DISPLAYSKIN:
DESIGN AND EVALUATION
OF A POSE-AWARE WRIST-WORN DEVICE

By

Paul Robert Strohmeier

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Abstract

The recent surge in wrist-worn devices has stirred an increasing interest in wearable technology, however, reactions to these devices are split and the use-case of these devices is still unclear. This thesis explores affordances and opportunities offered by wrist-worn devices through the design and implementation of DisplaySkin.

We approach the topic of wrist-worn displays by initially presenting a historical analysis of the development of the wristwatch. Based upon this analysis we present a series of design guidelines: we suggest that wrist-worn devices should be designed for non-focal attention, supply the user with contextual information, accommodate glance based interactions and consider the user's body pose.

Implementing these guidelines, we built DisplaySkin, a wrist-worn, pose aware device. DisplaySkin features a large flexible electrophoretic display and advanced sensing capabilities, allowing it to orient content towards the users face, independently of their body-pose. This design approach takes both new technological opportunities, as well as the cultural history of the wristwatch into account.

To evaluate DisplaySkin, we conducted two experimental studies. The first study investigates the effects of display size on a scrolling task, demonstrating that, even if the input area is kept constant, users are able to complete tasks faster using a larger display. In our second experiment we investigate the pose-aware display, demonstrating that using a pose-aware display improves reaction times when acknowledging notifications on a wrist-worn display.

DisplaySkin in various Application Scenarios:

Co-Authorship

The experimental evaluations on pages 46 – 60 and 68 – 72 were conducted collaboratively with **Jesse Burstyn**.

Dedications

I wish to dedicate this work to my grandfather, **Reverend Robert D. Keel**.
His teaching will always stay with me. Rifle, Ring & Cross.

I wish to thank my family: my grandmother, **Patricia** for her wit and spirit, my father, **Gerhard**, for teaching me to form my own opinion, my mother, **Hillary**, for teaching me to re-invent myself and my sister, **Sophie**, for teaching me more things than I could ever enumerate.

Preface

In June 2013 I first wrapped a display around my wrist. This was not long after the Pebble smartwatch started shipping. Samsung had not yet announced Galaxy Gear and the Apple Watch was not even a rumor yet. In many ways DisplaySkin is first of its kind: as of now there is no other device with its display-configuration and tracking abilities.

Whenever one sets out to do something which has not been done before, collateral knowledge is collected. The goal of this project was to build and evaluate a prototype wearable device. In doing so, however, I more or less stumbled upon themes as varied as the history of time telling devices, novel rapid prototyping methods and sensor design and implementation. While I did not expect to be exploring these themes, they ended up as part of the contribution I make with my thesis.

Doing work which pushes boundaries is only possible in an environment rich with tacit knowledge and practices. DisplaySkin was made possible by Jesse Burstyn's prior work with David Holman on prototyping with E Ink technology. Also, my experience working on PaperTab under Aneesh Tarun's supervision was invaluable. The Human Media Lab set the context from which this work could emerge. I would like to thank Audrey, Conner, David, Aneesh, John, Marty, Antonio, Peng, Joy and Jordan who all helped shape this environment. Finally thank you to Roel Vertegaal, for creating this inspiring environment, filled with talented people. I would also like to thank Roel for the opportunities and guidance he has provided me with, and for sharing his vision on this project and the other exciting work we have done together.

My thesis follows the path I took together with Jesse Burstyn in developing DisplaySkin. His work ethos, knowledge and willingness to discuss things in detail were invaluable to this work. Without him this project would not have been possible. Thanks also goes to Nicholas Fellion, who documented the process with pictures and video.

I also wish to thank Mélodie Vidal and Juan Pablo Carrascal for their time and patience in proofreading my work and holding my hand through the process of manifesting my thoughts into words, sentences and eventually this thesis.

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Glossary

Arduino
An Arduino is an open-source physical computing platform based on a prototyping board using Atmel AVR microcontrollers, and a cross-platform development environment for writing software for the board.

Bracelet Watch
Early wearable watches worn as jewelry by fine ladies during the Victorian times.

Catastrophic Failure
Catastrophic failure is a sudden and total failure from which recovery is impossible. The term is usually used in structural engineering. Describing batteries it is used for technologies for which minor damage does not merely lead to the battery failing, but to unstable conditions which can cause damage to its environment.

Context
The circumstances or setting of an activity. The information required to fully understand and assess what the user is currently engaged with. For example, if a user is in a location which they have not been before, suggesting that the user does not know their way. If the user is walking faster than usual, suggesting they are in a hurry. Awareness of the context of the primary activity helps provide appropriate contextual information.

Contextual Information
Information which supports the user in accomplishing their primary activity. A user at an unknown location might be able to accomplish their primary activity better with access to a map. A user who is in a hurry might benefit from knowing how much time they have before their next appointment.

Degrees of Freedom (DOF)
The number of sensory ‘dimensions’ measurable by a sensor, or a set of sensors. An accelerometer for example, can usually sense acceleration in three directions, acceleration in directions not directly measured can be inferred by the combined output of all three measurements. A gyroscope, can traditionally measure rotation in three directions, any rotation which does not occur along one

of the defined axis can again be inferred by the combined sensor reading. Together the three dimensional gyroscope and the three dimensional accelerometer have six degrees of freedom (6 DOF).

Do It Yourself (DIY)

‘DIY’ refers to methods of building, modifying or preparing something without requiring the support of experts or professionals.

Focal Attention

Focal attention refers to a type of attention in which the individual is deliberately, consciously focused on a certain thing to the exclusion of surrounding stimuli.

Glance-Based Interaction

Interactions which require nothing more of the user than to glance at an object. For example, the speed dial on a car, can be read by merely glancing at it.

Inertial Measurement Unit (IMU)

An inertial measurement unit is a device that measures velocity, orientation, and gravitational forces, using a combination of accelerometers, gyroscopes and magnetometers. IMUs are typically used in aircrafts, and have become commonplace in DIY circles, as they are an integral part required for flying most hobby aircrafts.

(Near) Infrared

Infrared (IR) is electromagnetic radiation with wavelength longer than that of visible light. Near infrared is the part of the IR spectrum closest to visible light, in terms of sensor design IR usually refers to frequencies between 780nm and 1500nm

Interaction area

The physical space which the user can take advantage of when interacting with a device. The interaction area of a trackpad is confined to its physical dimensions, while the interaction area of a mouse extends as far as the arm can reach.

Kinematic Model

A kinematic model is a mechanical model describing the motion of points and rigid bodies.

Mainspring & Fusee

The mainspring is a spiral torsion spring which powers mobile mechanical devices. The fuse is a mechanical system which enables the force of the mainspring to be constant.

Primary Activity

The activity which has the users focus. For example, a user might be searching for a building in a foreign city. The user is engaged in multiple activities, such as walking, avoiding other pedestrians or stopping at red traffic lights. The users primary activity is searching for the address, while the other activities described happen automatically without requiring the user to explicitly attend to them.

Pose-Aware Display

A display which is aware of the user's body pose relative to itself. This information is used to orient content appropriately. The auto-rotate function of most mobile devices could be considered a crude version of a pose aware display.

Projection

When speaking of a projected touch surface, we are comparing the sensor to a projector. It can be imagine like a simplified projector with an integrated camera. The sensor 'projector' emits light onto a projection area. When that projected area is touched, light is reflected back into the sensors 'camera'. The sensor can therefore turn any surface into a projected touch screen, as long as there is a line of sight.

Proprioception

Proprioception is the sense of our own body: the sense of the relative position of neighbouring parts of our body and strength of effort being employed in movement

Static Display

A display which displays content without adjusting it to the user's perspective. Static in this context refers to the displays orientation, not the content which is being displayed.

Thermoforming

Thermoforming is a manufacturing process where a plastic material is heated to a temperature at which it becomes pliable and then formed into its desired shape.

Touch resolution

The precision with which a touch sensor can measure the position of a finger. High touch resolution means that the sensor can detect detailed analog movements, as we are used to from capacitive touch sensors, while low touch resolution only allows discrete input, for example to input numbers on a number-dial.

Viewport

The viewport is the active area on a display through which one can view a document or application. For example, when browsing a website, one can adjust the viewport size, by changing the size of the browser window.

Wristlet

A predecessor of the wristwatch. Usually custom-made, these consisted of a pocket-watch secured within a leather strop which wrapped around the wrist.

Chapter 1

Introduction

1.1 Contextual interfaces with a cultural heritage

In the 1887 novel ‘A study in Scarlett’, Sherlock Holmes identifies that Dr. Watson’s sibling is a drunk, based on a scratch pattern he finds on Dr.Watson’s watch [31] [89]. In the first episode of the 2010 TV show *Sherlock*, ‘A study in Pink’, Holmes makes the same inference based on a scratch pattern he finds on Dr.Watson’s phone [118]. This example highlights that even though a device may use a completely new technology, its social and cultural significance may remain preserved. In the BBC’s modernized adoption of Sherlock Holmes, replacing the plot device of the watch with a mobile phone maintains the internal logic of the narrative [119].

Figure 1.1 – Sherlock accessing contextual information, such as the weather at different locations, using a smartphone [89]

This is not the only time that the TV show uses a mobile phone as a plot device. In fact, they are ubiquitous throughout the show. It is interesting that, while mobile phones play a recurring role, they are hardly ever used for making telephone conversations. Instead they are used to check the weather, check a timetable, look up something on the internet etc.: the main use of the smartphone, as a plot device and as a tool for Sherlock Holmes, is in gathering contextual information[1]. (Figure 1.1).

These are two recurring themes in this thesis: The persistence of cultural and social significance of mobile devices across different technological implementations and the use of mobile devices for accessing contextual information. We use these concepts to guide the design of a wrist-worn device. Technologies for displaying contextual information have a long tradition, dating back at least to the origins of the wrist-watch, if not even further. We believe that the smartwatch (Figure 1.2) is the logical successor to that type of device.

Based on our observation on how we traditionally use mobile technology, a wrist-worn device should not be designed assuming that the user will focus their attention at it. It should require as little attention as possible from the user, instead assisting them in completing whatever task has their attention. This can be accomplished by providing contextual, task relevant information, without requiring the user to explicitly engage with the device. Contextual information could be collected from various sources: for example, the body pose of the wearer could provide information on the activity the wearer is engaged in. The focus of this thesis, however, is not on how to collect contextual information, but rather how to present contextual information in a way that minimizes interruptions while maximizing the amount of information a user can potentially access.

Figure 1.2 – Sony Smartwatch displaying contextual information: Time and Weather [123]

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[1] Terms defined in the glossary, found at the end of this thesis, are underlined the first time they occur

1.2 Introducing the Smartwatch

The reason for focusing our research on wrist worn device is best demonstrated through the 2012 Gizmodo review of the Sony SmartWatch [123]. It is representative of the general attitude towards smartwatches which we observed when we first started working on our own prototypes. The concept of a lightweight interactive device that is worn on the arm appears appealing. Gizmodo's initial reaction to, for example, the Sony SmartWatch is euphoric:

> *" […] a delightful new way to do smartphone things without a smartphone. It could even look cool. Isn't this the kind of thing we're all supposed to secretly (or not so secretly) lust after?"*

However, things look quite different in practice. Once they actually test it, the Gizmodo team is quite disappointed. They find the interface clunky, they find touch input on such a small display cumbersome and they find that it is generally not a device they would want to use. The conclusion to their review is sobering:

> *"[The] SmartWatch is pathetic, frustrating, and empty."*

In the past few years, companies such as Apple, Google and Samsung as well as some new startups, most notably Pebble, have targeted the smartwatch market. In May 2012 Pebble's first Kickstarter campaign to collect funding for producing a smartwatch received over $10,000,000, setting the record for the best funded Kickstarter campaign ever [139]. Pebble launched a second Kickstarter campaign in 2015 for the third generation of their smartwatch attracting $9,000,000 within under 24 hours, and eventually breaking their previous record [64, 102]. Clearly there is a large public interest in this type of technology.

What makes the smartwatch such an appealing idea and why is it so difficult to get right? We believe that it is the great cultural heritage of wrist worn devices that is responsible for both the appeal of smartwatches, as well as many of the problems with their implementation. In this thesis we explore what we can learn from the history of wearables and where we should break from the traditions surrounding wristwatches. In this thesis we combine a historical analysis of the wristwatch with hardware and implementation considerations as well as theoretical considerations for designing interactions on wrist-worn devices.

1.3 The wrist-watch as a glance-based interface

The recent introduction of the Apple Watch has highlighted a design issue which warrants further investigation. Apple states that their watch is an excellent time-telling device [7]:

> *"You'll still be able to do with Apple Watch what you do with your current watch: tell the time (and if you want, the date) at a glance and trust that it's accurate."*

This very basic feature – telling the time at a glance – is something the Apple Watch, and similar smartwatches are actually surprisingly poor at: to preserve battery time, the Apple Watch turns its display off by default. The Apple Watch is activated for 6 seconds if the arm is placed in a 'time telling' pose, alternatively one can tap the watch to activate it for 17 seconds. This makes it difficult to casually glance at ones smartwatch and tell the time without actively engaging with it [140, 155].

Apple Blogger John Gruber notes several situations in which the Apple Watch, as a time-telling device, did not meet his expectations. This includes having coffee with a friend before an important appointment: towards the time he needed to leave, he would start glancing at his watch, so as to spend as much time as possible with his friend, while arriving in time for his appointment. Using the Apple Watch, Gruber was either required to artificially flick his wrist or activate the Watch with his other hand – a far heavier gesture than he was comfortable with. Other scenarios, which he found were no longer possible using the Apple Watch, were casually timing processes while cooking, or checking the time during activities which occupy his hands [140].

These observations point out an important quality of the traditional wristwatch: its content is accessible at a glance. In essence Gruber [140] and others [155] criticise the Apple Watch, because it requires a level of engagement higher than what they were expecting based on their experiences with traditional wristwatches. This points out that even the newest generation of available wrist-worn devices can benefit from further investigation into this design space.

1.4 Contributions

The core contribution of this thesis is DisplaySkin (Figure 1.3), a prototype wrist worn device with a large cylindrical Electrophoretic Display. The structural elements of DisplaySkin were manufactured in a custom process which involved 3D printing a frame which was subsequently thermoformed. Its display is a 7.2” customized PlasticLogic electrophoretic display. This display is augmented with a projected near infrared multi-touch sensor of our own design. There is a 9 degrees of freedom (DOF) inertial measurement unit (IMU) integrated in the device. This IMU is used for creating a kinematic model of the users arm, enabling DisplaySkin to position content such that it is in view of the user: if the user is viewing DisplaySkin from the top, information is displayed around the 0° position, while, if the user views the display from the side (as the reader is doing in figure 1.3) content is centered around the 90° position [19].

