To utilize the most space, a rectangular display would be the obvious choice. It also wouldn't have to be extremely flexible or round. On the other hand when using the garment-based display as a private display, the locations for the display are restricted to places visible by the user such as the forearm. The forearm highly restricts the size of the display and demands a highly flexible display with a possibly cylindrical form to utilize the most space.

3.1.4 Purpose of the Display

The purpose of the display just like the other dimensions of the design space highly depends on the use of the display as a private or public display. We discussed garment-based public display systems in the related work. Many approaches for mobile public display systems already exist, proposing different use-cases from enriching social interaction to displaying location-specific ads. A garment-based display for private use might be utilized to extend the screen of wrist-worn devices. This could provide the opportunity to display additional information that might be too big for the small smartwatch screen or also visualizing off-screen content. In the case of high-resolution garment-based displays, everything too detailed to see on a small screen could be displayed on the additional display.

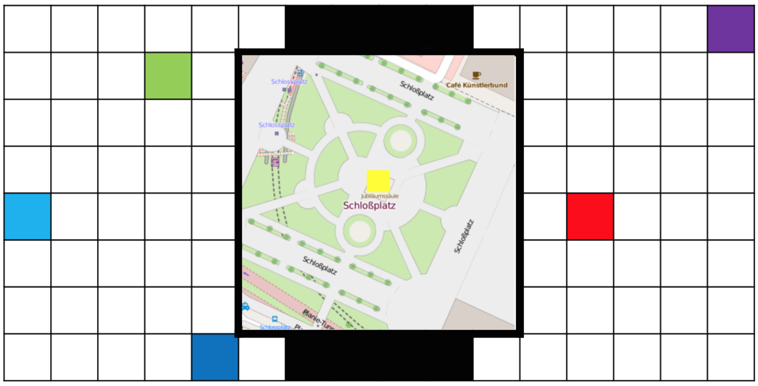


Figure 3.1: Off-Screen Visualization using a garment-based display. POIs (colored squares) not currently visible on the smartwatch screen are shown on the garment-based display.

3.2 Combining Smartwatches and Garment-Based Displays

The following section focuses on combining garment-based displays and smartwatches. We describe two different concepts to utilize garment-based displays to enhance the visual output of smartwatches. The first concept proposes an off-screen visualization technique using the garment-based display to show content that is located off of the smartwatch screen. The second concept proposes using the garment-based display to show additional information to the information already displayed on the smartwatch screen.

3.2.1 Off-Screen Visualization on Garment-Based Displays

Many approaches for off-screen visualization have already been explored. Some of those approaches were discussed in the related work (Chapter 2). These approaches point users in the direction of objects located off-screen using Arrows, Halos [BR03], CityLights [ZMG+03], Wedges [GBGI08] and other similar techniques. These techniques are all limited to using the edge of the screen of the utilized mobile device. A garment-based display located around or behind a smartwatch would provide additional screen space that could be used to enhance and refactor these off-screen visualization techniques.

A concept for an off-screen visualization technique using a garment-based display can be seen in Figure 3.1. In this Use-Case, Points of Interest (POIs) are shown on a map. The garment-based display is used to display the POIs that are not currently visible on the smartwatch screen. The display, in this case, a 16x8 pixel display, is placed under the smartwatch. The different POIs are displayed in various colors, on the screen of the smartwatch as well as on the garment-based display. The distance of the markers from the smartwatch screen is mapped onto the garment-based display.

3.2.2 Extending the Smartwatch Screen using Garment-Based Displays

The design space of a display enhanced forearm as an extension of the smartwatch screen has already been investigated [OYNS13]. This approach can be enhanced by using garment-based displays. In the following, we discuss two different use-cases for a display enhanced forearm.

One use-case in which the screen space of the smartwatch is extended onto the forearm, by placing the garment-based display next to the smartwatch, could be visualizing the heartrate when using a smartwatch or another fitness tracker during sport. The garment-based display could be used to offer additional information, an example of this can be seen in Figure 3.2. The smartwatch displays the current heartrate, and the display prototype offers the trend of the heartrate over time as additional information.

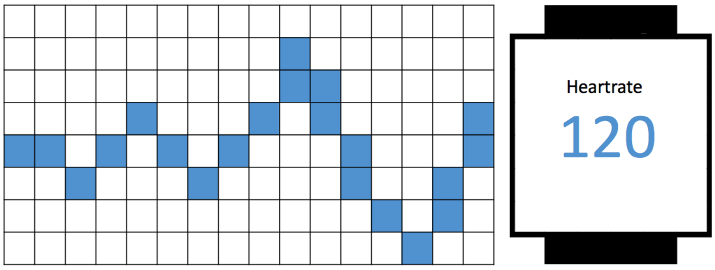


Figure 3.2: A garment-based display used as an extension of the smartwatch screen. The trend of the heartrate over time is visualized as additional information on a 16x8 pixel display.

Another use-case that utilizes the garment-based display as an extension of the screen space could be displaying notifications (see Figure 3.3) in a simple way. This could, for example, be realized by assigning symbols to important contacts or applications. The blue square in this example would make it quite easy to see that you have a notification from Jenny with just a glance while simultaneously displaying the message on the smartwatch.

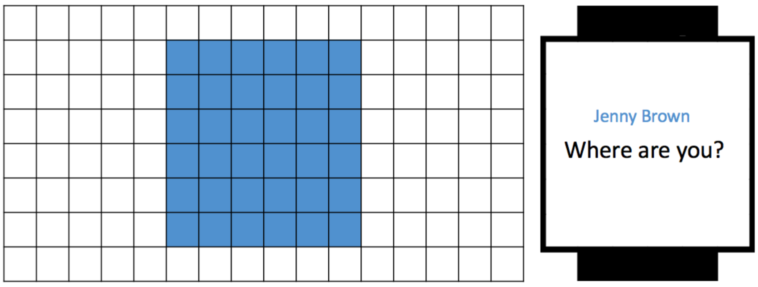


Figure 3.3: A garment-based display used as an extension of the smartwatch screen. A notifications is visualized as a symbol to make it easily visible

4 Exploring Location and Visualization Preferences

In this chapter, we explore the preferences of users for the locations of body-attached displays. We also propose different Use-Cases for body-attached displays as an extension of the smartwatch screen and explore how to visualize those Use-Cases.

4.1 Prototype

We developed a display prototype to examine the design space of garment-based displays as an enhancement for the visual output of smartwatches. Although the related work shows that garment-based displays are feasible in the near future (e.g., [ACCL, CMKK11]) they are not yet commercially available. Therefore, we chose a low-resolution 16x8 RGB LED matrix to simulate a garment-based display. To control the display via Bluetooth, we developed an Android application. The application enables the user to explore different visualizations on the display prototype by making every pixel controllable, meaning the user can set the color for every pixel and, therefore, display any pattern on the prototype. The graphical user interface of the Android application can be seen in the appendix in Figure A.1.

4.2 User Study

To explore the user's preferences for the location of the garment-based display on the body and for visualizing information on low-resolution garment-based displays, we conducted a user study. Sixteen participants between the ages of 20 and 31 (M=23.56, SD=2.9) participated in the study (3 female, 13 male). None of the participants owns or regularly uses a smartwatch.

4.3 Study Procedure

The study consisted of individual sessions of about 15 minutes for every participant. After obtaining informed consent, every participant was given a short introduction of the concept

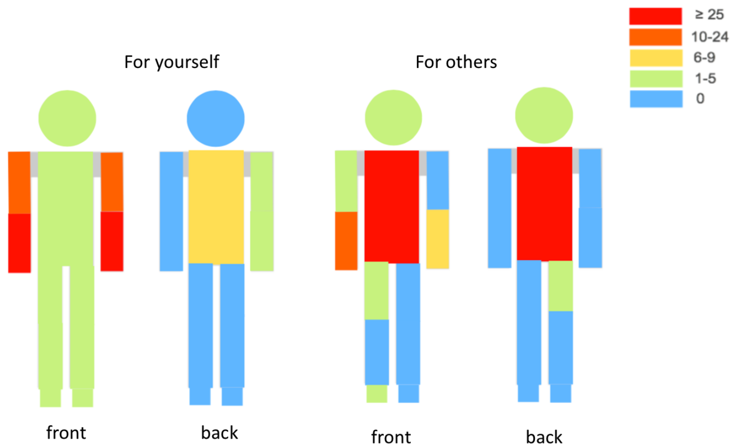


Figure 4.1: Overview of location preferences for body-attached displays.

and the prototype. Participants were encouraged to try out different visualizations on the display prototype. Then the participants were asked to fill out an initial questionnaire (see A.4) about their background. The order for the main questionnaires (see A.5) was determined by a Latin Square design.

Location Preferences To explore the location preferences, the participants were asked to mark their preferred locations for the display on a body sketch for every Use-Case. Once for personal and once for public use of the display.

Visualization on low-resolution Display To explore how participants prefer to see information on a low-resolution display, they were asked to visualize information for six common Use-Cases on a 16x8 pixel raster.

4.4 Results

The results are divided into the location preferences results and the results of the six Use-Cases. The results of the Use-Cases can be seen in full beginning in A.6.

4.4.1 Location Preferences Results

The participants were asked where to place the display for every use-case. Once for personal and once for public use. The combined results of all six use-cases can be seen in Figure 4.1. It is clearly visible that for personal use the participants would prefer wearing a textile-based display on their arms, thereby slightly preferring the lower arm to the upper arm. For public use participants seem to prefer putting the display either on the breast or on the back.

Probably because a large display which is visible from further away can be placed there. Some participants would also place the display on the forearm for public use.

4.4.2 Use-Case 1: Heartrate Visualization

For the first Use-Case, participants were asked to visualize the heartrate. Especially during sport displaying the heartrate is a typical application for sports trackers and watches. Some of the results can be seen in Figure 4.2. Most participants prefer to get the current heartrate displayed as a number, with some participants also preferring a heart symbol next to it as an identifier. Some prefer displaying only a graph of the heartrate over time or the number and an additional graph.

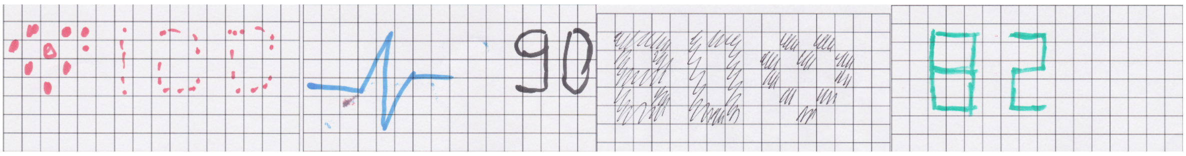


Figure 4.2: Results for the Use-Case Heartrate Visualization.

4.4.3 Use-Case 2: Notifications

For the second Use-Case, participants were asked to visualize notifications, for example from a messenger application. An extract of the results can be seen in Figure 4.3. Similarly to the heartrate many participants chose to display an envelope as an identifier for a notification and additionally the number of new messages or notifications. Some participants would prefer to get the whole message displayed by moving it through the display.

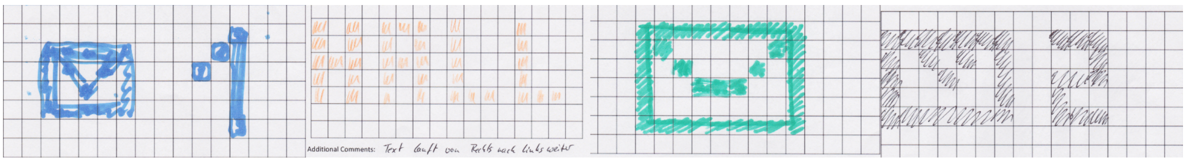


Figure 4.3: Results for the Use-Case Notification Visualization.

4.4.4 Use-Case 3: Navigation

For the third Use-Case, participants were asked to visualize a navigation application. Most participants chose to display arrows to point users in a certain direction. Some displayed an additional number to show when exactly the user has to for example turn left. One different idea was to display the route while marking the current position. Some results can be seen in Figure 4.4.

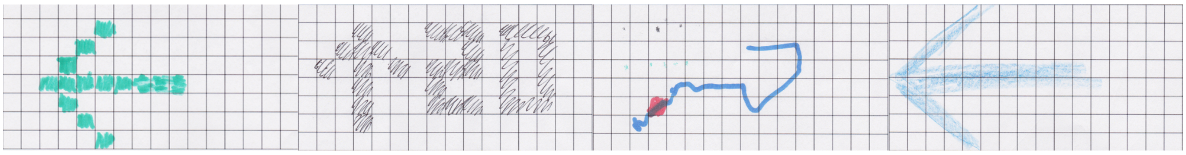


Figure 4.4: Results for the Use-Case Navigation Visualization.

4.4.5 Use-Case 4: Appointments

For the fourth Use-Case, participants were asked to display appointments. Here no distinct preference is visible. Some participants chose to display the current time or the time of their next appointment while some chose to display a date and others the time remaining until the next appointment. An extract of the results can be seen in Figure 4.5.

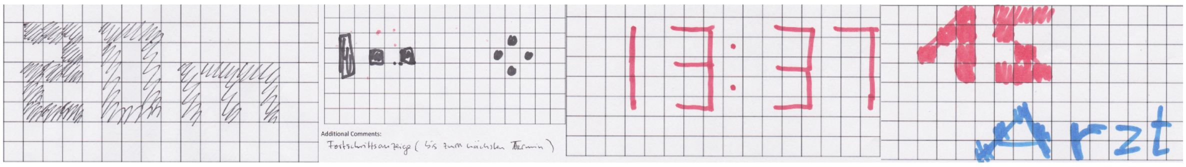


Figure 4.5: Results for the Use-Case Appointments Visualization.

4.4.6 Use-Case 5: Step Counter

The fifth Use-Case was displaying a step counter. The results can be seen in Figure 4.6. Here almost all participants chose to display the number of current steps. One participant drew a progress display to show how many steps of a daily goal have already been reached.

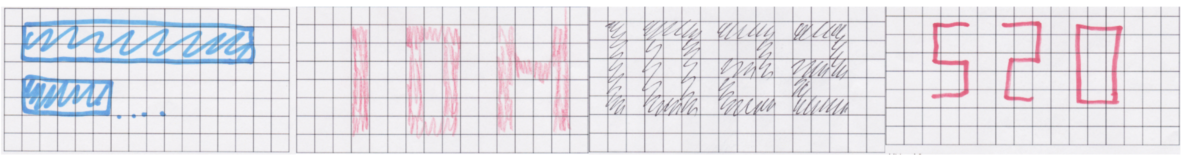


Figure 4.6: Results for the Use-Case Steps Visualization.

4.4.7 Use-Case 6: Weather

For the sixth Use-Case, participants were asked to display the weather. Most participants chose to draw a sun, rain, clouds or lightning bolts. Some additionally chose to display the current temperature. Part of the results can be seen in Figure 4.7.

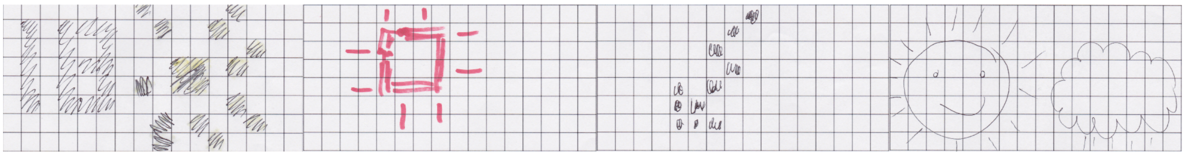


Figure 4.7: Results for the Use-Case Weather Visualization.

5 Implementation

This chapter concentrates on realizing the off-screen visualization concept presented in Chapter 3. We describe the implementation of the concept with the help of a display prototype, as well as the implementation of two known off-screen visualization techniques, Arrows and Halos. The implementation of Arrows and Halos is based on the description provided in Baudisch and Rosenholtz's [BR03] comparison of Halos to Arrows. The three techniques can be seen in Figure 5.1.

5.1 Off-Screen Visualization using the Display Prototype

We built the display prototype using a 16x8 RGB LED Matrix, attached to an Arduino Pro, which is connected to a Bluetooth Mate. The smartwatch used for the implementation is a Simvalley Mobile AW-414.Go smartwatch, with a 240x240 pixels, 1.5"-Touchscreen. In Chapter 3 we described a concept for an off-screen visualization technique using a garment-based display. The display is used to extend a map that is visible on the smartwatch screen. The POIs that are not visible on the part of the map shown on the smartwatch should be visualized on the garment-based display. To realize this concept we developed an Android application that uses the Google Maps API to display a map with several markers on it, which symbolize POIs. The goal is to display the POIs on the display prototype when they are not visible on the

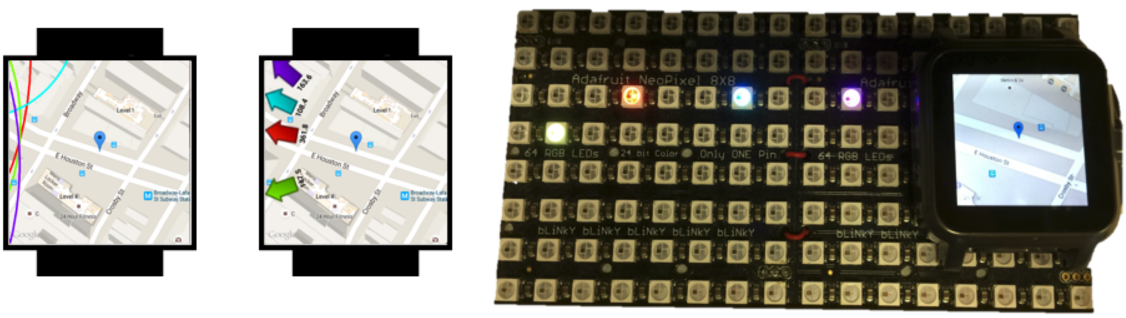


Figure 5.1: Depiction of the three implemented off-screen visualization techniques, Halos, Arrows, and Display Prototype.