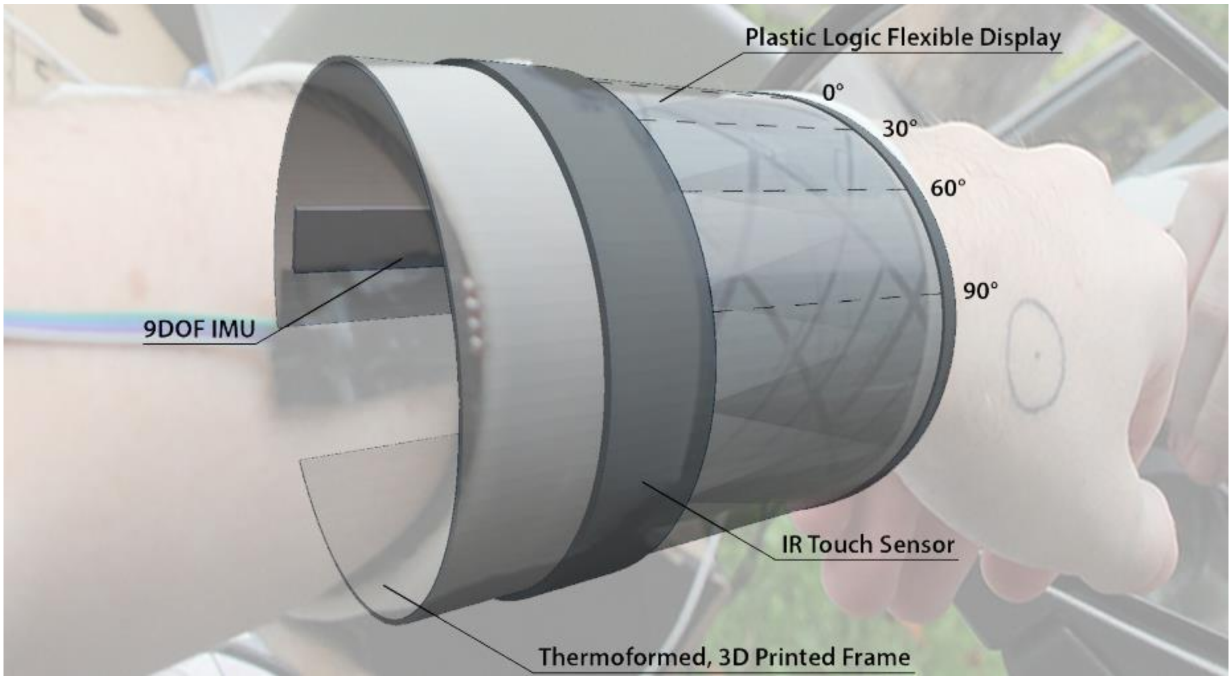

Figure 1.3 – Schematic overview of DisplaySkin

In this thesis, we use DisplaySkin to investigate issues related to the design of wrist-worn devices. Our initial investigation is a focused exploration of the effects of display sizes on interaction. This experiment was designed in reaction to design trends and interaction research surrounding wrist-worn products. Specifically, most wrist-worn devices have adopted the form factors of traditional wristwatches, resulting in a large body of interaction research dedicated to overcoming the constraints in display sizes. We believe that this constraint is an anachronism, which we need not limit ourselves to when designing wrist worn devices. In implementing our own prototype, we demonstrate that alternative form factors are possible. We evaluate the effects of the alternative display configuration by presenting the user with a list-scrolling task, and measuring task completion times. We simulated different display sizes by modulating the viewport of DisplaySkin. Our results indicate that larger displays do enable faster task completion. However, they also point out that the type of task chosen does not fully take advantage of the cylindrical form factor of the display and might not be the type of interaction a wrist worn device is best suited for.

Inspired by the results of our first experiment, by the history of wrist-worn devices and current research into wearable devices, we present a set of design guidelines. These guidelines emphasize the role of the smartwatch as supplementary devices: its role should be to support the user's primary activity. To do this effectively, it should not require the user's focused attention, instead wrist-worn devices should provide the user with supporting contextual information, while minimizing interruptions to the task at hand.

Based on these guidelines, we designed and implemented the pose-aware display. A pose-aware display has information of its position relative to the users face and adjusts information so that it is displayed in view of the user and oriented for optimizing legibility. By tracking the users pose in real time with an inertial measurement system we can adjust the placement and orientation of content while the user is moving, maximizing the availability of information to the user. We demonstrate the benefits of such a quasi 'always available' display by example of several interaction scenarios. In addition to these qualitative examples, we also conduct a quantitative evaluation of the pose-aware display. To better understand the benefits of a pose aware display, we compare it to a static wrist-worn display in an experiment investigating task interruption times. We find that users are significantly faster in reacting to a notification using the pose aware display than using the static display.

In the course of building and designing DisplaySkin and the supporting technology enabling the pose-aware display, we introduce novel prototyping methods and sensor designs. Like our historical analysis, these more applied aspects of our work are intended to support other designers in their own efforts and are part of the contribution of this thesis.

Chapter 2

History and Related Work

2.1 Introduction

The way we interact with digital technology is not only based on what the technology is capable of, but also on user requirements. A given requirement can be fulfilled by different technologies. For example, the Sumerian clay tablets and the printed book are very different technologies that satisfy the same requirement: storing information[2]. We are currently witnessing a transition from using devices we carry in our pockets, to devices we wear on our bodies. This transition is not as novel as we might think – a similar technological shift occurred around the beginning of the 20th century with the decline of the pocket watch and rise of the wristwatch. In this chapter, we will take a historical look at this transition, as it can support the design of a new generation of wrist worn devices. We suggest that the factors leading to the adoption of the wristwatch – the user requirements that the wristwatch was better suited to fulfill than the pocket watch – are the same today as they were then.

Recurring patterns in adopting technology can again be observed by comparing the digital watch in the early 1970's and the first drum watches in the 15th century. Similar parallels can be observed comparing today's smartwatches to the first wearable devices of the 16th century. The technology behind the first digital watches also enables new form factors and approaches that foreshadow some of the design recommendations we will make for future generations of smartwatches.

In the 15th century, the development of the mainspring and consequently the fusee enabled a whole generation of mobile technology. We believe that current advances in display and power storage technologies will have a similar enabling effect on the next generation of wearable devices. We will briefly outline technologies which were important considerations for our own design. While there is a large body of impressive prototyping work which relies on projection and simulation, we find it important to work as close to the actual target media as possible. We believe that simulations

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[2] We realise this is a simplification of a complex subject matter, but appeal to the reader to except this simplified example for the sake of our argument.

introduce their own unique constraints and affordances. Working with a physical prototype provides us with a tacit understanding of the subject matter that is important for understanding how a user will engage with the technology.

Contemporary research into wrist-worn devices appears to focus on the small size of their displays, which make controlling them with touch interfaces unpractical. There is a large body of work, focused on the size constraint of wrist worn interfaces, usually by means of expanding the interaction area. While the traditional form factor of the wristwatch appears to be the go-to design for most current wrist worn devices, we will highlight several design explorations aimed at exploring alternative form factors and display sizes. After discussing output methods and display configurations, we will introduce the concept of merging device and body, and discuss where on the body we should be placing wearable displays.

2.2 The History of the Wristwatch

There are countless stories of the invention of the wristwatch. It appears as though just about every watch-maker in the early 20th century claimed to have invented it. Jaquet and Chapuis mocked this trend in their book '*Technique and History of the Swiss watch'* [34]. They attributed the invention of the wristwatch not to a watch maker, but to 'naïve ingenuity':

> *"[A] good woman [was] seated on a bench in a public park, suckling her child. In order to observe the time, she had attached her watch around her arm. A passer-by was struck by this naïve ingenuity. On his return home, he soldered two lugs on to a lady's watch, and added a strap."*

In fact, like most inventions, there is no single origin of the wristwatch. The wristwatch has a tradition that dates much further back than the 20th century in which it became popular.

2.2.1 The Mainspring

Early time telling devices took advantage of diverse mechanisms to tell the time, including moving shadows [26], flowing water or sand [106] and pendulums [17]. None of these time telling methods were suited for mobile use, as they were either too large to conveniently transport or subject to inertial forces which would make them inaccurate when transported [17].

A technological innovation that made the first portable watches possible is the mainspring (Figure 2.1). A mainspring is a spiral torsion spring. It is wound, usually with a key, to store force. The stored force can be used to rotate a clockwork's wheels as it unwinds. To this day, it is used to power watches and other mechanical devices [17, 86, 109].

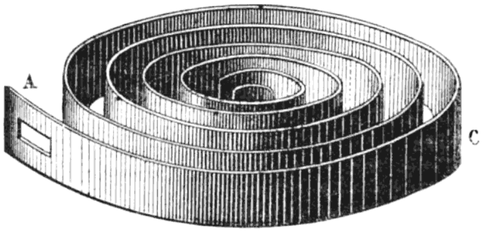


Figure 2.1 – Mainspring [71]

2.2.2 Drum Watches

The first mobile time-telling devices that made use of a mainspring had their origin in Nuremberg around 1500 [92]. Nuremberg was a wealthy city and had a rich tradition of lock- smiths who found that their skillset could also be applied to building mobile time-pieces.

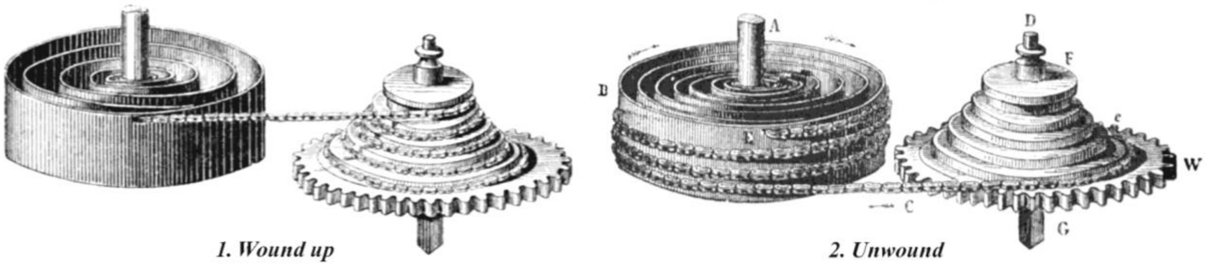
Figure 2.2 - Drum Watch with Sundial by Schissler (ca. 1560) [92]

The primary function of these early pocket watches was ornamental. If someone wanted to tell the time, they used a sun dial [17]. This is apparent in the drum-watch by Schissler (ca. 1560) which has a sun dial on its back (Figure 2.2). The mechanical watch was not reliable in of itself: the sun-dial at the back was required to correct the time of the mechanical watch. Its intricate gold-reliefs are additional indicators that this watch was appreciated for its ornamental qualities [92]. Another indicator of the ornamental qualities of these drum watches is evident in the practice of including them in portraits, for example in the following portrait of Ulrich Ehringer by Christoph Amberger (ca. 1530, figure 2.3) [17, 92].

Figure 2.3 - Portrait of Ulrich Ehringer holding a Drum Watch (ca. 1530) [92]

A problem with the mainspring is that its tension is not consistent. Therefore a watch powered by a mainspring would initially go too fast, and as the mainspring unwound, gradually slow down. Attempts were made to introduce a minute hand, but were not especially popular: due to the idiosyncrasies of the mainspring, it was common for mechanical watches to be off by 30 minutes or more, rendering the minute hand meaningless [17, 109].

A solution to this problem was introduced towards the end of the 16th century in the form of the fusee (Figure 2.4). The fusee used a spiral winding to correct for the varying tension of the mainspring. It lead to an appreciation of the minute hand and later even to the adoption of the seconds hand. Other factors that helped improve the precision of the watch were brass mechanics which were introduced about 1600. These had less friction and a better precision than the steel components previously used [17, 109].



1. Wound up
2. Unwound

Figure 2.4 - The Fusee [29]

These innovations, however, did not change the culture and practices surrounding the telling of time: ‘Real’ timekeeping was done by clocks in watch- and church-towers. At night, the watchmen on patrol would additionally call out the hours (this, in fact, is also where the term ‘watch’ for a time-keeping device stems from). These traditional systems were considered more useful than a handmade and expensive watch [17].

In summary, the first mobile time telling pieces were adopted not because they were useful, but because they were prestigious. Even once the technology had matured to a point that the pocket watch could potentially be a useful tool, the traditions and practices surrounding time telling made the idea of a pocket watch unappealing [17].

2.2.3 The Bracelet Watch and Other Fashion Technology

By the 16th century, watches had become an explicit fashion accessory. Mary Queen of Scots, for example, owned a small watch, shaped like a skull (Figure 2.5), which she commonly wore. She eventually presented the Skull Watch to her maid of honor, Mary Seton [17, 27, 87]. Other watches were shaped as animals, insects or flowers [17].

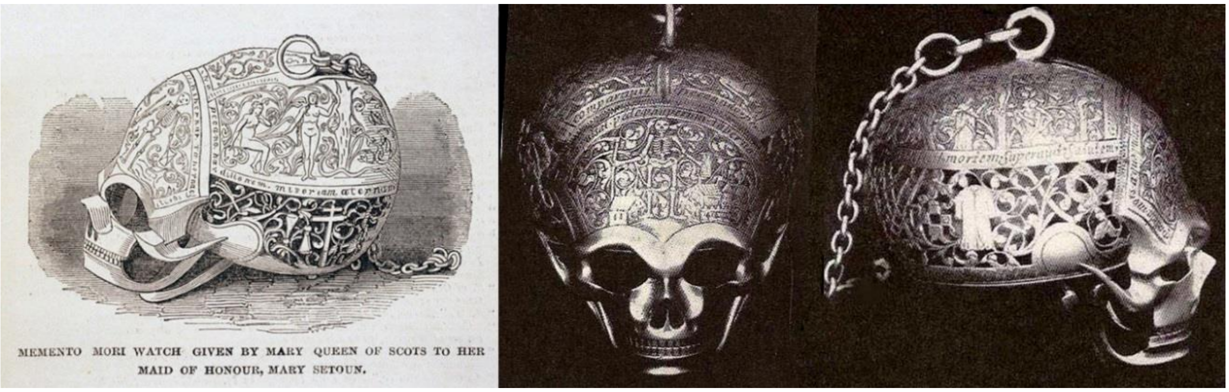


Figure 2.5 – Skull Watch owned by Mary Queen of Scots (ca. 1585) [144]

At the court of Queen Elisabeth I, a watch was selected to match one's outfit, just as one would choose a suiting coat or hat. These watches were usually worn on a chain or ribbon around the neck and were intended to be seen by others. A given watch usually came with multiple cases. The ladies of court could remove the clockwork and place it into a case that suited their mood of the day. These cases were decorated with jewels, bones, gold ornaments and enamel paintings [17].

In addition to the watch-jewel worn around the neck, watchmakers started embedding their pieces into other objects such as bracelets and rings [53] (Figure 2.6). One of the earliest records of such bracelet watches dates back to 1571 and was worn by Queen Elisabeth I. Another famous early 'wristwatch' is the bracelet watch Patek Phillippe manufactured for the Countess Koscowicz of Hungary (Figure 2.6) [165].

Figure 2.6 Patek Phillippe's bracelet watch (left, ca. 1868) [165] **and watch embedded in ring, conveniently doubling as a crucifix, by Jakob Weiss (right, ca. 1585)** [53]

While there may have been a practical appeal of bracelet watches, the bracelet watch was still far away from what was to become the wristwatch. For one, the bracelet watch was considered effeminate which made it taboo for Victorian men to wear. There were also practical considerations: the bracelet watch was not designed to be durable, making it unpractical as a timepiece. Pocket watches were more robust and safely protected in the pouch of a waistcoat [17, 142]. Finally they were designed as lockets, and had to be opened for time telling. Figure 2.6 shows both the bracelet watch and the watch-ring in their open states (the bracelet watch opens to the left, when closed the watch-face would be covered by a large jewel), while the skull watch (Figure 2.5) needs to be opened at the jaw to reveal the internal clockwork [144].