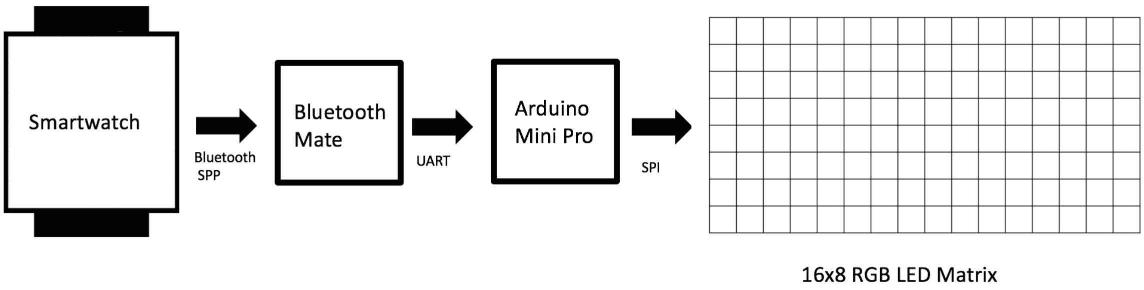


Figure 5.2: Communication between Smartwatch and Display Prototype.

smartwatch screen. In the following, we first describe the communication between smartwatch and display prototype and then the calculation of the POI positions.

5.1.1 Smartwatch - Display Prototype Communication

A sketch of the communication between smartwatch and display prototype can be seen in Figure 5.2. A 16x8 RGB LED Matrix is used to simulate a low-resolution garment-based display. The display is connected to an Arduino Mini Pro, which is connected to a Bluetooth Mate via UART, which enables the Smartwatch to communicate with the display prototype via Bluetooth. To control the display with the help of an Android application, an image is generated on the smartwatch and transferred to the Arduino. The Bluetooth Mate connects the smartwatch with the Arduino through relaying of the serial connection data. Therefore, the smartwatch and the Arduino have a logical serial connection. To show the image on the display a package is transfered which contains the values for all of the 16x8 pixels. For the communication each pixel of the image is encoded in 8-bit truecolor. The partition can be seen in Figure 5.3, the 8 bits describe the red, green and blue values, with 3 bits for red, 3 bits for green and 2 bits for blue.

Bit	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
Data	**R**	**R**	**R**	**G**	**G**	**G**	**B**	**B**

Figure 5.3: 8-bit truecolor, each pixel is represented by one 8-bit byte

Then the data is transfered with the help of frame alignment and byte stuffing [TW13]. Frame alignment is used to guarantee the synchronization between sender and receiver, therefore ensuring that the beginning of the image isn't shifted. A start and an end flag are defined. An

Listing 5.1 Frame Alignment Decoding

```
void loop() {
      if(Serial.available()) {
            char readChar = Serial.read();

            if(!inFrame && readChar == START_ESC) {
                  inFrame = true;
            } else if(inFrame) {
                  if(escaped || (readChar != START_ESC && readChar != END_ESC)) {
                  //interpret char as data
                  addPixels(readChar);
                        escaped = false;
                  } else if(readChar == END_ESC) {
                        onFrameFinished();
                        inFrame = false;
                  } else if(readChar == START_ESC) {
                        escaped = true;
                  }
            }
      }
}
```

Escape flag is defined which equals the start flag, in case a character which is used for the flags occurs in the data. If this is the case the escape flag is placed in front of the ambiguous character before the frame alignment, marking that the character is data and not a flag. In the last step the data is sent over serial to the Arduino. There the data is decoded, first the frame alignment and then the colors. The decoding of the frame alignment can be seen in Listing 5.1.

5.1.2 Calculation of POI positions

To map the POIs onto the display, we calculate their positions on the additional display. We determine the position by calculating a rectangle in geographic coordinates left of the visible region of the map (on the smartwatch screen). This is visualized in Figure 5.4. We calculate the rectangle to check if the POI is located inside of the rectangle and if it is to calculate the POI on the screen by using the position of the POI relative to the rectangle. In the following the calculation of the left rectangle is realized:

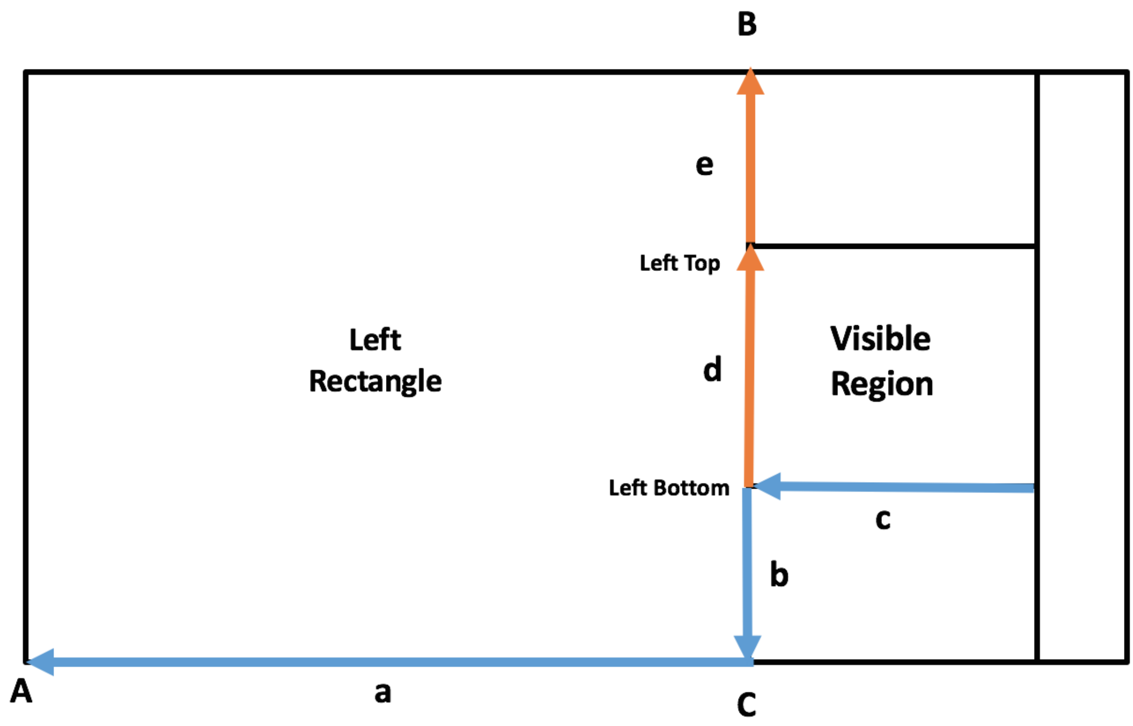


Figure 5.4: Calculation of the rectangle left of the Visible Region.

To calculate d the difference of Left Top and Left Bottom is taken.

Calculate B:

$h : \textit{height factor}$

$B = \textit{left Top} + h \cdot d$

Calculate A:

To calculate c the difference of left Bottom and right Bottom is taken.

$C = \mathit{left\ Bottom} - f \cdot d$

w : *width factor*

$A = C + w \cdot c$

The left square is created from A and B.

5.2 Halos

As a comparison to the off-screen visualization with the display prototype we implemented Halo [BR03]. Our implementation of Halo can be seen in figure 5.1. The Halos are circles drawn around defined POIs, whereby the location of a POI is the center of the circle. The circles have to overlap in the visible screen area of the smartwatch, therefore the further away the POI is the larger the circle has to be and the position of a POI can be inferred.

The radius of the circle is calculated the following:

t_i : *distance between display center and POI*, $i \in \{1, ..., \text{number of POIs}\}$
w : *distance between display center and display edge*
$p \in [0, 1]$: *paramter to define how much the circle is visible in the display area*
r_i : *radius of the circle*

$r_i = t_i - p * w$

5.3 Arrows

As another off-screen visualization technique, we implemented Arrows. The arrows point in the direction of the POIs which aren't currently visible on the smartwatch screen. They also show the current distance to the POIs in meters. In the following we calculate the position of the arrows on the smartwatch screen.

First we look at the line from the center of the screen to the POI.

c : *display center*
d : *direction vector pointing from center to POI*
$l(t)$: *line from center to POI*
p : *arrow position*

$$l(t) = c + t * d$$

We calculate all intersections of $l(t)$ with the border lines e_i of the display, mainly the parameter t_i.

$$t_{\text{min}} = \min\{t_i | t_i \geq 0\}$$

Now we calculate the position of the arrow.

$$p = l(t_{\text{min}})$$

The rotation of the arrows is defined by the vector connecting c and p.

6 Evaluation - Comparing Off-Screen Visualization Approaches

To evaluate the off-screen visualization concept using the display prototype a user study was conducted. The display prototype was compared to two classic off-screen visualization techniques Arrows and Halos based on Baudisch and Rosenholtz's [BR03] comparison of Halo to Arrows. Sixteen participants between the ages of 18 and 26 (M=21.94, SD=2.05) participated in the study (5 female, 11 male). None of the participants owns or regularly uses a smartwatch.

6.1 Tasks

The study consisted of two independent tasks. One map with ten markers was used, always randomly showing four of the ten markers (Figure 6.1). An additional marker was always used as the starting point for all tasks.

Task 1: Closest The user's task was to locate the closest marker on the map, indicated by each of the three of screen visualization techniques (Figure 6.2). The task was explained as a situation in which the user wants to find the closest restaurant on a map.

Task 2: Locate The users's task was to locate the red marker on the map, indicated by the color of the arrow, halo or led on the display prototype (Figure 6.3). The task was explained as a situation in which the suer wants to locate a specific restaurant on the map.

6.2 Study Design and Setup

The study used a Latin square design for both of the two tasks. Each participant repeated Task 1 three times for each of the three off-screen visualization techniques. Then each participant repeated Task 2 three times for each of the three techniques with the addition of using the display prototype in the four different screen sizes 1x4,4x4,6x6 and 8x8 pixels (see Figure 6.4), therefore task 2 was overall repeated six times. During the execution of the tasks, the

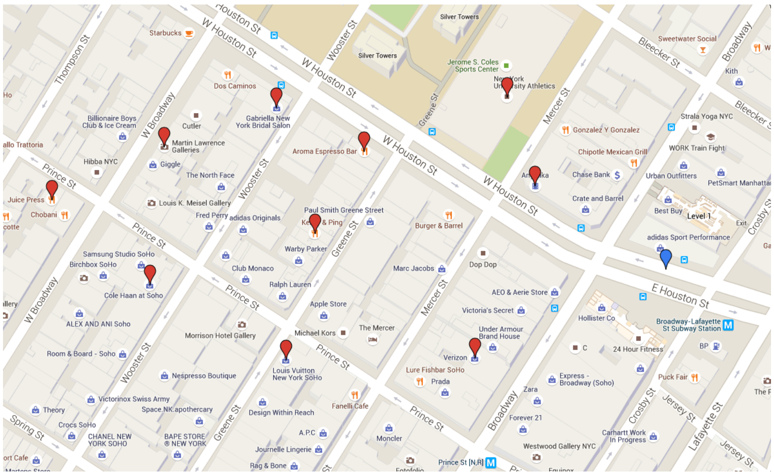


Figure 6.1: The ten markers (red) used for both tasks. The blue marker thereby being the starting point (Map data: Google).

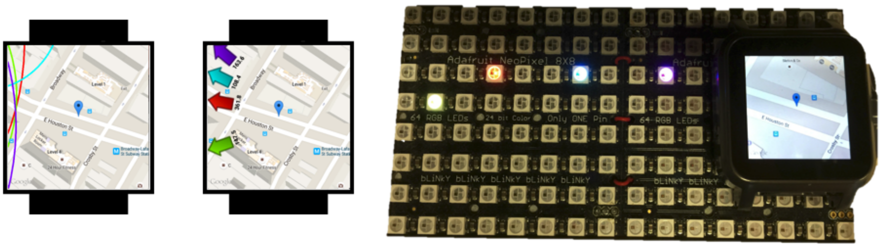


Figure 6.2: Halos, Arrows, and Display used for Task 1.

display prototype was placed on the left forearm with the watch attached to it (Figure 6.5). To compare the different off-screen visualization techniques as well as the different display sizes, we measured the task completion time, error rate and the covered distance.

6.3 Study Procedure

The study was carried out in individual sessions of about 20 minutes. After receiving signed consent, the participants were given a short introduction and demonstration of the three off-screen visualization techniques. Participants first carried out Task 1 and then Task 2. During Task 1 they were asked to fill out a standard SUS questionnaire after each used technique. After finishing both tasks participants were asked to fill out a final questionnaire which asked the participants to rate all techniques used in both tasks in reference to the estimation of distance and direction, on a scale from 1 to 5 (1=simple and 5=difficult) and also to answer some demographic questions.

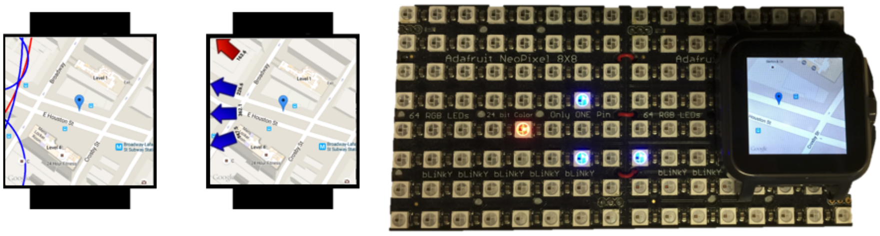


Figure 6.3: Halos, Arrows, and Display used for Task 2.

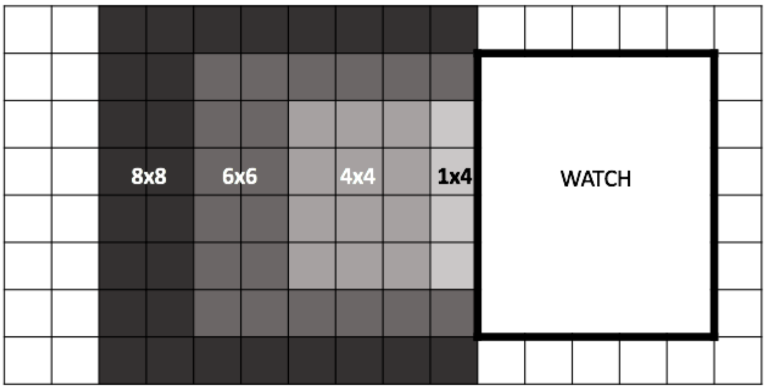


Figure 6.4: Overview of display sizes used for Task 2.

6.3.1 Hypotheses

We investigate the following hypotheses:

H1: The off screen visualization increases the task performance time for finding objects that are not located on the screen.

H2: The larger the display size the faster the participants perform the second task.

6.4 Results

In the following sections the results for Task 1 (Locate the closest Marker) and Task 2 (Locate the red Marker) are described as well as the overall preferences of the participants.

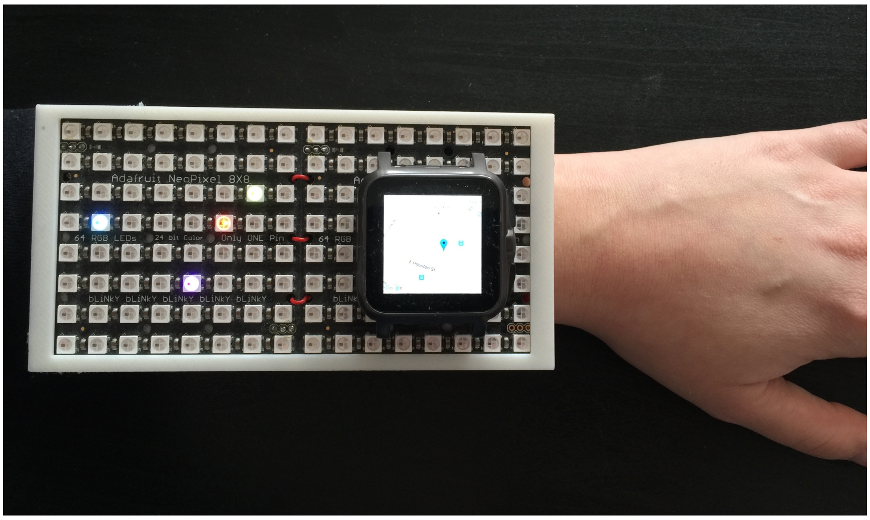


Figure 6.5: Setup of the study. The display is placed on the left forearm with the smartwatch attached to it.

6.4.1 Task 1: Closest

For task 1 participants located the closest markers fastest with the Halos with a mean task completion time of 5.57 seconds (SD=2.44) and 5 errors. The number of errors thereby meaning that participants clicked on the wrong marker 5 times in overall 48 runs of the task (3 times for 16 participants). The mean completion time for Arrows were 7.50 seconds (SD=4.57) with 8 errors and 10.31 seconds (SD=8.06) with 12 errors for the Display Prototype. More information can be seen in Figure 6.6. We carried out a single factor ANOVA to compare the task completion times for the three tested off-screen visualization techniques. There was a statistically significant difference between techniques ($F(2,45) = 4.413$, $p = .0178$). However, post-hoc t-tests with Bonferroni corrected comparisons, between all techniques could not show statistically significant differences.