The first wearable devices were not adopted for any utilitarian purpose, but where explicitly used as fashion items. The tradition of swapping the casing of watch, to make its appearance suit the outfit one was wearing is somewhat reminiscent of the various decorative casings available for most mobile smartphones. It is also similar in concept to the different styles of watchstraps available for the Apple Watch which play an important factor in their marketing campaign.

2.2.4 The Wristwatch

It is towards the end of the 19th century that the wristwatch gained acceptance as a tool. With the beginning of industrialization, watchmaking was no longer the painstaking labor of a single talented individual. Instead, companies would manufacture specific parts in larger quantities. This allowed the price of watches to drop and the quality of the devices to improve. Aviators, motorists and hunters started to use wristwatches [17, 51] as they allowed them to tell the time without disrupting their primary activity.

More importantly, new military strategies and technologies made precise coordinated timings a necessity. This lead to a wide adoption of watches by soldiers. Initially soldiers commissioned saddle makers to create leather wrist-bands to hold their pocket watches (Figure 2.7, right) [17]. The significance of the wristlet is that, unlike the bracelet watch, the watch face was always exposed, thereby enabling the wearer to tell the time without requiring any engagement beyond a quick glance.

These wristlets were eventually replaced by the wrist-watch. In 1880 the Swiss watchmaker Girard Perregoux manufactured the first large batch of wrist-watches for the German Military. These watches enabled German soldiers to handle weapons, heavy machinery and artillery while monitoring the time [17, 142].

The British Military started using wristlets produced by Mappin & Webb at around the same time (Figure 2.7, left & Figure 2.8). There are records of these watches being used in colonial conflicts around 1880, in the Sudan Campaign of 1898 and during the Boer Wars of 1899 [17, 142] (Figure 2.8).

Figure 2.7 - The 9th Bengal Lancers in India ca. 1897 (front left soldier is wearing wristlet) [18] **and close up of wristlet.**

Watchmakers to the Admiralty

Mappin's Famed 'Campaign' Watch

This fine movement wristlet watch was first used in great numbers at Omdurman. And desert-experience is the severest test a watch can have.

During the last Boer War it renewed its high reputation for reliability under trying conditions.

It is compensated and jewelled. In silver case with stout inner dome, it is absolutely dust and damp-proof.

It is fitted with a luminous dial, which shows the time on the blackest of nights.

£2 : 10 : 0

Mappin & Webb LTD

Silversmiths to His Majesty King George V.

158-162, Oxford St., W.   2, Queen Victoria St., E.C.
220, Regent St., London, W.

Royal Works.————Sheffield.

Figure 2.8 - Mappin & Webb advertisement stating their watch was used at the battle of Omdurman in 1898. Artistic depiction of the 21st Lancers charging at Omdurman by John Edward Chapman, 1899 [141]

With the invention of phosphorous paints, it became possible to tell the time in the dark, further expanding the use case of the wristwatch. The Radiolite wristwatch by Ingersoll, which used this phosphorous paint, became an important tool in WWI. This marked a change in attitude towards the wristwatch. Before WWI wristwatches were mainly used by people who today might be called ‘early adaptors’. During WWI Ingersoll produced up to 20.000 wristwatches a day. By the end of WWI it is estimated that about fifty million wristwatches were in use and the technology was widely used by people of all backgrounds [17].

2.2.5 History of the Wristwatch: Conclusion

From the first drum watches to the wristwatch there is an arc of technological development which is indicative of how the adoption of smartwatches may proceed. We find that initially the new technologies enabled by the mainspring and the fusee were used by a select few. The functionality of the device was secondary, the main focus was either on the device as an ornament, a demonstration of wealth and the appeal to be what we would today refer to as an ‘early adopter’.

Eventually two things occurred: The technology matured both in terms of the quality of the devices as well as in terms of manufacturing processes. More relevant to us, as designers of technology, is that its use case was recast. By removing the watch-face from the locket and placing it in direct view of the wearer, users could tell the time by merely glancing at it. This allowed the technology to recede into the background: supplying information, rather than requiring engagement. It is this recasting of the wristwatch from an extravagant luxury item designed to draw attention, to a contextual, glance-based interface, designed to recede from attention, which lead to its widespread adoption.

2.3 The Digital Watch

There is a similar technological arc present in the development of digital watches. However, working with new technologies also lead to series of new concepts that we will highlight in this section. Still, the current generation of smartwatches suffers from some of the same issues as the wearable technology of the 16th century did. They are popular and fashionable, however beyond that their use case is not clearly defined yet.

2.3.1 Ornamental Devices

In 1972 the Hamilton Watch Company presented ‘Pulsar the Time Computer’, the first commercially available digital watch. In 1975, the Hamilton Watch Company introduced the first interactive digital watch, adding calculator functionality (Figure 2.9) [111].

Figure 2.9 - Pulsar Time Computer [30] [3]

There are many similarities between the Pulsar (Figure 2.9) and the drum watches by Schissler (Figure 2.2). They were clearly marketed as luxury items. Both the original Pulsar Time Computer, as well as the Calculator Watch were originally released in a limited edition featuring 18 karat gold and sold for $1500 and $3650 respectively [111]. Just like the mechanical watch had drawbacks compared to the sun-dial, the digital watch was significantly less practical than watches with a physical display: due to the high power demand of the LED display, it only would display the time once a button was pushed and, of course, required batteries to operate. The calculator on the 1975 model was also not particularly useful as a tool compared to the portable calculators available, for example, from Texas Instruments. The Pulsar was, however, prominently featured in Playboy [52] and featured in the James Bond movie ‘Live and Let Die’ [77]. Like the early Drum Watches, these devices were status symbols, worn to impress: showing off wealth, influence and technological prowess.

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[3] Original images posted by user ‘Stealth-wagon’ on http://www.pistonheads.com/gassing/topic.asp?t=754644

Similar to early mechanical watches, these digital watches were also great feats of both engineering and craftsmanship. They were designed and built before infrastructure existed which would allow them to be mass produced. To put this in context, these were the days of main-frame computers, more than five years before Apple would demonstrate the first commercially successful ‘personal’ computer. Their internal organization demonstrates both the beauty and ingenuity of their designs (Figure 2.10).

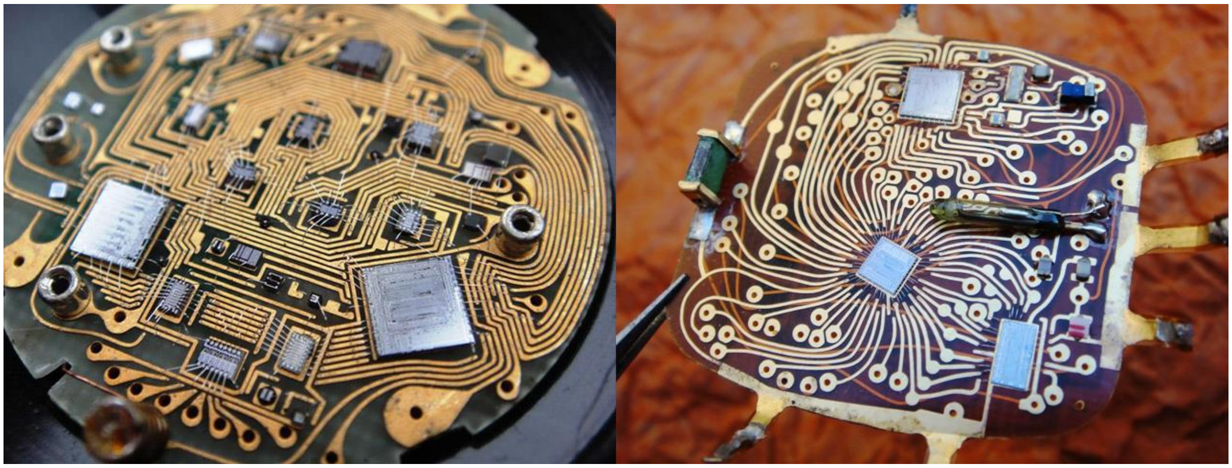


Figure 2.10 - 'Motherboards' of the Uranus (left) and a Pulsar Calculator Watch (right) [110]

2.3.2 New concepts introduced with the digital watch

Solar watches appeared almost at the same time as the battery-only models. Due to the additional technological and structural constraints introduced by the added photo-voltaic elements, designers had to rethink the layout of the watch, forcing them to explore alternative form factors. Early solar watches reconfigured the display to point towards the side, rather than upward, leaving the upward position free for the photo-voltaic power harvesting systems. Examples of such watches are the Synchronar [133] (Figure 2.11, left) and the Nepro Alfatronic [96] (Figure 2.11, right).

Figure 2.11 - Synchronar [133] **and Nepro Alfatronic** [96]

One of Seiko's contributions to the digital watch in the early 1980's was linking it wirelessly to a larger input module. This approach combines the advantages of a lightweight mobile device with the benefits of having a larger base station for more complex input (Figure 2.12). Another interesting wristwatch was introduced in 1990 by the German watchmaker Junghans [152]. The consumer appeal of their Mega 1 was that it set the time automatically, using a radio signal it received through an antenna integrated with the watchstrap. The alternative form factors of the solar watches, linking watches with larger input devices and using the strap as a functional element are all design choices that are actively explored in contemporary HCI research.

In the years to come, various companies contributed technological prowess and design ideas to the digital watch. Notable are Texas Instruments, who were able to produce very cheap digital watches due to their integrated circuits [138] and companies such as Casio who worked on expanding the functionality of the digital watches with integrated sensors [25]. Providing a comprehensive overview of all such developments is, however, beyond the scope of this thesis.

Figure 2.12 - Seiko Calculator Watch [121]

2.3.3 Expanding the functionality of the digital watch

A recurring design goal for smartwatches is to turn them into full-fledged general purpose computers. In 1998 wearable technology pioneer Steve Mann [126] and shortly after him researchers at IBM [95] designed and built wrist-watches running Linux distributions (Figure 2.13). While IBM went on to collaborate with design firm Citizen on product designs [61, 95], Mann himself was disappointed with the result. In his own words "conclusion: smartwatch not too useful" [127]. He abandoned this line of research in favor of his interest in head-mounted devices.

Figure 2.13 – Linux watch by Mann [126]**, OLED and LCD versions of Linux watch by IBM** [95]

The idea of more general purpose wearables was followed up upon by Microsoft. In 2004 they presented their visionary Smart Personal Objects technology (SPOT) [90, 153] which used FM signals for communication. The idea behind SPOT was to provide useful bits of information to any device that might need them, including news updates and messages over MSN Messenger [153].

SPOT was never able to fully establish itself, as their proprietary radio service was outdated almost immediately after inception due to the proliferation of cellular data and eventually WiFi. The service was discontinued by Microsoft in 2008 [153].

Figure 2.14 – Samsung SPH-WP10 Phone Watch [115]

A similar approach to adding functionality to the wristwatch, though less visionary in scope, was followed by Samsung, who, starting in 1999, introduced a series of phone watches with the SPH-WP10 (Figure 2.14). They expected them to "be a big hit with the youth market" [115]. It was not until their 2014 Galaxy Gear 2 that Samsung had significant success on the wearable market.

2.3.4 Current SmartWatches

In recent years, various companies have attempted to gain a foothold in the wearables market. Notable among those are Pebble [101] along with other, more established companies such as Sony, Qualcomm, Motorola, Samsung, Apple & Google (Figure 2.15).

Figure 2.15 - From left to right: Moto 360, LG G Watch, Samsung Gear Live [6], **Apple Watch** [8], **Pebble Time** [64]

It is interesting to note that the current generation of smartwatches is mainly designed by companies known for their smartphones, not for their watches. While the manufacturers have attempted to expand the functionality of the smartwatch, it appears that they are emulating the look and feel of traditional wristwatches. It should also be pointed out that there are only limited attempts in expanding the input and output space of the smartwatches. Instead, many companies appear to be miniaturizing both the physical design and interaction design of smartphones and adding straps to make them wearable. This is most apparent with products such as the Samsung PhoneWatch, but can also be observed when comparing the shape and design of the Apple Watch to the current generation of the iPhone.

2.3.5 The Digital Watch: Conclusion

There are parallels between these smart-watches and early wristwatches. For example, the marketing campaign surrounding the Apple Watch focused on its aesthetic, and the different available styles [9]. Though initially announced in September 2014, it is not until March 2015 that Apple presented videos demonstrating how to actually use their Watch [28]. It appears that the functions of the Apple Watch are only complementary to its primary purpose as a fashion and lifestyle accessory, making it reminiscent of both the Hamilton Pulsar (Figure 2.9) and Schissler’s Drum Watch (Figure 2.2).

It should also be noted that even the most recent generation of smartwatches constrains itself to the traditional shape of wristwatches, while adopting interaction methods traditionally used with mobile phones. We believe these to be arbitrary design choices, based purely on tradition, and not on functional considerations. In this thesis we intend to demonstrate an approach to redesigning the smartwatch focusing on its function as a contextual information device. In doing so, we break with tradition in terms of the devices form factor; however our functional considerations are deeply rooted in the history of wrist-worn devices.

2.4 Enabling Technologies

Just as the fusee and the mainspring were crucial for the development of the wristwatch, we believe that there are a series of core technologies which will drive the development of smartwatches. This is not intended to be an exhaustive list, but rather features two technologies which were important to us in conceptualizing and implementing DisplaySkin.

2.4.1 Flexible Displays

In the early 20th century, mobile technology transitioned from being carried in a pocket, to being strapped to the wrist. In order to make that transition, the technology was required to be more robust, because of the environmental forces it would be subject to when worn on the wrist. We are currently witnessing a similar process of technology migrating from the pocket to the wrist. A technology which will be relevant for this transition is that of flexible displays.

There are a number of reasons that make flexible displays a desirable technology for wrist worn devices. While the rigid displays on most portable devices today are relatively durable, they are designed with the assumption that they are carried in a pocket. Flexible displays represent a step towards increased ruggedness, as they are less likely to break or crack, which makes them better suitable for being worn on the wrist. Flexible displays are also lighter than traditional displays, making them more comfortable to wear. Finally, flexible displays can bend to conform to the shape of the user's wrist and allow a device to open and close, changing shape so that removing the device from the wrist becomes more convenient.

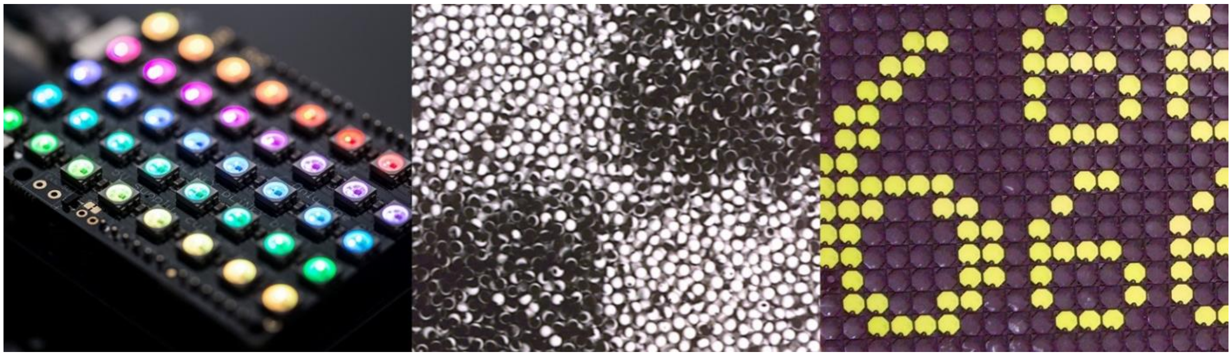


Figure 2.16 – LED display (left), bi-stable Gyricon beads (center) [159]**, and magnetically actuated bus display (right).**

Most displays consist of a combination of driving circuitry and display technology. The displays we are accustomed to on digital devices such as phones or laptops are controlled by an active matrix backplane. This active matrix is an array of transistors which have individual control over each pixel and, if applicable, subpixel. The display technology itself consists of light emitting elements (Figure 2.16 left), bi-stable materials (Figure 2.16 center) or actuators (Figure 2.16 right) which are inert, except if they receive input from the active matrix backplane.

Figure 2.17 - PaperPhone [68]**, Snaplet** [137] **and DisplayStacks** [40]

E Ink, a technological successor to Xerox's Gyricon technology [33, 159] was one of the first viable display solutions for flexible displays. Using backplane technology developed by the Arizona State Universitie's Flexible Display Center, one of the first flexible E Ink prototype was presented in 2008 [60]. These displays were later used in prototypes by the Human Media Lab, such as PaperPhone [68] (Figure 2.17 Left), Snaplet [137] (Figure 2.17 center) and DisplayStacks [40] (Figure 2.17 right).

While the Flexible Display Center eventually focused on thinness rather than flexibility, Plastic Logic developed large flexible active matrix display arrays [2]. Again, E Ink technology was chosen for the display. These displays were, for example, used in PaperTab [135] which was presented at CES 2013. Plastic Logic also developed color E Ink displays, which they used to create a mockup of what a color E Ink wrist worn device might look like (Figure 2.18) [105].

Figure 2.18 – Color smartwatch mockup by PlasticLogic [105]

As flexible backplane technology has matured, large display manufacturers such LG and research companies such as Universal Display Corporation have started using them to create flexible organic light emitting displays (FOLEDs) [108, 145], which have since been used in smartphones such as the Galaxy Round [116] and the G Flex [73] introduced in 2013. Unlike electrophoretic displays, FOLEDs are full color, have a high pixel density and a high refresh rate capable of playing video. This provides FOLEDs with a number of advantages over electrophoretic displays.

Flexible displays offer the opportunity to design devices with novel form-factors, including objects with non-flat surfaces and bezel-less displays. In practice, such devices with non-planer form factors are still barely explored and the few explorations usually use projection [3, 15, 16, 149] or other simulation techniques [4, 55, 125]. In this thesis we will be taking advantage of flexible displays for exploring previously unrealized device form factors.

2.4.2 Thinfilm solid state batteries

The largest component of most mobile devices is its battery. A lightweight, soft and flexible display alone is of little use, if the battery is rigid and heavy. Such a device needs battery technology which is similarly well fit for its form factor. Current batteries are designed based on the assumption that a devices is fully charged and then is used as it discharges. Current trends in wireless technologies and energy harvesting systems suggest that the way in which we use our batteries will change. Instead of batteries designed to last as long as possible on a single charge, there will be growing demand for batteries with lower capacity, but improved charging behavior [114, 166], which will allow them to better take use of power-harvesting methods and wireless charging. Finally, as battery technology is deployed closer and closer to the body, safety becomes an increasing issue. The Lithium Polymer batteries, which are the current go-to technology for mobile devices are a candidate for catastrophic failure in the form of explosions and fires [76]. We believe that wearable technology requires a higher standard of safety of their power-supplies.

An interesting candidate for the thin, flexible, device of the future are thinfilm batteries. While their capacity is somewhat lower than that of Lithium Polymer batteries, their form factor creates interesting new opportunities for device design. Important benefits of thinfilm batteries are that they are flexible [103], can be designed in arbitrary two dimensional shapes and that individual cells (Figure 2.19, left) can be stacked to create larger batteries (Figure 2.19 right) [114]. Thinfilm batteries also have both better charging capabilities and higher cycle life than lithium polymer batteries. As an added bonus they are essentially safe: even if short circuited, or otherwise damaged, they do not create excessive heat buildup, nor do they contain any fluids which can leak [114].

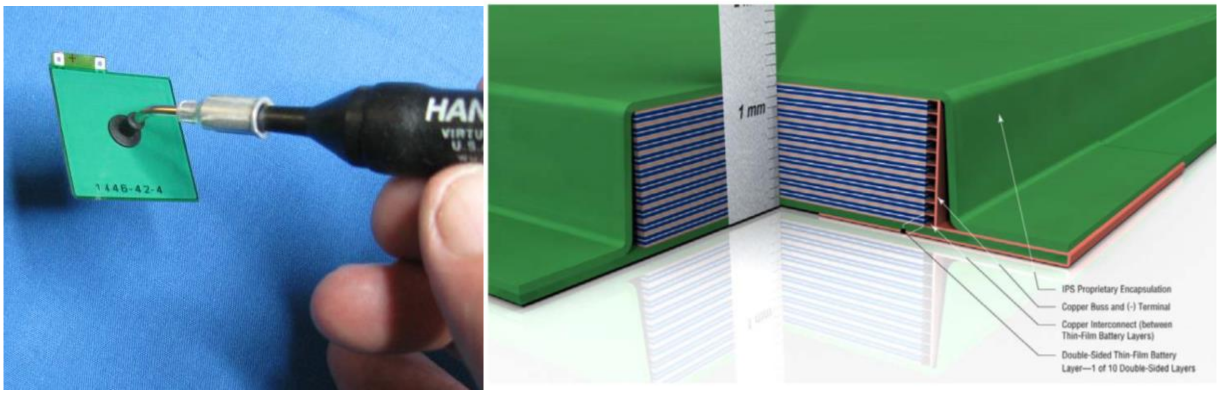


Figure 2.19 - Thinfilm, solid state, cell (left) and battery concept (right) [114]

Our prototype device will not include any integrated batteries. However, the form factor and power requirements would allow it to be realized using thinfilm technology. In fact, a similar combination of display and battery technology is used in the CST-01 (Figure 2.20) [63]. This digital watch combines a thinfilm segmented display and battery technology with wireless charging and communication, demonstrating how these technologies interact harmoniously, enabling elegant and simple devices.

Figure 2.20 – CST-01, wristwatch [63] **with segmented E Ink display, powered by thinfilm micro-energy cell**

2.5 Contemporary Research

2.5.1 Input Methods

Touch interfaces are a popular input medium for mobile devices. There are various reasons for the popularity of touch. These include its relatively strong performance compared to other input devices such as miniature joysticks, the coupling of input and output medium that aids compact hardware design, and that it is an intuitive method of interacting with digital media [12]. However, the small form factor of these devices leads to the the 'fat finger' problem: the softness of the fingertip makes the interactions imprecise and the relatively large size of the finger compared to the display leads to occlusion [12].

There are various strategies to sidestep these limitations. For example, Potter et al. demonstrated that an offset curser can improve targeting precision [107]. Vogel and Baudisch developed this idea further by dynamically displaying the target area next to the finger, when occlusion makes the selection ambiguous [151]. Benko et al. explore this idea further by including bimanual gestures for occlusion free touch interactions [13]. A creative way of sidestepping this problem all together is to place the touch interface behind the device [12], which has also been explored for both bimanual interaction and various cursor mappings [50, 164]. Behind-device interactions avoid occlusion because the user touches the back of the device rather than the display.

While these strategies are feasible for handheld devices, they are not practical for wrist-worn devices. Due to the size of current wrist-worn devices, which is even smaller than most handheld devices, using offset cursors is impractical, and behind device interactions are not possible. It is clear that wrist-worn devices require their own interaction methods, designed specifically with their affordances and constraints in mind. In the following section, we will be introducing some approaches for improving interaction on the wrist.

Extending Interaction Area

While interaction design for handheld devices commonly focuses on improving touch interactions, research into input for wrist-worn devices tends to gravitate towards finding additional input modalities, external to the display of the device. For example, Perrault et al [104] extend the input area of a smartwatch by making the watchstrap touch sensitive. Perrault uses the extended touch area for menu and list navigation, as well as gesture-space for eye-free input. Funk et al [38] use this method for text entry (Figure 2.21). These prototypes are somewhat reminiscent of the

Junghans Mega 1 [152], as they also consider the wrist-strap as an active element in the functional design of the device.

Figure 2.21 - Touch Interface on Wristband by Funk et al [38]

Ashbrook et al. explore how the inside of a bezel can be used as a guide to make touch interactions on a round display more precise [10]. Oakley et al. point out that very small devices are becoming more commonplace, and are not limited to wearables. They describe a strategy that avoids occlusion by moving the interaction to the edge of the device, augmenting the outside of its bezel with a series of outwards facing capacitive sensors (Figure 2.22, right) [97].

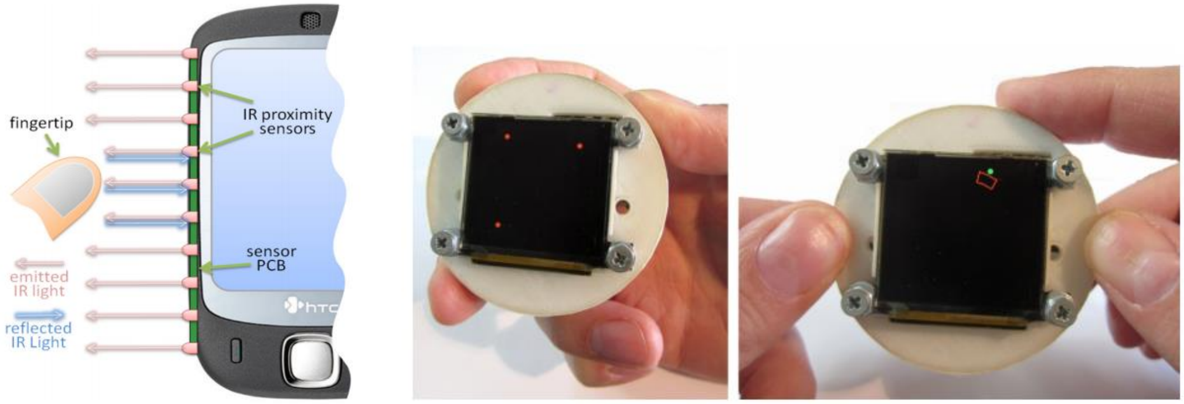


Figure 2.22 – Principles of SideSight (left) [21]**, device with capacitive touch on the edge** [97]

Moving the interaction even further away from the device, various projects explore using the area around it as an input space. This includes SideSight [21] (Figure 2.22, left) which was initially designed for mobile devices and was adopted for with-wrist worn devices by Knibbe et al [67]. Both systems use infrared sensors pointing outwards from the bezel to detect gestures in the surrounding area. This allows people to use the table a smartphone is placed on, or the skin around a smartwatch, as an interaction surface.

Using the skin as a touch surface is a recurring theme in HCI research. For example, Nakatsuma et al. [94] detects finger position on the back of the hand using a combination of piezoelectric and infrared sensors. Makino et al. [85] measure the force and linear position of a finger between two infrared sensors placed on the arm. Ogata et al. [98] present SkinWatch, which uses both touch on the skin and skin manipulation around the device as input (Figure 2.23) Ogata et al. use the same sensing approach as Makino et al. for map navigation and picture editing.

Figure 2.23 - Skin manipulation around the device as input [98]

While Makino and Ogata focus on continuous input on the skin, Harrison et al. presented several prototypes which investigate sensing discrete input on the skin. For example, increasing screen real estate by moving buttons off the device and on to the skin (Figure 2.24) [70]. Harrison also demonstrated the use of acoustic triangulation and frequency matching to infer where the skin is being tapped [46]. This is implemented in Skinput which uses the surface of the arm and hands as tappable interface to wearable devices.

Figure 2.24 - Skin Buttons [70]

The prototype presented by Ogata re-implemented many interactions originally introduced by Xiao [160] Using a mechanical system, Xiao et al use pan, twist, tilt & click of the device as input method (Figure 2.25). They demonstrate the high level of control this method provides by using it to play a first person shooters on the wrist [160].

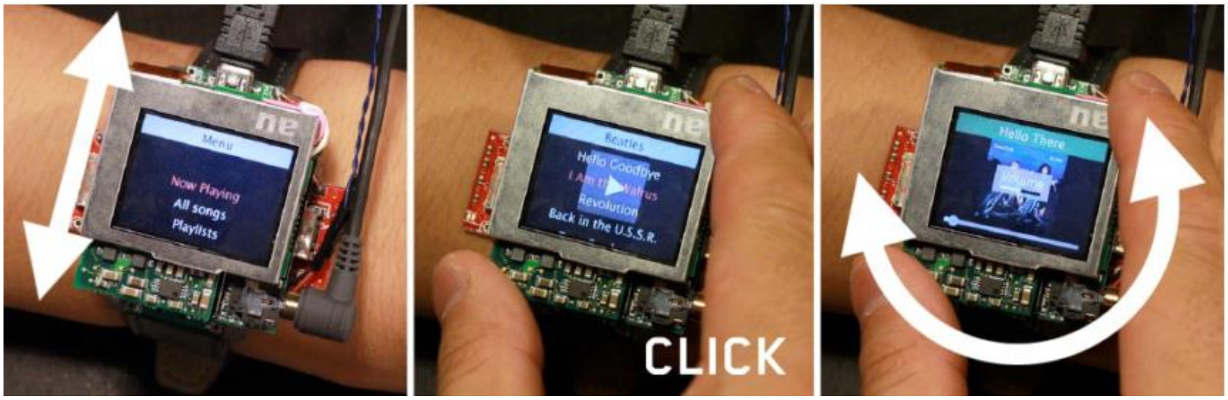


Figure 2.25 – Mechanical input with 9 DOF [160]

Another approach to expanding the interaction space of wrist worn devices is sensing the 3D space around the device. An example of this is Abracadabra [49] by Harrison et al. Abracadabra augments the finger with a magnet and uses magnetic tracking to identify the position of the finger in 3D space. Yang and Grossman also augment a finger, however they use a camera for turning any surface into an interactive touch area [163]. An unconventional but recurring method of sensing 3D gestures around a device are retractable-string based interfaces, which can measure the angle at which a string meets a device, and the distance it extends (Figure 2.26) [14].

Figure 2.26 – Projection based prototype for string based interface [14]

What these prototypes and explorations have in common is that they focus on offering alternatives to using the display as a touch interface. As mentioned before, coupling of input and output, the strong performance of touch interfaces and the compactness of the hardware make the touch display a compelling input device. The motivation behind this research is that as displays become smaller, they reach a point where touch interactions simply are no longer feasible. Once that point is reached, these methods become appealing, as they overcome the limitations of the small displays used with most wrist-worn devices.

Using Gestural Input

A drawback of the above methods is that they require both hands for interaction. The hand wearing the device must be held steady for the other hand to reach and interact with the device. This requires a significant amount of attention and effort for a device which was originally designed as a lightweight contextual information display.

An approach that does not have this problem is decoupling the input from the device all together, by enabling gestural input. For example, Rekimoto uses capacitance for determining the shape of the wrist, by which he infers gestural information [112]. More recent explorations have used Thalmic Lab’s MYO to a similar effect [62]. Other work which uses gestures decoupled from a ‘device’ includes work by Harrison. He uses a PrimeSense depth camera to track arm positions and gestures [44, 45]. While not the focus of this thesis, we also have designed both resistive [130] and infrared [129] implementations for one handed gestural interactions with wrist-worn devices, which we will discuss at a later point.