Figure 6.7 shows the paths participants moved. Each line represents the path of one participant from the start marker to the supposed closest marker. The blue lines show the Arrows movement, the orange lines the Halos movement and the red lines the Display movement. The mean distance moved for Arrows was 180.06m (SD=128.79m), the mean distance for Halos was 221.35m (SD=318.96m) and the mean distance for the display was 405.31m (SD=637.86m). The visualizations show that participants always started moving in the correct direction, they never initially started moving in the right direction. Except for some outliers which took huge detours participants mostly moved straight to the closest markers. The display technique has at least three outliers which probably also influenced the task completion time. One participant moved 2.12km although the closest marker was only 363m away. Another participant moved 2.66km with the closest marker being 166m away, and a third one moved

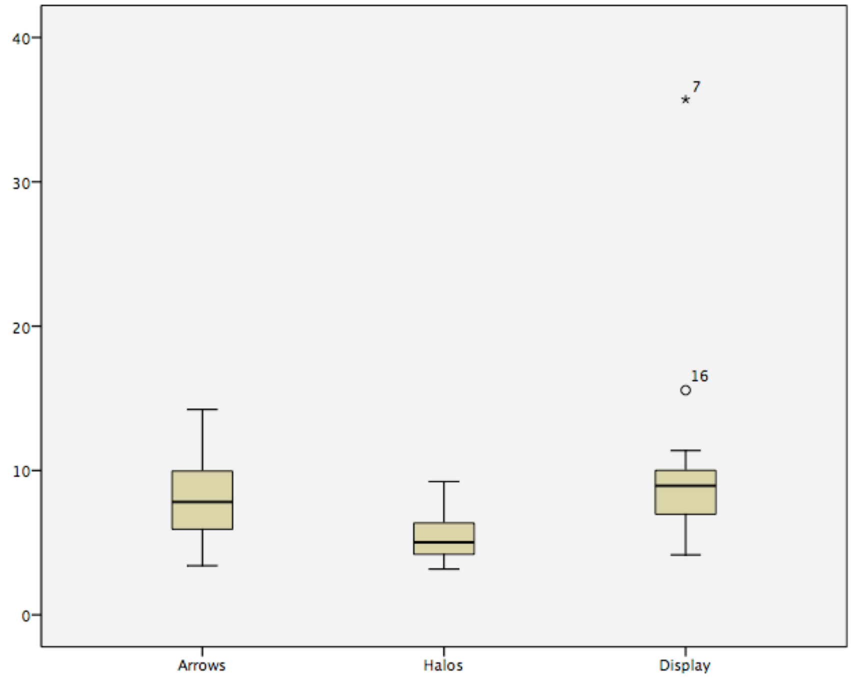


Figure 6.6: Comparison of task completion times in Task 1 of Arrows, Halos, and Display.

3.27km with the closest marker being only 2.74m away. The Arrows technique on the other hand had no significant outliers and the Halos technique only one which moved 2.21km while the marker was only 362m away.

If we leave out this outliers in the results, the Display comes even closer to the completion time of the Arrows technique. The Halos completion time changes from 5.57 seconds to 5.32 seconds (SD=1.65), the completion time for Arrows changes from 7.5 to 7.73 seconds (SD=2.34) and the task completion time for the display changes from 10.31 seconds to 8.12 seconds (SD=2.05).

6.4.2 Task 2: Locate

In task 2 participants were the fastest with Halos with a mean completion time of 5.07 seconds (SD=1.40) and 6 errors. The number of errors thereby meaning that participants clicked on the wrong marker 6 times in overall 48 runs of the task (3 times for 16 participants). The Arrows performed the second best with a mean task completion time of 6.28 seconds (SD=3.16) and 7 errors. For the displays the 6x6 display performed best with a mean task completion time of 7.83 (SD=3.12) and 8 errors. Participants were the slowest with the 4x4 display with a mean task completion time of 9.28 seconds (SD=4.46) but also made only 3 mistakes, which

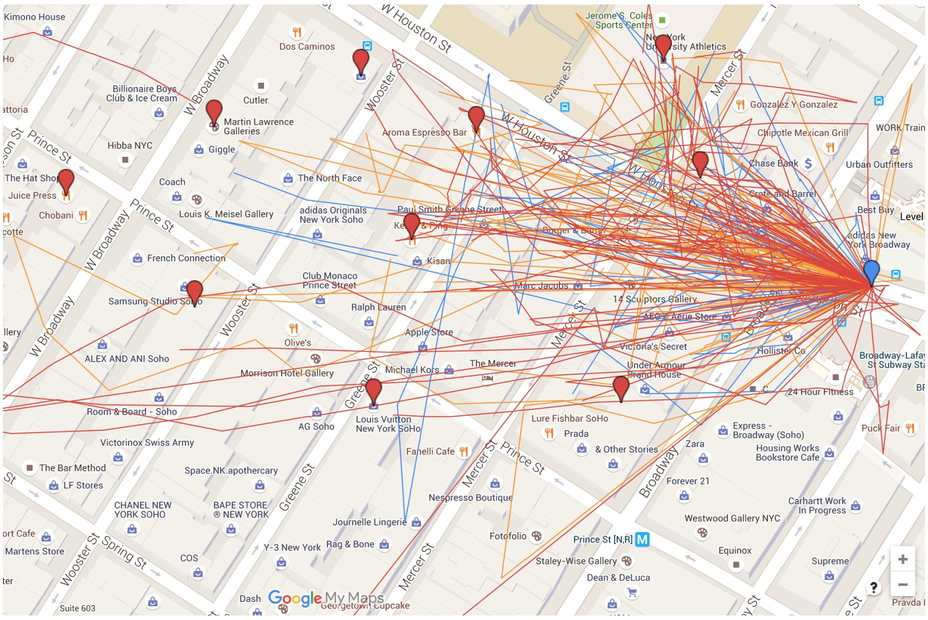


Figure 6.7: Distance covered from start marker to goal markers for all participants using Arrows (blue), Halos (orange), Display (red). (Map data: Google)

was the lowest number. More information can be seen in Figure 6.8. We carried out a single factor ANOVA to compare the task completion times for the six tested off-screen visualization techniques. There was a statistically significant difference between techniques ($F(5,90) = 6.229$, $p = .0001$). However, post-hoc t-tests with Bonferroni corrected comparisons, between all techniques and display sizes could not show statistically significant differences.

6.4.3 Overall Preferences

All three techniques received SUS scores in the high 70s, which according to Bangor et al. are good scores [BKM08]. The Arrows technique received a 78.28 (SD=15.69) SUS score which is slightly lower then the scores of Halos (SD=14.37) and Display (SD=13.51) which are both 79.06. More detailed results can be seen in Figure 6.9. A single factor ANOVA could not show statistically significant differences ($F(2,45) = 0{,}0153$, $p = 0.985$).

For the question "How easy was it for you to estimate the distance to a marker?", the Task 1 display received the best rating with a mean of 1.69 (SD=0.79). The 6x6 and the 8x8 displays also received good ratings with a mean of 1.81 for the 6x6 (SD=0.91) and the 8x8 display (SD=0.91). The 1x4 display received the lowest rating with a mean of 3.06 (SD= 1.44). This was expected since it is not possible to estimate the distance to a marker with a display width of only one pixel. Arrows and Halos received similar ratings with Arrows receiving a mean

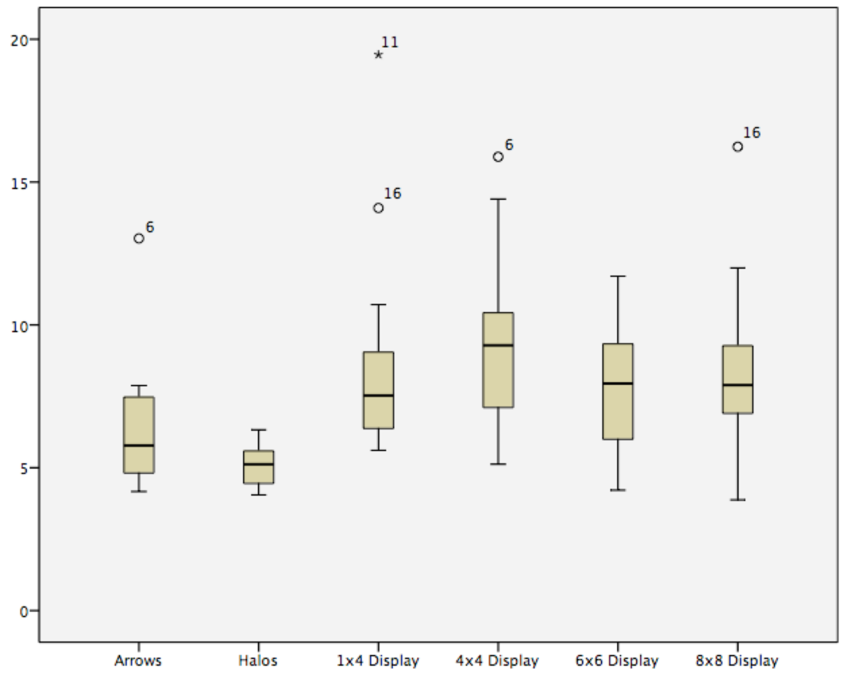


Figure 6.8: Comparison of task completion times for Task 2.

of 2.75 (SD=1.69) and Halos receiving a mean of 2.5 (SD=1.21). More details are shown in Figure A.15.

For the question "How easy was it for you to estimate the direction in which a marker is located?" the Arrows received the best rating with a mean of 1.19 (SD=0.54). The Task 1 display and the 8x8 display also received good ratings with the Task 1 display ratings having mean of 1.5 (SD=0.63) and the 8x8 display ratings having a mean of 1.44 (SD=0.73). The Halos received the lowest rating with a mean of 2.31 (SD=1.19), followed by the 1x4 display with a mean of 2.19 (SD=1.22). More details are shown in Figure A.16.

6.5 Discussion

Our results suggest that the off-screen visualization technique realized with the display prototype performs comparable to the two established techniques Arrows and Halos. Although the display was not faster comparing the task completion times (H1), there was no statistically significant difference found between the three techniques, showing that the display is at least competitive to Arrows and Halos. This conclusion is also supported by the fact, that the task completion time of the display is close to the completion time of Arrows if we leave out the huge outliers. The display size did not have the expected impact on the performance of the

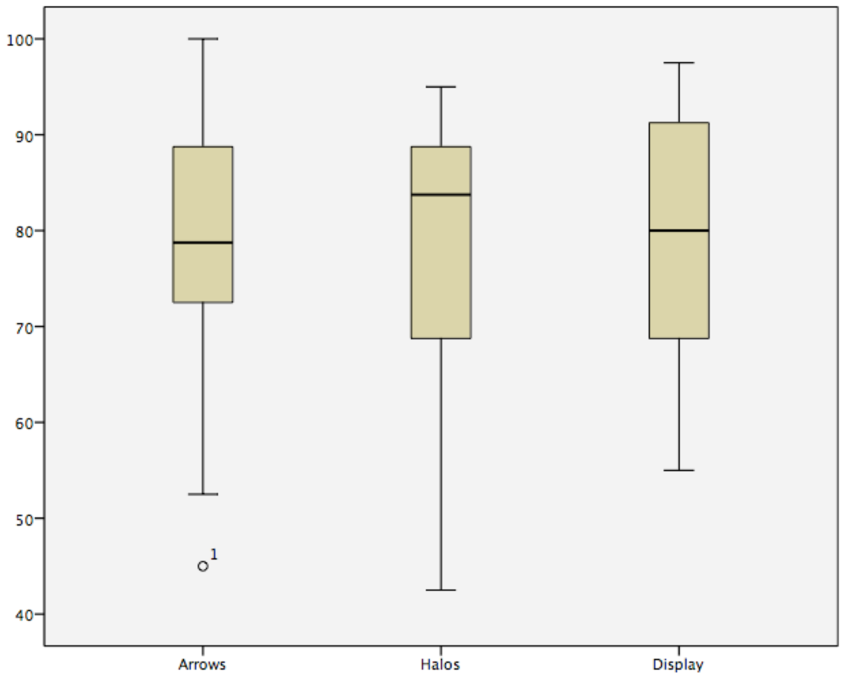


Figure 6.9: SUS Scores for Arrows, Halos and Display (Task 1).

second task (H2). We expected participants to perform faster the bigger the display, but this trend is not visible in the results. However, the significance of the results is slightly limited by the high variance of the results. Also, the communication over Bluetooth or, in general, wireless communication always has certain delays that could influence the results.

7 Conclusion and Future Work

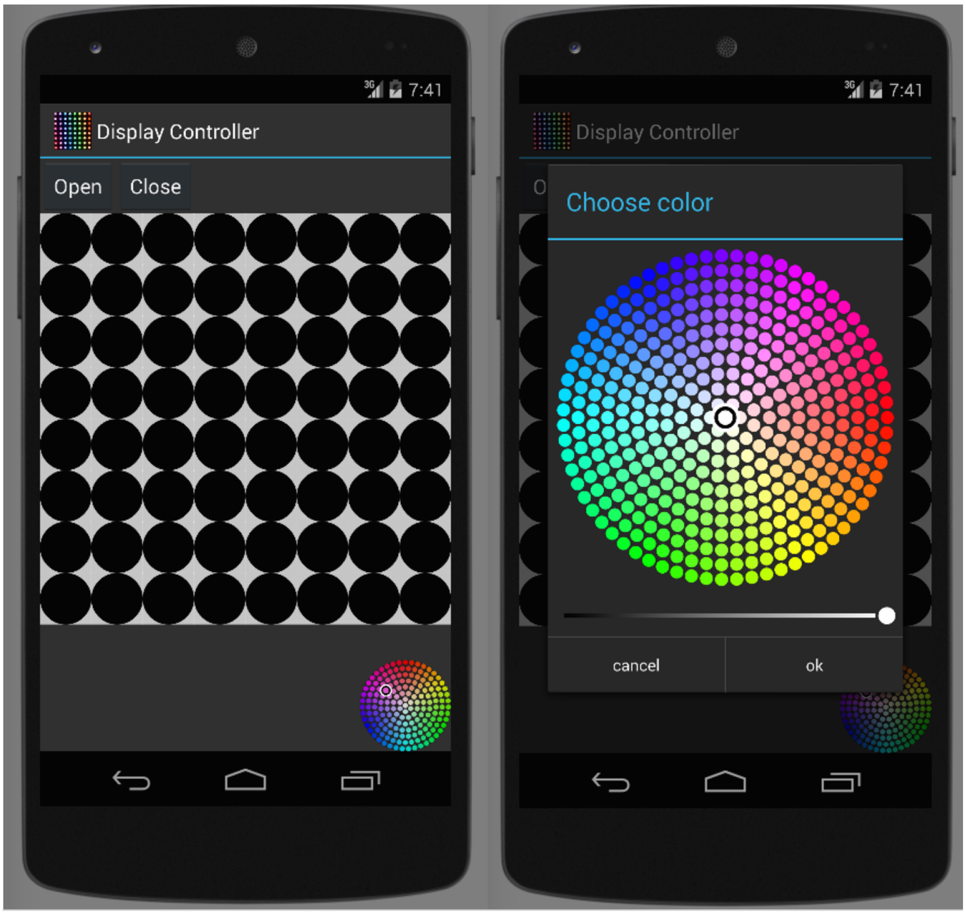
This work explored the possibility of enhancing the visual output of smartwatches using garment-based displays. To get an overview of the different topics relevant to this work we first looked into the related work. Thereby focusing on Smartwatch Interaction, Off-screen Visualization, and Display Technology. The most commonly used output technology for smartwatches is visual output. In contrast to vibrational or auditory output, it is also the most limited by the small screen of the smartwatch. Therefore, we focused on overcoming this limitation. First, we analyzed the design space for garment-based or, in general, body-attached displays while differentiating between the use of the display as a private or public display. We discussed the location on the user's body, the resolution, the size and form factor as well as the purpose of the display. Then we proposed the concept of an off-screen visualization technique that uses the garment-based display to show content that is located off of the smartwatch screen. Another concept we proposed was to utilize the garment-based display to extend the smartwatch screen by showing additional information to the content already visible on the smartwatch screen. In a user study, we explored the location preferences of users for body-attached displays. Since we built a low-resolution display prototype to simulate a garment-based display we also explored the users preferences for visualizing content on low-resolution displays. We decided to implement the off-screen visualization concept as well as two already known off-screen visualization techniques, Halos, and Arrows. The implementation of Halos and Arrows is based on the description provided in Baudisch and Rosenholtz's [BR03] comparison of Halos to Arrows. We evaluated our off-screen visualization concept by comparing it to Halos and Arrows in a user study. Thereby we also explored four different sizes for the display prototype. For each technique participants had to locate markers on a map. For the first task they had to locate the closest marker and for the second task the red marker. We measured task completion times, error rate and distance covered. The study results suggest that our technique is at least competitive to the two known off-screen visualization techniques Halos and Arrows. The fact that the display performed slightly slower than the other two techniques might have been influenced by the communication over Bluetooth since wireless communication in general always has a certain delay. Another factor could be the high variance of the results. We couldn't find the expected correlation between performance and display size, which was that participants perform faster the bigger the display.

Future Work

We mostly focused on implementing and evaluating the off-screen visualization concept. Therefore, it could be interesting to implement other use-cases. In Chapter 3 we proposed using a body-attached display to show additional content to the one already visible on the smartwatch screen. We could implement this approach for the use-cases discussed in Chapter 4. Since we asked participants in the user study which visualization they would prefer for each use-case we could implement the mot commonly suggested visualizations. Both concepts could be enhanced by building an actual garment-based display. This could be done by exploring the technologies discussed in the Related Works chapter. A flexible display would also enable us to explore different locations for the display on the body such as the upper arms the thighs or even the feet. Furthermore, since we only focused on using the garment-based display for personal use, we could also explore garment-based displays in the context of mobile public displays.