These systems no longer explicitly require a ‘device’. Instead the body as a whole acts as an interface to an interactive medium. Doing so opens up the design space to use proprioception (our sense of the position and orientation of our body parts) as a feedback mechanism. For example, Li et al. create virtual shelves which a user can reach for. The proprioceptive feedback users receive when reaching for items helps the user remember where items are located [74]. Chen et al. suggest similar interaction methods [22], for example, navigating data by moving mobile devices relative to the body and creating a mnemonic map by storing and retrieving information at chosen locations on and around the user’s body. Lopes et al. demonstrate a more abstract interaction language for mobile devices which also relies on proprioceptive feedback, focusing on wrist interactions [78].

A drawback of these interaction methods is that they require us to be free to move our bodies at will. They also overload our sense of proprioception in ways which might not be suitable, depending on context. When riding a bicycle, for example, we are not free to use our bodies to engage in this type of interaction. Our experience of our body is important when bicycling, providing us with important feedback, enabling us to balance as we move through the streets. Rather than overloading this feedback mechanism with additional layers of meaning, we suggest that a device could make use of such information to infer the context within which it is being used.

A slightly different but related mechanism was, for example, explored by Tarun et al [137, 154]. Tarun allows the device to conform to the shape of the body, resulting in a different shape when wrapped around the wrist as a smartwatch or held to one's face for a phone call. Snaplet can sense its shape configuration and adjust its functions accordingly. We suggest that wrist-worn devices could take advantage of the user's body configuration in a similar way.

2.5.2 Infrared Sensors

In our design process, we used infrared (IR) sensors for prototyping and also for the implementation. This approach has a long history, and there is a significant amount of related work, most prominently, frustrated total internal reflection introduced by Jeff Han [43]. Our sensors however are more closely related to earlier work by Han on the bidirectional properties of LEDs [72, 80]. Microsoft Research introduced prototype devices using this approach, including SideSight for creating a touch interface around a device [21], and ThinSight, an augmented gesture sensing LCD display [54]. Similar sensors to our approach are used for various other applications, from touch-less interactions in public restrooms to optical pickups in musical instruments [122] and sensing touch interactions with the skin [85, 98].

2.5.3 Output Methods

The small display of most smartwatches requires special attention on the output design as well. Haptics have been a popular method: haptic impulses can serve as indicator or act as a low bandwidth communication channel [81]. Haptic features can also provide guidance for eyes-free input [10]. Other methods of haptic output which have been explored are temperature displays based on Peltier elements [158].

Xu et al. [162] explored using low resolution visual information and demonstrate prototypes of traditional watch faces augmented with discrete visual indicators. The rationale behind her work is that information displayed on a wrist-worn device should be discernible at a glance, suggesting that focused interactions, such as reading the full content of an e-mail are most likely going to be rare.

Lopes and Baudisch [79] use electrical stimulation on one arm to provide haptic feedback to the other arm. A less invasive method of literally twisting-one's-arm was demonstrated by Nakamura [93] who used what he calls the 'hanger reflex' to induce an involuntary twisting.

The idea of glanceable information, as discussed by Xu at al. will be recurring in our own work. Using the body as an output medium, as demonstrated by Lopes and Nakamura, is interesting in relation to the concept of proprioceptive feedback. It is also relevant to design explorations which remove the idea of 'device' and may be an interesting path for future work to explore.

2.5.4 Display Sizes & Configurations

The shape and arrangement of wrist-worn displays has been investigated by various researchers within the field of HCI, however, the area has only received relatively little attention and warrants further research. Lyons et al. explored a segmented cylindrical display which is worn around the wrist [82]. In their prototype device, Facet, they used a series of small displays arranged in bracelet shape. They suggest rotating Facet as an interaction, and, like DisplaySkin, extract relative orientation of each of the displays segments using inertial data. Based on their orientation, segments can have different functions. Using a similar prototyping platform, Olberding et al. explored displays as an extension of the body [100]. They present interactions with a series of displays placed along the upper arm, considering them as both private and public displays and using occlusion by clothing and body pose as functional aspects of interaction (Figure 2.27).

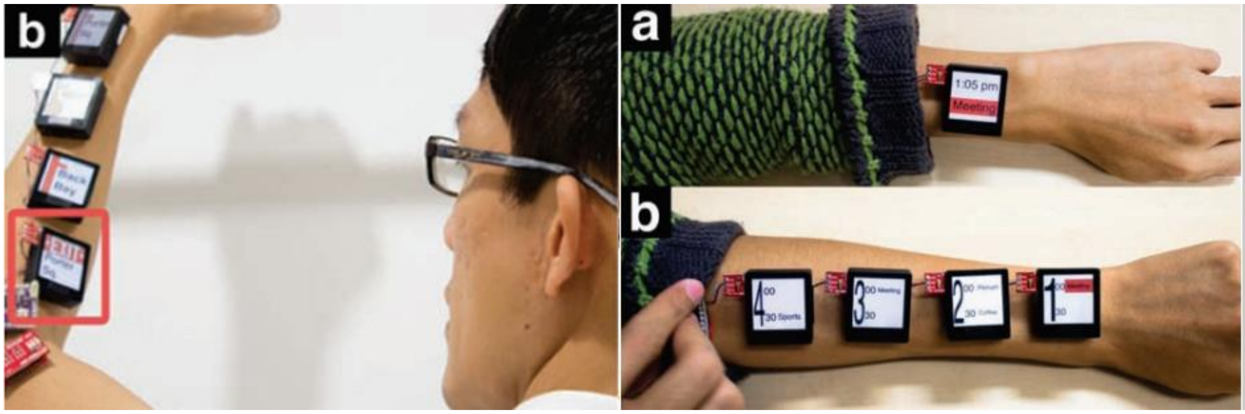


Figure 2.27 - Augmented forearm. Public display (left) and private display (left in red box) as well as modulating semantic zooming by rolling up the sleve (right) [100]

2.5.5 Integrating body and device

Chris Harrison explores scenarios that completely remove the idea of a device: Armura [45] and OmniTouch [44] demonstrate interactions with projected displays on the skin, using hands and arms as interaction surface (Figure 2.28) and enabling the user to transiently integrate objects with their body, using them to expand their interaction vocabulary. Exploring a similar premise of the body as an interactive medium, Katia Vega introduces the concept of beauty technology [147]. Vega uses makeup [66], fake eye-lashes [36] and hair extensions [146] as interfaces.

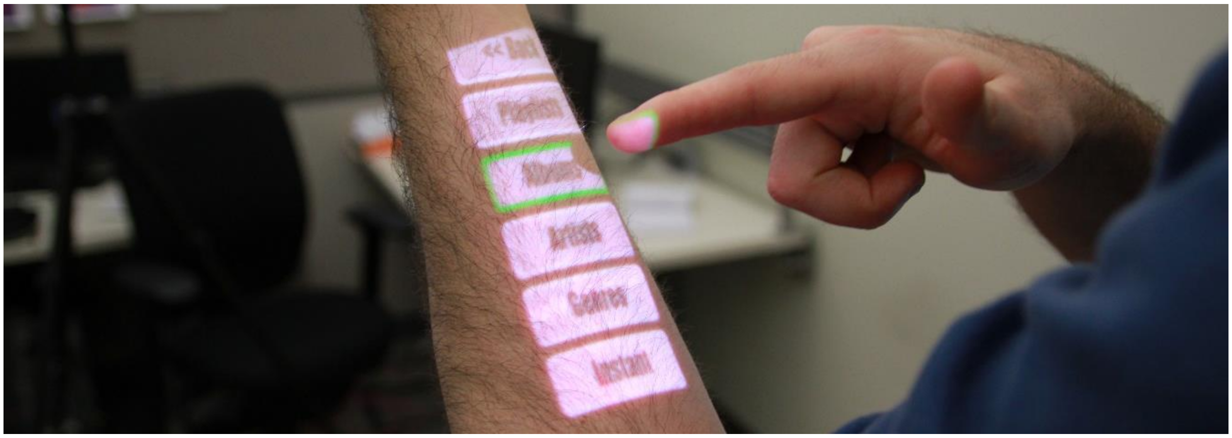


Figure 2.28 – The arm as interaction and display surface [45]

2.5.6 Placement of and Access to Mobile Technology

Ashbrook et al. conducted an experiment which required users to access information using a smartphone or a smartwatch and found that participants are significantly faster in retrieving information using the smartwatch [11]. There is a small body of work which further explores where on the body a wearable device should be placed to minimize interruptions and be socially acceptable. This research takes both the user and people interacting with the user into account. Harrison et al. explored where on the body users are able to react fastest to a notification, demonstrating that notifications on the wrist lead to fastest reaction times compared to various other locations on the body [47]. Cheng et al. [24] and Strohmeier & Kamphof [132] explore touching and touch interfaces on other peoples bodies, suggesting the wrists to be a viable public interface. Harrison also demonstrates that in terms of other people interacting with wearable technologies, the arms and hands are the preferred surface for others to touch and look at [48]. These results also suggest that wrist worn devices can serve functions beyond how we currently engage with wearable technology. The wrist as a location for a display also has the benefit that we, based on proprioception, always know its location. Finally, especially with high-skilled manual tasks, such as surgery, a wrist worn display is as close to the focus of attention without causing occlusion of the task at hand.

2.5.7 Head Mounted Displays

While some, such as wearable computing pioneer Steve Mann, may argue that head mounted displays make wrist worn computers obsolete [127] there are many reasons why one might disagree with this assumption. For one, the social acceptance of head-mounted displays is still very low [88]. This is possibly because passers-by have limited to no understanding of how the user is currently engaging with the head mounted display [83]. A near-eye device which sidesteps this problem is Loupe by Lyons et al [83] (Figure 2.29). Because Loupe needs to be actively brought to ones face for accessing information, onlookers have a clear understanding if the user is engaging with the device or with their environment. This approach limits the opportunities for non-focal interaction, as the user is required to actively seek information. We believe that many of the opportunities provided by head-mounted displays can also exist for wrist worn devices. While the wrist is not continuously in the user's field of view, it usually resides at least at its periphery, and is easy to move into ones field of view. Engaging with a wrist worn device is, to a certain extent, a public activity enabling third parties a sense of access to the interaction. Wrist-worn devices are also more familiar to onlookers, which may provide further benefits regarding social acceptance.

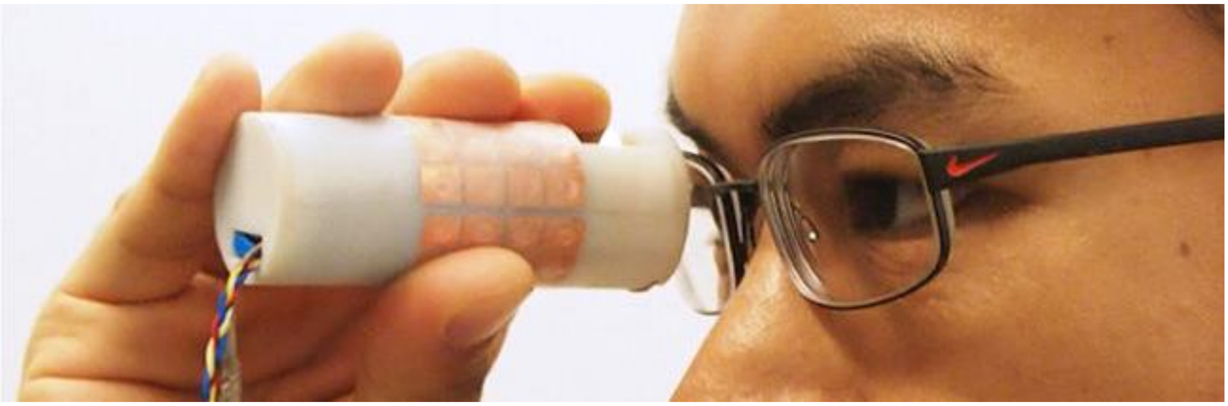


Figure 2.29 – Loupe [83]

2.6 Conclusion

Looking at the history of the wristwatch, we have pointed out that the mechanisms responsible for early *adoption* of technology, be it the drum watch or early wearables are different from the mechanisms that lead to a wide *acceptance* and proliferation of those technologies. Particularly wearable devices were initially adopted as fashion items. Once the devices were no longer identified as a fashion-only device, but had practical purposes, it was used not only used by so called ‘early adopters’ but accepted and used by the population at large.

The digital watch emphasizes that it is not the technology which dictates how it is used, but rather our requirements of it. This is apparent in the parallels between various stages of adoption of digital and analog watches. Current smartwatches still do not have a clearly defined use-case or interaction language. We believe that a clearly defined re-casting of the smartwatch as a contextual device, focusing on the requirements which lead to the adoption of the wristwatch in the first place – a glance-based, contextual information display – may help establish the smartwatch as a useful tool, rather than a vanity product.

Looking at the current related work, there are two issues which are apparent. The first is that a large portion of design research investigating wrist worn devices seems to focus on the small display size. While we do acknowledge that there is a value to this research, we believe alternatives should also be explored, as there is no intrinsic reason for the small display size current wrist-worn devices have. Therefore, the first part of this thesis sets out to demonstrate that larger display sizes are possible and to investigate the benefits of using a larger display.

A second theme are investigations that blur the border between the user and the device: research that engages with the body as an element of the interactive medium. This is the design principle that underlines the second part of this thesis. We take a step back to reflect on what the specific benefits of a wrist-worn device are for the user. Based on recurring patterns observed in the history of wrist-worn devices and based on the results of our first experiment, we developed a pose-aware display that will be introduced and investigated in the second half of this thesis.

Chapter 3

Building DisplaySkin, Evaluating Viewport Sizes

Based on the literature, display size is considered a limiting factor for interactions on the wrist. We believe that the display size is not just a technological constraint, but also a constraint we artificially impose on our designs based on the traditional form factor of wrist worn devices. In this section, we describe the manufacturing process of DisplaySkin, a wrist worn device with a 7.2” diagonal display. The display is 3” by 6.5” making it substantially larger than, for example, the 1” by 1.2” inch display of the Apple Watch [19]. For manufacturing DisplaySkin we developed a novel combination of thermoforming and 3D printing as well as a custom touch sensor, which are both contributions in this thesis.

After implementing DisplaySkin, we set out to test how different display sizes might influence interactions on wristworn devices. We chose a list scrolling task for our evaluation, as it is representative of browsing apps on the Apple Watch [28] and because it has been used in a previous exploration by Perrault et al. [104]. We compared three display configurations by adjusting the active viewport size.

3.1 Implementation

Here we outline the construction of the physical structure of DisplaySkin and the design of the multi-touch sensor. We opted to build our own device rather than use existing hardware as this enabled us the freedom to explore the form factors we were interested in. We were interested in creating a physical device, rather than a projection based exploration. Dealing with the challenges of overcoming the constraints provided by a physical medium offers the opportunity to explore the affordances of that medium. This may lead to design choices and discoveries based on factors one would not have dealt with using projection or other simulated approaches.

Our laboratory had previously explored flexible displays in mobile devices. Making the leap from thin-film devices such as PaperPhone [68], MorePhone [41], FlexView[20] or PaperTab [134] to a device wrapped around the wrist is relatively obvious. In fact Tarun et al. had already done so with Snaplet [136]. Unlike Snaplet however, we opted for a display wrapped around the entire wrist.

3.1.1 Technologies Used in DisplaySkin

The core element of DisplaySkin is the Plastic Logic flexible Display (Figure 3.1). Plastic Logic produces flexible TFT-Matrixes which can be used for flexible touch-sensing, flexible camera arrays or as driving circuitry for FOLED or electrophoretic displays [2].

Figure 3.1 – Flexible Plastic Logic Display, used in PaperTab [134]**.**

Plastic Logic provides display evaluation kits to demonstrate their flexible backplane technology with electrophoretic displays. These kits consist of a Freescale Linux embedded computer, custom driver hardware and a 10.7” display.

The display itself consist of multiple layers with unique functions fused together (Figure 3.2). The bottom layers is a protective plastic sheet. Merged to that is the active matrix substrate which controls the electrophoretic display. The electrophoretic display is sandwiched between the active matrix substrate and a color filter, which in turn is protected by another plastic encapsulation sheet.

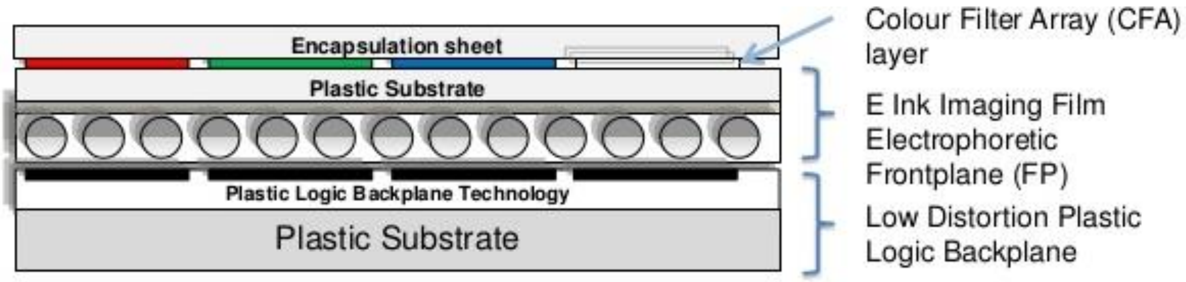


Figure 3.2 - Layers of Flexible display [2]

While these displays provide us with a strong prototyping platform, they have a series of limitations. For example, the display is flexible, but its connectors are not. Therefore the physical connection between the display and its data and power connectors is prone to damage. Another limitation of these displays is the driver software. It is only capable of showing images, but not video. However, in order to do some of the more advanced interactions we envisioned, we needed to continuously redraw the display at a reasonable refresh rate. To overcome this limitation we used FlexKit [56], written by Holman and Burstyn. Their custom driver enabled fast updates up to 12 fps, which is fast enough for simple video animations.

3.1.2 Assembling the Display

Several steps were necessary to transform a PlasticLogic display into DisplaySkin. One of our first obstacles was that the display was too large. We had to reduce it in size, so it could wrap around the wrist comfortably.

As mentioned, the display is updated through power and data connectors forming a bezel on the top and left of the display. If one cuts the display, all pixels that have an intact horizontal and vertical line connecting to this bezel remain intact. Within this constraint, the display can be cut to arbitrary shapes. We cut the display to a size which allowed it to wrap around a wrist, wide enough to display information in arbitrary orientations (Figure 3.3).

Figure 3.3 - Cutting the Flexible Display

Another problem we encountered is that the display deteriorates from being bent. Minor bends do not stress the material to an extent where it is damaged, however, if bent for a longer duration, or to a sharper curvature, the stress causes the bond between the individual layers to break. This is because the layers are flexible, but not elastic. When the display is bent, the inner layers are compressed. This creates stress on the bonds between the layers. The compressed side will 'pop out', breaking the bond between the active matrix layer and the electrophoretic display. Cutting the display further weakens the bonds, making it more likely to deteriorate.

To wrap the display around the wrist, we had to find a way of creating the required curvature without damaging the display. We therefore adressed these issues of 'popping' and connectors breaking by creating a 3D printed frame. Once printed, we slid the display inside this frame (Figure 3.4). The 3D printed structure protects the connectors by supplying them with additional re-enforcement and reduces the likelihood of the display 'popping' by applying pressure to the display from both sides, preventing the individual layers from separating.

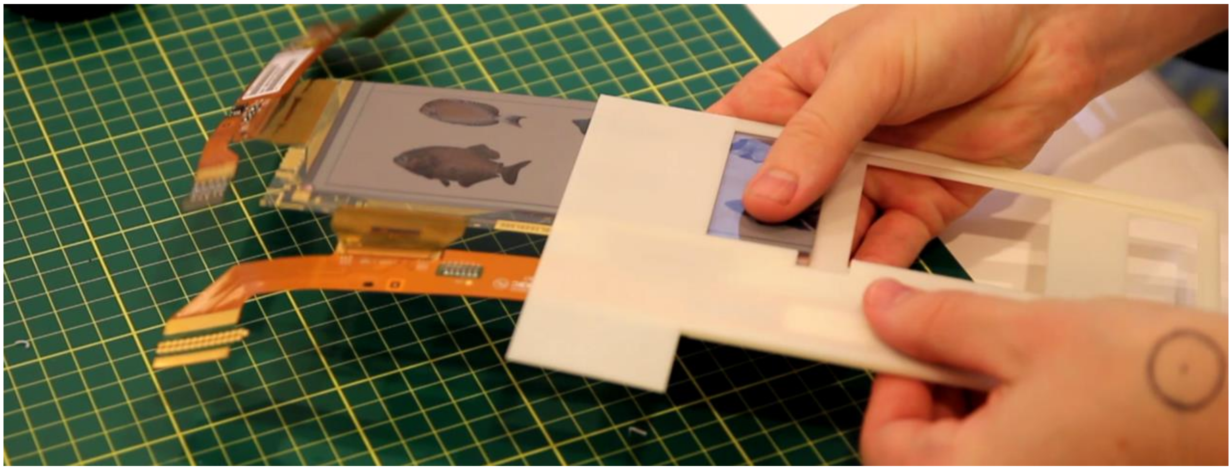


Figure 3.4 - Inserting Flexible Display in 3D printed frame

Once placed inside the 3D printed mold, we thermoformed the entire structure to give it its final curved shape (Figure 3.5). Bending the entire structure when heated allowed the top protective layer to expand, while the bottom layer could minimally contract. By enabling the top layer to expand and the bottom layer to contract, we reduce the internal tension of the display, making our prototype sturdier. There was, however, a negative side effect, as the color filter was no longer aligned after this procedure, preventing us from displaying color images.

Figure 3.5 - Heat-Shaping the Display

After heat shaping, the resting state of the display was cylindrical and it could comfortably be wrapped around the wrist (Figure 3.6). Although the structure maintained its cylindrical resting state, it was flexible enough for opening to wrap around the hand. Once on the arm, a magnetic clasp secured it in place.

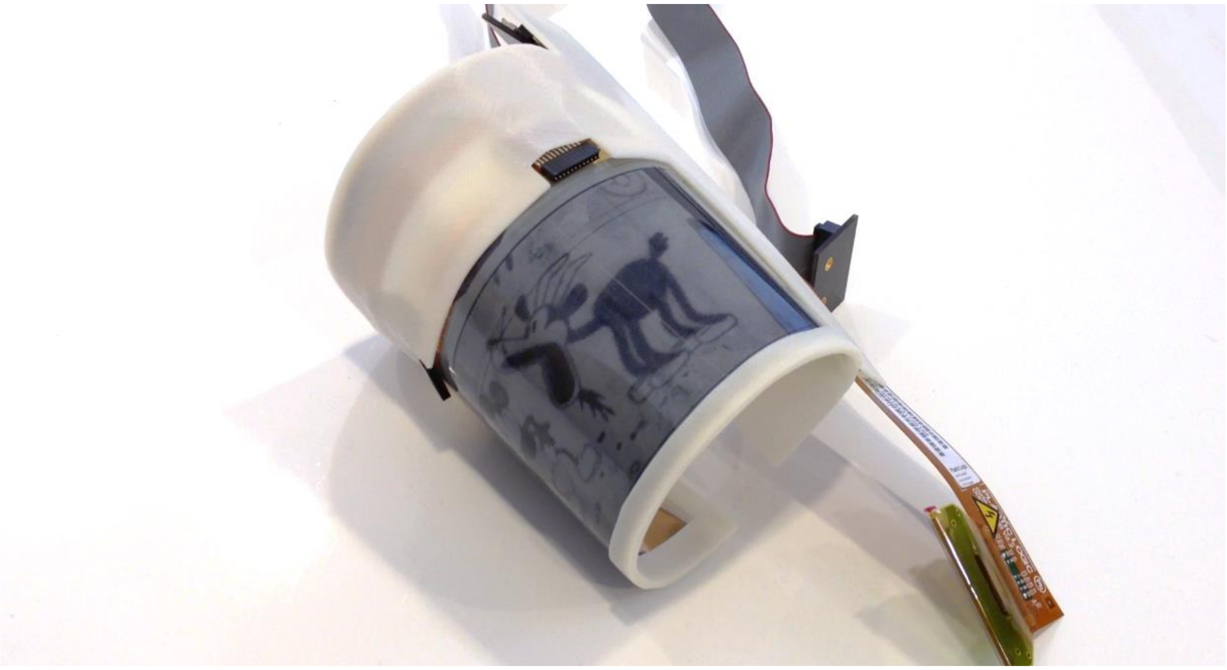


Figure 3.6 – DisplaySkin in its thermoformed resting state

While cutting electrophoretic displays had previously been investigated by Gomes et al [41, 42] the process of heat-shaping the electrophoretic display is novel. To the best of our knowledge, thermoforming a 3D printed structure is also a novel prototyping method. The heat-shaping process developed for the physical form of DisplaySkin arose from necessity, however, we believe it is a generalizable method which may also prove beneficial for prototypes which are not subject to our specific constraints: 3D printing a cylinder in its final shape would take significantly longer than 3D printing it unrolled and consequently heat-shaping it. This process also has the benefit that the final cylinder is elastic along its circumference. If directly printed, the internal structure of the cylinder would make it difficult to bend for opening and closing. Doing so might even break or otherwise damaging the print.

3.1.3 Designing the Touch Sensor

Traditional Sensing Approaches

There are numerous ways of detecting touch on a surface [21, 43, 54, 70, 72, 91], two of the most popular methods are capacitive and resistive sensing [5, 37, 57, 99]. Resistive sensors generally consist of a layer with variable resistance between two conductive layers. If the two conductive layers are compressed, the resistance decreases, which can be used to measure the strength and location of a touch [37, 57]. Capacitive sensors are, strictly speaking, proximity sensors. An electrode on the touch surface is charged, and the time it takes for the charge to dissipate is measured. This discharge time is increased if a finger is in close proximity of the electrode, as the conductive finger, the non-conductive air and the conductive electrode together from a capacitor. This leads to the electrode maintaining its charge longer than it otherwise would. The change in discharge times can be measured to detect touches [5, 99].

Touch Sensing on DisplaySkin

The combination of a curved, bendable surface and electrophoretic display make sensing touch on our prototype challenging. Commercially available flexible capacitive overlays work very poorly with electrophoretic technology as the capacitive field of the display drowns out any capacitive signal induced by human fingers. Resistive overlays do not work with flexible displays, as any change in curvature is also a change in internal pressure, making them unusable.

Discrete resistive pressure sensors can be placed underneath the device, however the resulting touch resolution typically is poor [129]. Discrete DIY capacitive sensors can also be placed underneath the display as demonstrated by Gomes and Vertegaal for MorePhone [41]. The touch resolution of MorePhone, however, was also very low. A further problem with placing a sensor underneath the display is that DisplaySkin is wrapped around the arm. The arm introduces sources of false positives for both the capacitive and resistive solutions.

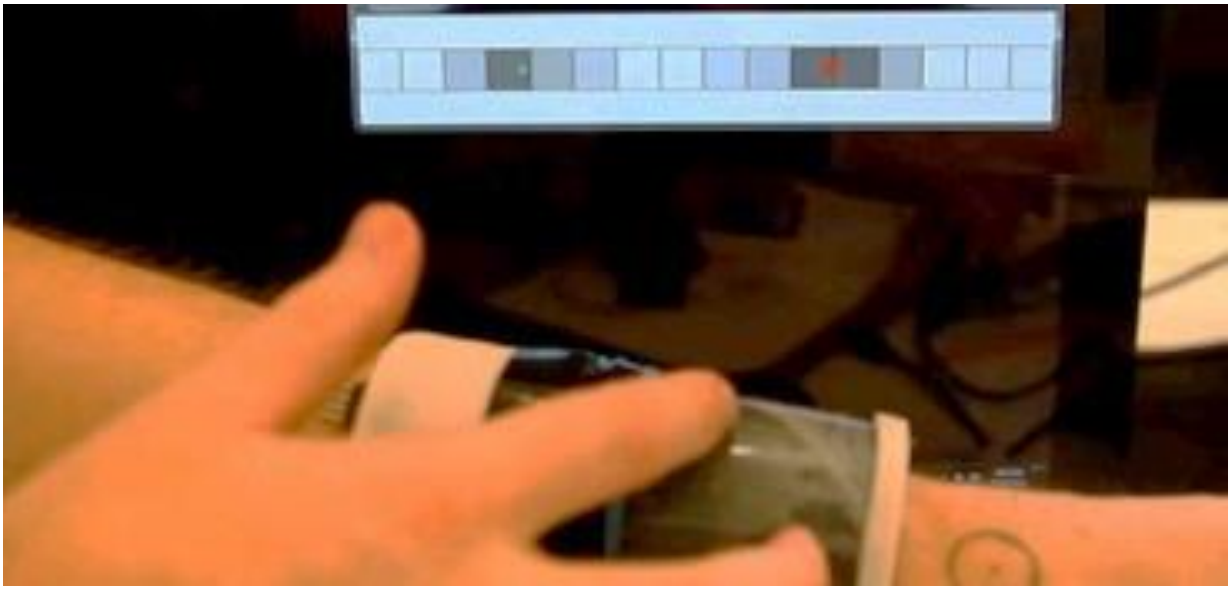


Figure 3.7 - Visualization of data readings from projected touch screen [129]

IR Sensors

Near-infrared (IR) sensing solutions can be used as an alternative to resistive or capacitive sensors [129]. Like capacitive or resistive touch solutions, near-infrared (IR) sensors (Figure 3.7) can be manufactured in arbitrary configurations. IR sensors, however, do not have any of the previously mentioned drawbacks of resistive or capacitive DIY solutions. IR sensors can be used for sensing touch, pressure and, acting as proximity sensors, can also sense the approaching finger in mid-air. This makes them a well suited sensor for expressive, dynamic interactions. IR sensors also do not require access to the interaction surface; instead of acting as an overlay or substrate, they can be projected on the interaction surface from the side. This enables touch interactions using the skin as touch-surface, for example in the proximity of a wrist watch.

Principles of IR Touch-Sensing

IR touch sensors consist of two elements: an IR emitter and an IR phototransistor (Figure 3.8). If an object comes within the proximity of the emitter, light is reflected back, allowing a measurable voltage to propagate through the phototransistor. Such a system can also measure finger-pressure, as the flesh of the finger changes its IR reflectivity with pressure [129].

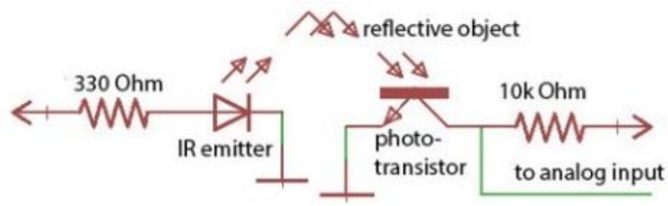


Figure 3.8 – Basic Components of IR sensing circuit [129]

We use flexible circuits [131] to enable the sensors to conform to the curved surface of DisplaySkin, while making them as thin and lightweight as possible. We treat the incoming sensor readings as pixels in an image and use blob-tracking algorithms for determining touch and gesture information. The accuracy of the sensors in x & y dimensions depends on the density of its IR-emitter and photo-transistor arrays. The accuracy on the z axis (distance from sensor) depends on the distance between emitter and photo-transistor, their viewing angles, and the strength of IR illumination.