A Appendix

A.1 Android Application - Exploring Location and Visualization Preferences



A.2 Study Guide - Exploring Location and Visualization Preferences

Study Guide

1. Introduction

- "This study is part of my bachelor thesis and explores how the visual output of smartwatches can be enhanced using garment-based displays."
- "This is done by evaluating six possible use-cases. "
- "This is the prototype, a 16x8 display which can be controlled with this android app. " *(Explain App)*
- "You can withdraw your participation in this study at all times"
- "The study begins with an initial questionnaire and a consent form. Then the questionnaires for the six use-cases are filled out one after another."

2. Hand over Consent Form and get signature
3. Hand over Questionnaire A
4. Hand over Use-Case Questionnaires 1-6 *(Explain Use-Cases)*

A.3 Consent Form - Study 1 and 2

Consent Form
Study Title

Participant-ID.: _____ Name: ___________________

I understand the nature of this study and I was informed that I can cancel my participation in the study at any point. All collected data will be used for research purpose only and is collected anonymously.

Date ________________ Signature ______________________

A.4 General Questionnaire - Exploring Location and Visualization Preferences

Questionnaire A
Enhancing the Visual Output of Smartwatches using garment-based Displays

Participant-ID.: _____ Name: ___________________

Part A – General Questions

A.1 Gender [ ] Female [ ] Male

A.2 Age ______ A.3 Course of Studies _________________________

Part B – Usage

B.1 Do you own a Smartwatch? [ ] Yes [ ] No

B.1.1 How regularly do you use your Smartwatch?

[ ] Rarely use it

[ ] Occasionally use it

[ ] Often use it

B.1.2 What do you use your Smartwatch for?

[ ] Looking and acting on notifications

[ ] Health and Fitness Apps

[ ] Checking the weather

[ ] Navigation

[ ] Checking Appointments

[ ] Other: ______________________________

____

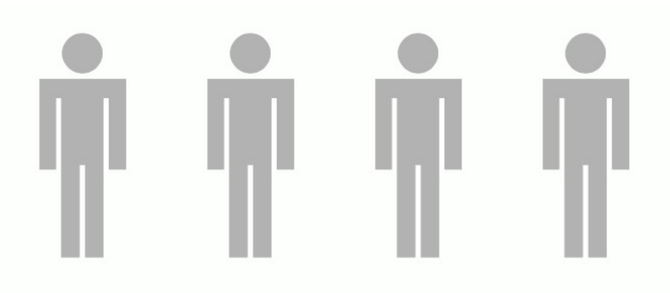
A.5 Questionnaire Use-Case X - Exploring Location and Visualization Preferences

Questionnaire B.X **PID___**

Use-Case X: ---- Visualization
---Description---

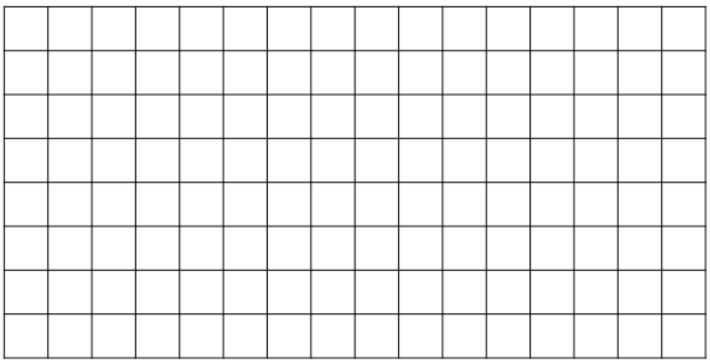
Where on the body should the display be placed to display this information? (Please mark below)

For yourself **For others**



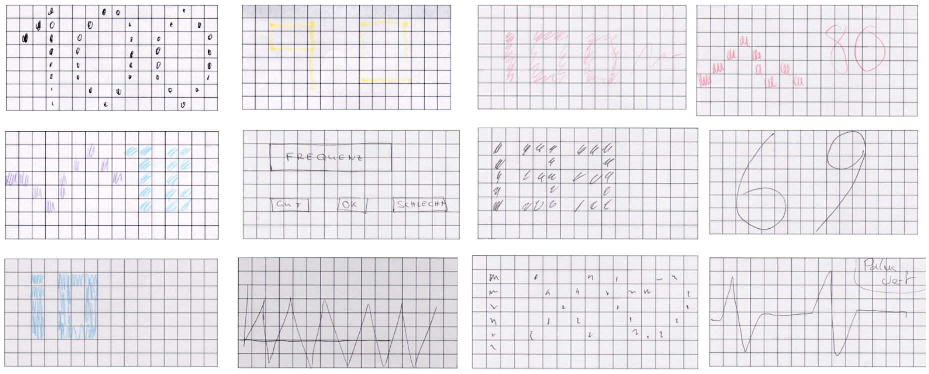
Front **Back** **Front** **Back**

How should this information be displayed (16x8 display)?

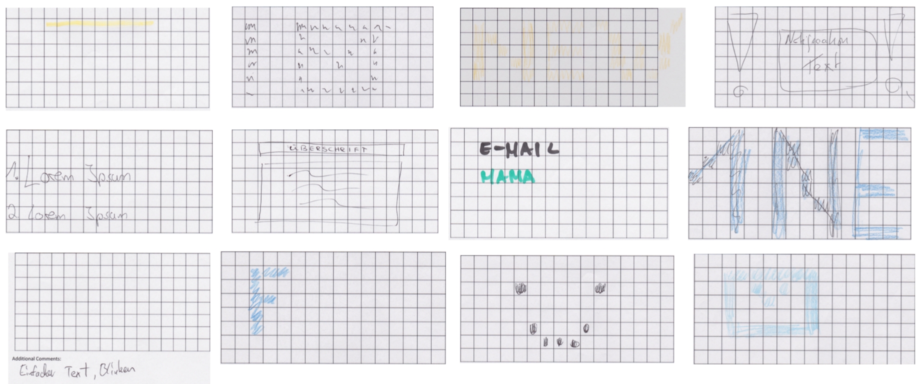


Additional Comments:

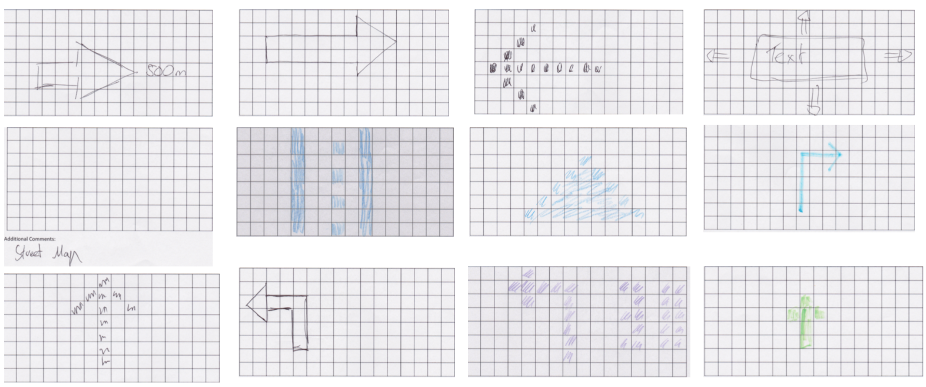
A.6 Results Use-Case 1



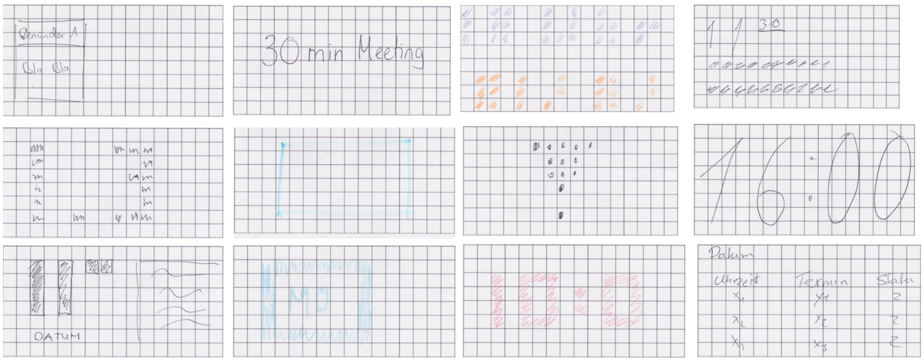
A.7 Results Use-Case 2



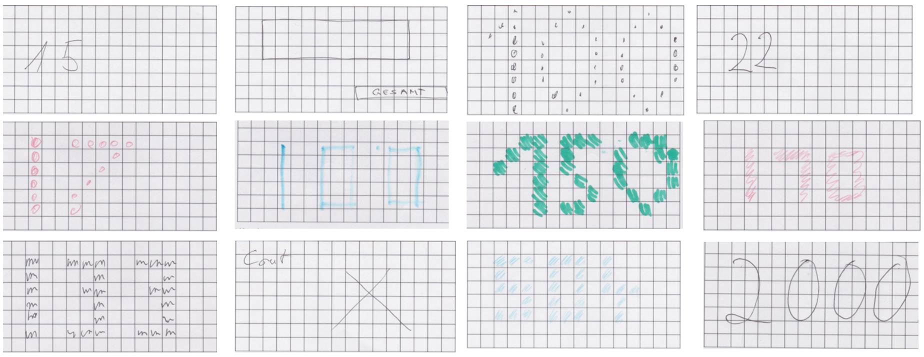
A.8 Results Use-Case 3



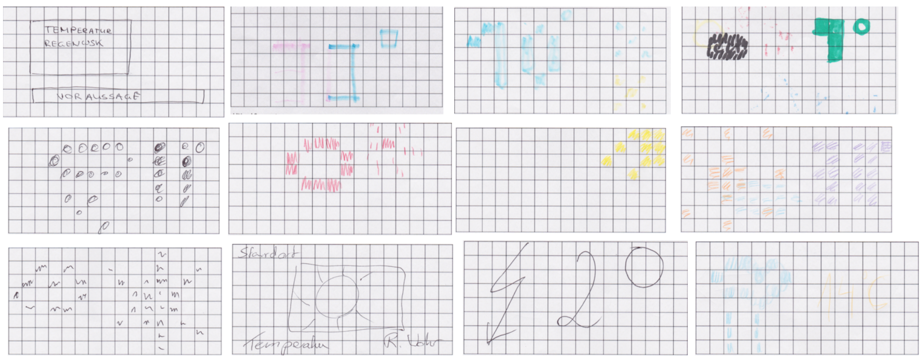
A.9 Results Use-Case 4



A.10 Results Use-Case 5



A.11 Results Use-Case 6



A.12 Study Guide - Comparing Off-Screen Visualization Techniques

Study Guide

1. Introduction

- "This study is part of my bachelor thesis and compares three different off-screen visualization techniques"
- "Two classic off-screen visualization techniques, Arrows and Halos" are compared with a display prototype simulating a garment-based display"

2. Hand over Consent Form and get signature

3. Short Demonstration and Explanation of Arrows, Halos and Display Prototype

a. "You always start from the same location"
b. "Zooming is not possible"
c. "Arrows point in the direction of markers and also show the distance in meters".
d. "Each marker is located in the center of a Halo, the larger the part of the Halo visible on the watch display is, the further away is the marker."
e. "The display prototype shows the location of the markers."
f. "There are 4 different display sizes used in the study, 8x8, 6x6, 4x4 and 1x4."
g. The 1x4 display indicates the distance to a marker through brightness."

4. Task 1

5. SUS Questionnaire after each technique

6. Task 2

A.13 SUS Questionnaire - Comparing Off-Screen Visualization Techniques

Questionnaire A **Task ___________________** **PID___**

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

A.14 Questionnaire B - Comparing Off-Screen Visualization Techniques

Only the distance estimation questions are included in the appendix, since the others are exactly the same except for asking for the direction estimation instead of the distance estimation.

Questionnaire B
Comparing Off-Screen Visualization Techniques

Participant-ID.: _____ Name: __________________

Part A – General Questions

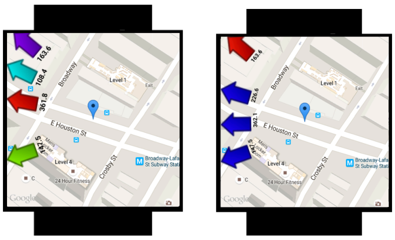
A.1 Gender [ ] Female [ ] Male

A.2 Age _____ A.3 Course of Studies ______________________

A.4 Do you own or regularly use a smartwatch? [ ] Yes [ ] No

Part B – Distance Estimation

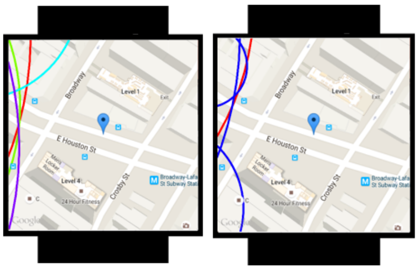
Part B.1 - Arrows



How easy was it for you to estimate the distance to a marker?

Simple				Complicated
1	2	3	4	5

Part B.2 – Halos

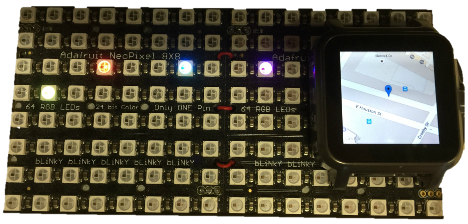


How easy was it for you to estimate the distance to a marker?

Simple				Complicated
1	2	3	4	5

Part B.3 – Display Prototype

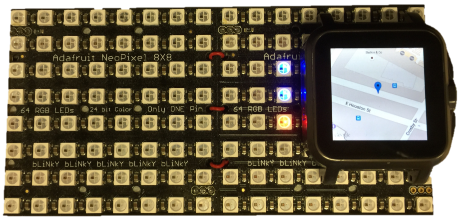
Part B.3.1 – Closest Task Display



How easy was it for you to estimate the distance to a marker?

Simple				Complicated
1	2	3	4	5

Part B.3.2 – 1x4 Display

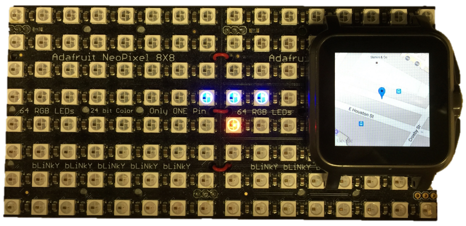


How easy was it for you to estimate the distance to a marker?

Simple | Complicated

1	2	3	4	5

Part B.3.3 – 4x4 Display

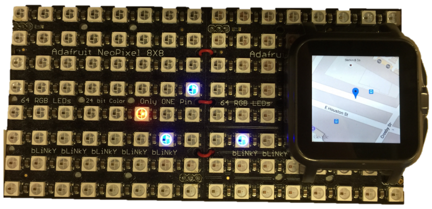


How easy was it for you to estimate the distance to a marker?

Simple | Complicated

1	2	3	4	5

Part B.3.4 – 6x6 Display

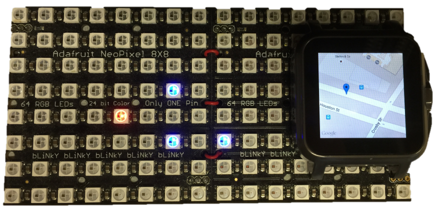


How easy was it for you to estimate the distance to a marker?

Simple — Complicated

1 2 3 4 5

Part B.3.5 – 8x8 Display

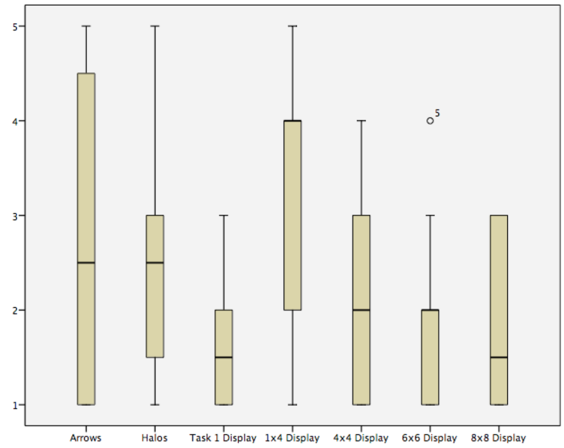


How easy was it for you to estimate the distance to a marker?

Simple — Complicated

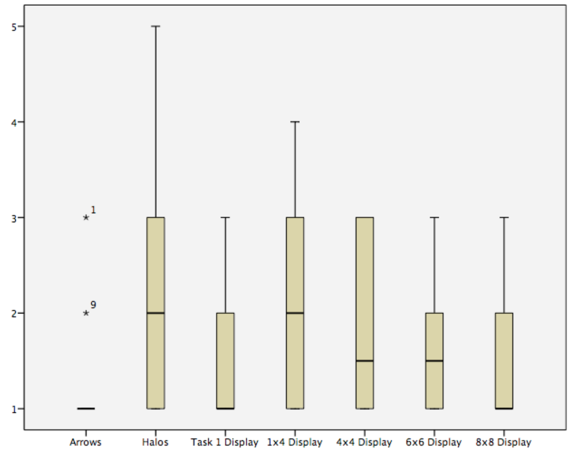
1 2 3 4 5

A.15 Results for "How easy was it for you to estimate the distance to a marker?"



Results for "How easy was it for you to estimate the distance to a marker?" on a scale of 1 to 5 (1=simple and 5=difficult).

A.16 Results for "How easy was it for you to estimate the direction in which a marker is located?"



Results for "How easy was it for you to estimate the direction in which a marker is located?" on a scale of 1 to 5 (1=simple and 5= difficult).

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I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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