Projected 2D Touch Sensor for DisplaySkin

For detecting touch interactions on the curved surface of DisplaySkin, we created a linear array of alternating IR emitters and photo-transistors (Figure 3.9). For our emitters, we chose the SFH 4045N by Osram. The specific emitter was chosen because of its wavelength (950nm), its relatively small viewing angle (18°) and because it can be mounted at right angles. For the receiving elements we chose the PT12-21C/TR8 by Everlight, as it closely matched our emitter's wavelength (940nm), has a wide viewing angle (120°) and can also be mounted to a circuit at right angles. We found that this setup maximized the resolution of the sensor: the small viewing angle of the emitter reduced the ambient saturation of IR light, while the wide angle of the receiver enabled us to use software interpolation between multiple receivers to enhance precision. We further reduced the incoming ambient IR by encapsulating emitters and phototransistors in opaque silicone (Figure 3.9, bottom and right). Because the interaction area is projected, this sensor is suitable for touch sensing on flexible electrophoretic devices, such as DisplaySkin [19]. Using this sensor, we were able to detect the fingers position with an accuracy of +/-3mm on the x axis. The sensor was sampled ~ 60 times per second, which made it significantly faster than our display speed (12fps). The sensor therefore did not introduce any additional latency into our system.

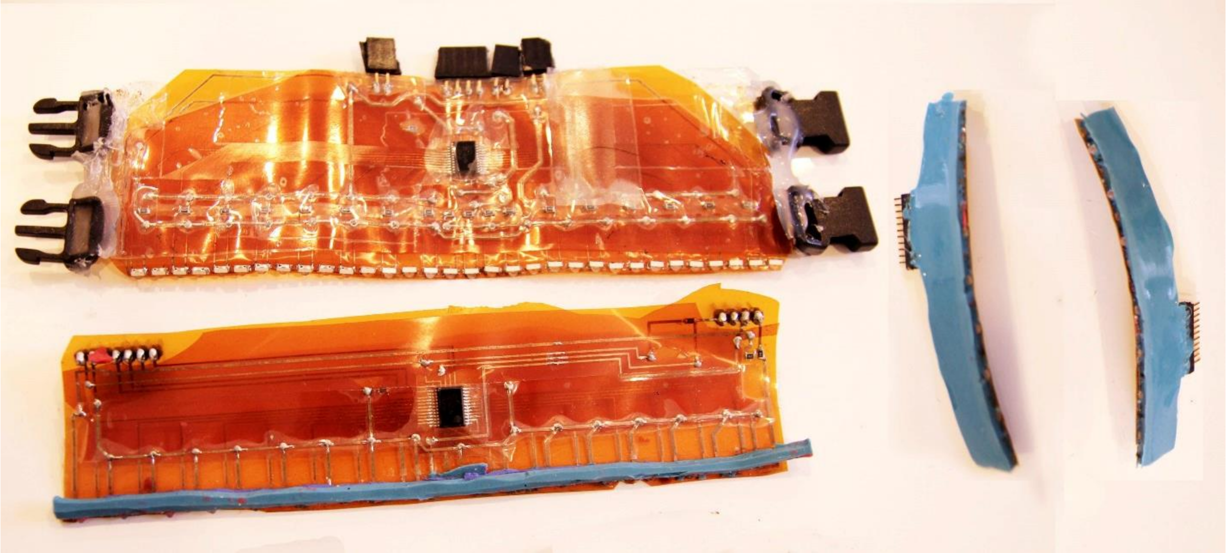


Figure 3.9 –prototypes of linear IR multitouch sensor used with DisplaySkin [129]

Limitations & Concluding Thoughts on the IR Sensor

In laboratory settings and for experiments and evaluations our sensor performed reliably, as ambient IR could be controlled. In outdoor situations, IR from sunlight saturates the phototransistors, potentially reducing the usability of the sensor. This effect can be mitigated by taking two consecutive readings: one with active IR illumination and one without. Using the differences between these readings for image processing can enhance the usability of IR sensing in situations with high ambient IR.

Like the thermoforming method presented, this sensing approach was developed for DisplaySkin, but we believe it is also generalizable. It can turn any surface into a multi-touch area without requiring an overlay or access to the surface from underneath. This makes it a prime candidate for exploring touch interactions on the skin, which take advantage of the dual feedback of skin touching skin. The approach we use is also easily customizable and can be appropriated for various special purpose sensing applications.

3.2 Evaluating the Effects of Different Display Sizes

Once the physical prototype was completed and the multitouch sensor implemented, we conducted our first experiment: evaluating what impact different display sizes have on task completion times in a list searching task.

3.2.1 Experimental Motivation

Emerging technologies such as flexible displays, batteries, and circuits enable innovative form factors for wrist-worn devices. Despite these advances, most currently available smart-watches follow the design of conventional watches: a small display attached to the wrist by a flexible strap. This design has largely gone unquestioned in the past hundred years [17].

The physical limitations of the traditional wrist-watch layout also limit the range of potential interactions. For example, a small display has a reduced area for touch input and is especially susceptible to occlusion [67, 150]. Also, when creating menu items on small displays they need to take up a large area of the available screen real estate, as the finger is very imprecise in selecting targets [58]. This is especially problematic as the small display area means that only very little information can be displayed at one time, requiring more user input than larger displays would, for example, when scrolling through a list of items or reading text.

There is a large body of research investigating these issues, but while input for small displays has been studied in detail, less attention has been devoted to studying the actual effects of display size: Might a larger display improve interaction, independently of problems related to input? If the interaction space is kept constant, does a larger display support more efficient or new styles of interactions?

3.2.2 Experiment

Task

Participants were presented with a scrollable list of 184 countries, sorted alphabetically. In each trial, an external display prompted the participants with the name of a country and asked them to find it within the list. In all conditions, participants used relative touch scrolling with inertia to navigate the list. Once the target item was visible, they tapped it to complete the trial. Although the viewport size varied between trials, participants were free to navigate using the entire touch surface of the display. In other words, the available input area remained constant throughout all conditions.

Task Motivation

The scrolling task was chosen based on a previous experiment by Perrault et al. which also used the entire wrist-strap as an input surface [104] and because it is an activity often required of users in current smart watch designs, for example, when selecting an app from the application menu on the Apple Watch.

Figure 3.10 - Small (left), medium (center) and large, cylindrical, display (right).

Conditions

We used two independent variables, display size and target distance. We simulated three display sizes using different viewports on the electrophoretic screen (Figure 2). The *small display* was a 1.55” (Figure 3.10, left) rectangle on the top of the wrist, similar to most smartwatches and the display used by Perrault et al. [104]. The *medium display* consisted of a 4” rectangle that started at the top of the wrist and covered the visible area of the display, as viewed from above. The *large, cylindrical, display* (Figure 3.10, right) condition spanned the entire surface of the prototype.

We used 4 target distances, a subset of those evaluated by Perrault et al. [104]: 5 items, 20 items, 80 items, and 160 items. Each item had a height of ~1 cm. In the small display condition, the 5th item is not visible at the start of the trial. It is, however, immediately visible in the large and cylindrical conditions.

Measures

Our dependent measure was navigation time, measured from the onset of the prompt to when the participant tapped on the correct target.

Experiment Design

We used a 3x4 factorial within-subject design with repeated measures. Our factors were: display size (small, medium, and large) and target distance (5, 20, 80, and 160 items). Each participant performed 6 trials per combination of factors, for a total of 72 trials. Condition order was counter-balanced between participants. The experiment lasted approximately 45 minutes, including practice. Participants practiced with each display size until they achieved less than 10% improvement between trials.

Questionnaires

We asked participants to rate each displays size on: how efficient it was for searching, if it enabled a good overview of the data, and if it was useful for bimanual interactions. Each question was structured using a 5-point Likert scale of agreement (1: Strongly Disagree-5: Strongly Agree).

Participants

The experiment was conducted with 12 participants (9 male, 3 female) between the ages of 17-29. Most participants were right handed (9/12) and only 3 wore a wristwatch. All participants had some familiarity with touch gestures, e.g., on a smartphone or tablet. They were paid $10 for their participation. Left handed and right handed participants completed the same task.

Hypotheses

We hypothesized that larger display sizes would have faster navigation times (H1). As a control, we also hypothesized that larger target distances would result in longer navigation times (H2).

3.2.3 Results

Experiment Results

We analyzed the collected measures by performing a repeated measures ANOVA using display size (3) x target distance (4) on navigation time. Table 3.1 outlines the means and standard errors for list navigation time.

We found a significant main effect of display size ($F_{2,22}=24.13$, $p < 0.001$) on list navigation time. Pairwise post-hoc tests, with Bonferroni corrected comparisons, revealed that the small display was significantly slower than both the medium and large (cylindrical) display sizes ($p < 0.001$). As expected, the analysis also showed that target distance was a significant factor ($F_{3,33}=303.11$, $p < 0.001$). Pairwise post-hoc comparisons, Bonferroni corrected, confirm that navigation times differed significantly between all target distances ($p < 0.001$).

		Display Size		
		Small	**Medium**	**Large (Cylindrical)**
	Overall	17.65 *(0.64)*	13.19 *(0.58)*	12.37 *(0.57)*
Target Distance	***5***	7.21 *(1.27)*	2.92 *(0.95)*	2.60 *(0.76)*
	20	11.59 *(2.14)*	8.03 *(2.12)*	6.94 *(1.09)*
	80	20.56 *(2.14)*	15.65 *(1.76)*	14.95 *(1.82)*
	160	31.24 *(3.37)*	26.17 *(2.90)*	24.98 *(3.08)*

Table 3.1 – Targeting times in seconds and their standard deviations

Questionnaire Results

Table 3.2 displays the median scores of the questionnaire responses. We analyzed the data using a Friedman's one-way ANOVA by Ranks on the participants' ratings, with Bonferroni corrected Wilcoxon Signed Rank post-hoc tests (evaluated by dividing the standard alpha of 0.05 by the number of comparisons, $\alpha = 0.0167$). Results showed a significant effect of display size on participants' ratings of their ability to use bimanual interactions (Friedman's χ^2 (2)=15.62, $p < 0.001$). Post-hoc comparisons reveal that the large (cylindrical) display was rated higher than both the medium display ($Z = -2.714$, $p < 0.007$) and the small display ($Z = -2.716$, $p < 0.007$), and the medium display was rated higher than the small display ($Z = -2.511$, $p < 0.012$).

Results also showed a significant effect of display size on participants' impression of how efficiently they could complete the task (Friedman's χ2 (2)=14.15, $p < 0.001$). Post-hoc comparisons reveal that the large (cylindrical) display was rated higher than the small display ($Z = -2.738$, $p < 0.006$) and the medium display was also rated higher than the small display ($Z = -2.653$, $p < 0.008$).

We also found significant differences in how users experienced their overview of data for the different display sizes (Friedman's χ2 (2)=13.82, $p < 0.001$). Post-hoc comparisons revealed that the large (cylindrical) display was rated higher than the small display ($Z = -2.694$, $p < 0.007$) and the medium display was also rated higher than the small display ($Z = -2.766$, $p < 0.006$).

	Small	Medium	Large (Cylindrical)
The display enabled bimanual interaction	2	3	4
The display supported task efficiency	2	4	4
The display provided an overview of the data	2	4	4

Table 3.2– Questionnaire Results (Median response. All different values are also significantly different. The large display trended towards a higher result than the medium display for all questions. 1 = Strongly Disagree, 5 = Strongly Agree).

3.2.4 Discussion

The results of our experiment suggest that there is a benefit of increasing the display size for list navigation tasks. Results confirm our hypothesis (H1) that display size has a significant effect on navigation time: the medium and large display sizes allowed for faster task completion. These results show that the current display sizes of smart watches limit the ability to efficiently navigate through information, even if the interaction space is larger than the display. As expected, we confirmed our control hypothesis (H2) that larger target distances would result in longer navigation times.

Participants took advantage of the larger interaction area. For the small display condition most participants used a non-active area below the viewport for scrolling. This allowed them to scroll without causing any occlusion of the active area. This demonstrated that our results are not confounded by the known input issues of small displays. It also suggests that for most currently available devices which do not have the extended input area, the occlusion introduced by touching the small display would lead to even slower task completion times than the ones we found for the small display.

Like most scrolling experiments, we observed that the task is composed of a number of sub-tasks: 1) the participant estimates the target position relative to their current position in the list; 2) rapidly scrolls towards the target, either under- or over-shooting; 3) brings the target into the viewport with slower and more precise scrolls and 4) selects the target.

When the target is already visible within the display, participants are able to skip step 2), an opportunity provided by the medium and large, cylindrical, display sizes in the smallest target distance condition. For larger target distances, this particular benefit does not occur. The overall results, however, suggest that these two sizes provide a significant advantage for steps 1) and 3), by providing the participant a better view of surrounding targets. Specifically, we see that the absolute performance differences between target distance conditions are fairly stable across display size conditions—suggesting a constant advantage provided by increased display size. The relatively constant delta between navigation times for each list length is easily visible in a bar-graph (Table 3.3)

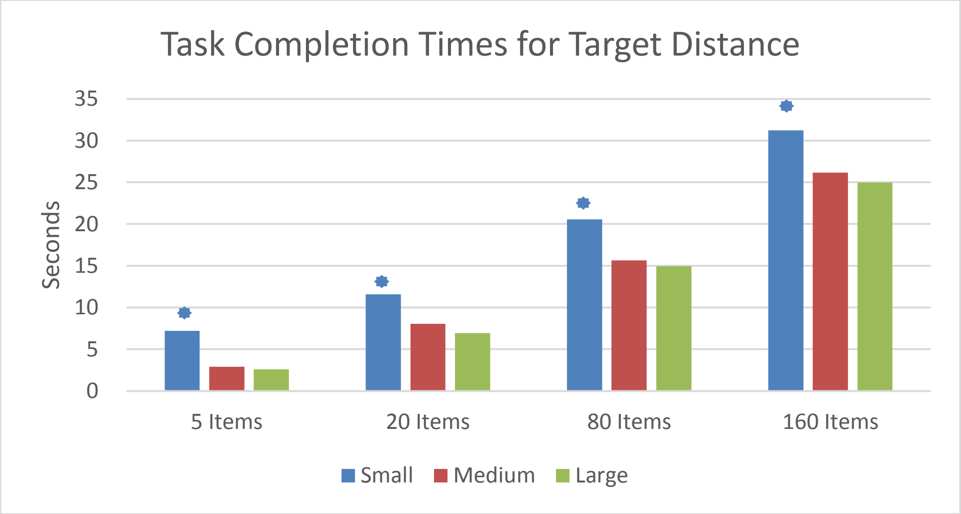


Table 3.3 - Task completion times for target distance and display types in seconds, star indicates $p < 0.05$

We would like to point out that the absolute navigation speeds are different from those observed by Perrault et al. [104]. This difference in task completion times was likely due to implementation differences in the scrolling physics model, which in our case was constrained by the slower refresh times of the electrophoretic display used in DisplaySkin. This lead to a slower scrolling behavior, which effected absolute task completion times. Relative task completion times (the ratio between times to scroll through different list lengths) are however in agreement with Perrault et al.

Effects of a Cylindrical Display

Bimanual Interactions

During our experimental evaluation, we observed distinct strategies in how participants interacted with different display sizes (Figure 3.11). Many participants chose to support their left hand on the table, as our experiment required them to scroll through lists for an extended period of time, which they reported to be tiring despite breaks. With the small display size, participants often rested their entire palm on the table (Figure 3.11 - A). In the large display size condition, participants often lifted their hands, supporting the weight with their fingers (Figure 3.11 - B), while orienting the active display area towards their face. In the cylindrical display condition, participants usually lifted their hand from the table (Figure 3.11 - C) to leverage bimanual interactions.

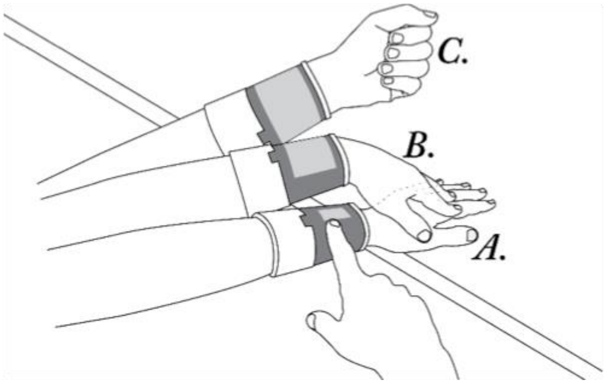


Figure 3.11 - Typical hand positions for different Display Sizes

We noticed two ways in which participants used bimanual interaction with the cylindrical display. When participants were close to the target, but it was not immediately visible, they would rotate their wrist to bring it into view. In addition, participants also used the rotation of their left hand to correct for the actions of the right: To accommodate for the inertial scrolling, they commonly rotated their wrist to respond to an overshoot or in anticipation of an upcoming target.

These behaviors are supported by the questionnaire results. When asked to rate appropriateness for bimanual interactions, 75% of the participants stated that the large, cylindrical, display supported bimanual interactions (rating it with a 4 or 5), compared to 41.7% for the medium display and only 16.7% for the small display condition.

Mobile Interactions

The reason participants lifted their wrist off the table during the medium display size condition was to orient the display towards their face. Viewed from the right angle, the viewport spanned the entire width of the wrist. When the active display area is oriented towards the face, the medium and large display sizes were visually identical. This, however, is true only if a user's body is in the correct pose for interacting with the display. The use of bimanual interactions for completing the search task points to another affordance of the cylindrical display: it can be viewed from various angles.

While the difference between the task completion times for the medium and large, cylindrical, display sizes was not significant, we believe this to be based on the static nature of our experimental setup. In day-to-day life, our bodies, and especially our hands, are usually in motion. Outside of a laboratory setting, we would expect this property of the cylindrical display to demonstrate additional benefits over the medium display.

Our results demonstrate that there is a significant benefit of larger display sizes with respect to task efficiency, at least for list navigation tasks. This suggests that, while increasing the interaction area has its own advantages, there is value in creating wrist-worn devices with larger displays. At the same time, a display that wraps around the entire wrist was not significantly faster than one that covers the top of the wrist. Users can, however, view a cylindrical display from any angle; they are not constrained to a specific pose. This freedom allowed the participants to explore different positions of the arm and the wrist, in turn inspiring them to navigate with bimanual gestures—demonstrating that while the cylindrical display was not more efficient than the large display in our controlled experiment, the form factor may provide additional benefits for mobile interaction.

Towards Glance-Based Interactions

The task chosen for our evaluation may not have been best suited for exploring the benefits provided by a cylindrical display. As discussed earlyer, wrist worn devices are, due to their constant availability, in a similar design space as head mounted displays. An advantage of a wrist worn device is its long cultural heritage and stronger social acceptance, while a drawback of most smartwatches is that while they are constantly accessible, they do not provide a constantly available display area the way head mounted displays do. This constantly available display however provides designers with a powerful tool to facilitate peripheral interactions.

Looking at the history of the wristwatch, peripheral, glance-based interactions are what initially made it popular in the first place. The wristwatch provided people with a simple way of accessing supplementary information, while minimizing interruption to their primary activity [124]. This design principle is at the core of much of the interaction research surrounding head mounted displays. For example, Vidal et al. use eye tracking to measure the focus of attention of users wearing head mounted displays. Vidal uses this information to design interfaces which are contextually appropriate: available when needed, and receding to the periphery if the user's attention, is elsewhere [148]. In many ways this makes wearable displays the spiritual successor of the wristwatch.

The affordances of DisplaySkin however enables an interesting hybrid medium somewhere between the static watch face, and the dynamic, always available, head mounted display. Because of its cylindrical display, DisplaySkin always has active pixels which are facing the user. We can take advantage of this by continuously re-orienting content towards the viewer to create a small window to the digital world which moves with the user, never far from the periphery of their vision. Such a device would be a suitable platform to combine both the positive affordances of the wristwatch and of head mounted displays.

While this thesis so far has focused on the history, form factor and display size of wrist worn devices, in a next step, we will take a closer look at using a wrist worn device as a glance-based interface, intended to supplement primary activities. We will initially outline our design principles before discussing our example implementation of these design principles: the pose aware display.

Chapter 4

Pose Aware Display

4.1 Concept

In our related work, we introduced various stories of how the first wrist-watch might have been invented: A mother suckling her child. An aviator pushing the boundaries of flight. Motorists using dangerous and experimental vehicles. Soldiers engaged in meticulously planned assaults. Hunters stalking their pray. All these scenarios have a common thread: the people adopting the technology are not interested in the device itself. They are engaged in an activity which is important to them. The wristwatch is a convenient tool which supports fully concentrating on a primary activity, while having access to supplementary information. The reason the wristwatch is convenient, is that it provides this supplementary information with minimal distraction [19].

Figure 4.1 – DisplaySkin with pose-aware contextual information

Once we had found this common thread, we realized that this design goal is just as relevant today as it was then: mobile devices provide people with contextual information. This information may benefit a primary activity, assuming the information is easily accessible. The use case of a wrist-worn device has not changed: just as in the 19th century wrist-watches were used to provide contextual information to the primary activity at hand, a smart watch will most likely be used in the same manner. As alluded to in our introduction, we have observed that in the previous years, smartphones have taken over as the primary device for accessing contextual information. However, it appears that this use cases for smartphones will be migrating back to our wrists, as it is easier to glance at one's wrist for information than it is to pull one's phone from one's pocket [11].

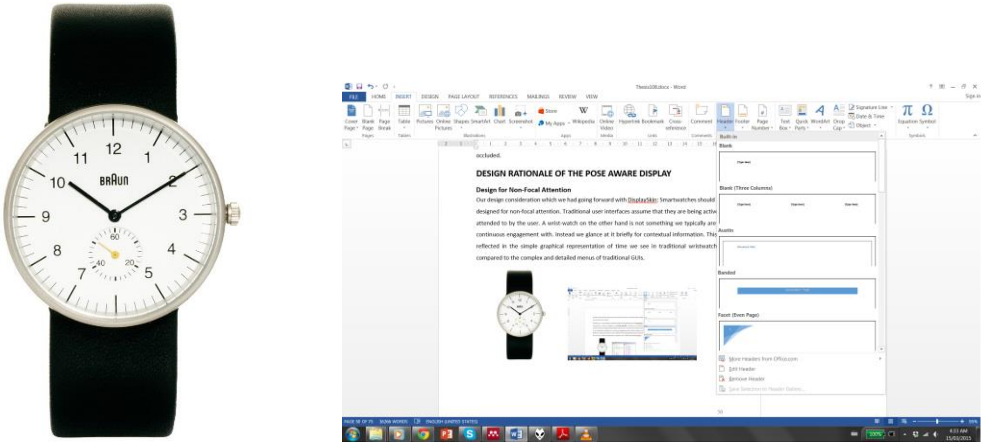
Our evaluation of different display sizes in the previous chapter demonstrated that one of the strengths of the cylindrical display used in DisplaySkin is its potential for mobile interactions and the quasi-always available display provided by its cylindrical form-factor. When implementing further interactions with DisplaySkin, we therefore decided to utilize these affordances, most importantly that the cylindrical display minimizes occlusion for most body poses. This allows the device to function as a contextual interface and also enable the user to access information in contexts in which a traditional smartwatch would be occluded (Figure 4.1).

4.1.1 Design Rationale for Wrist-Worn Devices

Design for Non-Focal Attention

One of the advantages of a wrist-worn display is that it is usually located not far from the focus of our interaction. Gruber, for example, describes how, when he grinds his coffee in the morning, the effortless access he has to his wristwatch allows him to gage how long the beans have been grinding, without removing focus from the coffee grinding machine [140].

Based on this affordance of conventional watches, a key design consideration which we had going forward with DisplaySkin was that Smartwatches should be designed for non-focal attention. Traditional user interfaces assume that they are being actively attended to by the user. A wrist-watch on the other hand is not something we typically are in continuous engagement with. Instead we glance at it briefly for contextual information. This is reflected in the simple graphical representation of time we see in traditional wristwatches compared to the complex and detailed menus of traditional GUIs. In figure 4.2 we provide an example of these two design paradigms side by side.



occluded.

DESIGN RATIONALE OF THE POSE AWARE DISPLAY

Design for Non-Focal Attention

Our design consideration which we had going forward with DisplaySkin: Smartwatches should
designed for non-focal attention. Traditional user interfaces assume that they are being activ
attended to by the user. A wrist-watch on the other hand is not something we typically are
continuous engagement with. Instead we glance at it briefly for contextual information. This
reflected in the simple graphical representation of time we see in traditional wristwatch
compared to the complex and detailed menus of traditional GUIs.

Figure 4.2 - Watch compared to the cluttered GUI of most applications

We argue that it is not useful to copy methods which have proven useful for focal interaction, conceptually shrinking a computer and placing it on the wrist. Instead, we suggest enhancing the existing light-weight affordances of the traditional wristwatch.

Design for Contextual Information & Minimal Interruption

In her motivation behind the design of her shimmering smartwatches, Xu states that she finds the scenario in which we read the full text of an e-mail on our watch is unlikely to occur [162]. Not only do we agree that such a scenario is unlikely, we also believe it is undesirable. To accommodate using a smartwatch as a non-focal device, the information accessible to the user must also be designed accordingly.

We envision DisplaySkin to be used with contextual information. Currently it is common to use mobile devices for accessing contextual information to support a primary activity: for example to consult a map when searching for a location in a foreign city. For the user to access this contextual information, the benefit of having this contextual information must outweigh the interruption introduced by accessing the mobile device. The user wandering through a foreign city is more likely to take advantage of map-data and GPS information if this does not require them to stop and pull a phone from their pocket. If one wishes to encourage accessing contextual information, it is important that information is both appropriate and available as quickly as possible, with minimal disruption of primary tasks. As demonstrated by Harrison [48], the placement of smartwatches on the wrist is ideal for supporting this type of activity as it is easily attended to. Going forward, we wish to further support this type of lightweight interaction.

Enable Glance-Based Interactions

As stated by TechCrunch, the most basic affordance of a traditional wristwatch is that one can access information by merely glancing at it [155]. With the rising complexity of smartwatches, this very basic feature is often no longer provided [140]. We argue that this trend ignores the most valuable feature of wrist-worn devices.

Watches are, traditionally, glance-based device, offering contextual information without requiring continuous engagement. Smartwatches should continue this tradition by supporting fast interactions which may consist of nothing more than a fleeting glance. These fleeting interaction are only possible if the user does not need to activate the device or search for content. In many scenarios the wrist is an ideal placement for such a device, however, depending on one's activity and the body pose associated with, the display might be out of view or occluded. The design of smartwatches benefits from considering glanceability as a design factor. Glanceability can be improved by means of clear graphic design, of hardware such as a cylindrical display which minimizes occlusion and by using software which presents information such that it is as easily visible as possible.

Consider Body Pose

Whether a wearable device can be glanced upon or not is largely determined by body pose. Body pose is also indicative of the type of activity a user is engaged in and can be an important implicit or explicit input tool. Just as Vidal [148] uses visual focus as a metric for assessing the user's requirements of a head-mounted display, we believe body pose to be an important indicator for engagement with a wrist-worn device. We argue that having access to information about the users body pose is important for designing lightweight interfaces for wrist-worn devices.

While we appreciate the design motivation behind gestural watch interfaces [65] and devices which make active use of our proprioceptive sense [22, 78], we caution against overloading body motion and its feedback: our proprioceptive feedback and body language already is laden with information, it helps us understand and express our emotional states [113, 128] and is invaluable in completing day to day activities. Instead of overloading these information channels, we suggest taking advantage of them to infer activity and mood as well as optimizing information retrieval.

4.1.2 The Pose Aware Display

While DisplaySkin's cylindrical display has active pixels on every side of the hand, which minimizes occlusion, this affordance of the cylindrical display is only useful if we know which active pixels are currently viewable by the user. We therefore need to measure the users pose and calculate where we can currently display information, so that it is not occluded. Additionally, to make glancing at information as effortless as possible, we can then rotate content so that it is oriented correctly towards the user's face. We propose measuring the configuration of the user's arm in relation to the rest of the body and dynamically moving information onto an area of the display that is visible. Presenting information in non-occluded areas is what makes the pose-aware display feasible in the first place, while orienting information towards the users further reduces interruption times, because it improves the readability of any text displayed on the device [156].

There is some previous research addressing similar problems. Cheng et al. [23] suggest adjusting a displays orientation based on the users face, however, like most current devices, Cheng at al. only enables two fixed orientations of content (landscape/portrait). In contrast, Wilfinger et al. [157] used accelerometer data to continuously rotate content on steering wheel displays. Both of these systems rotate content around a single dimension. We are suggesting a display which has access to and takes advantage of the relative rotation between users face and the wrist in all three spatial dimensions.

We call such a device *pose-aware*: a device which re-orients its content towards the user, rather than requiring the user to orient their body towards the device. A pose aware display requires two elements: a cylindrical display and a kinematic model of the body. By wrapping a display around the wrist, DisplaySkin already has a surface with pixels always visible, independent of the rotation of the arm. In order to implement this we need a system that measures the use of the user's arm in relation to the rest of the body. Once DisplaySkin has access to this information, we can dynamically move information onto this area of the display that is visible to the user.

4.1.3 Building the Pose-Aware Display

Measuring Body Pose

For prototyping a pose-aware display we needed a method to detect the user's motions and body configuration. We envision DisplaySkin to be used in mobile interactions. With mobile we mean both ‘in motion’ as well as ‘at different locations’. Based on this, we came up with the following design constraints for our sensing solution: It must be wearable and it cannot require an instrumented environment. To design interactions using body pose or gestures as input, being able to track the wrist alone already provides us with a rich interaction space to explore. We therefore focused on tracking the motion of the wrist and arm.

In the following section we will present three methods we explored in designing a wearable system for measuring body pose. While we finally opted for an established method – kinematic tracking – we will first present two of our earlier explorations as their simplicity make them a useful and novel prototyping approach.

Detecting Wrist motion using resistive stretch sensors

One approach to measuring body pose information which we found worth pursuing is creating clothing which can sense its deformation. For example, Gioberto et al. used stitching patterns of conductive thread as a sensor for estimating joint angles [39]. Our own initial exploration in this direction was a system called WristFlicker [130], which detects both wrist flexion and rotation through stretch sensors embedded in a sleeve (Figure 4.3).

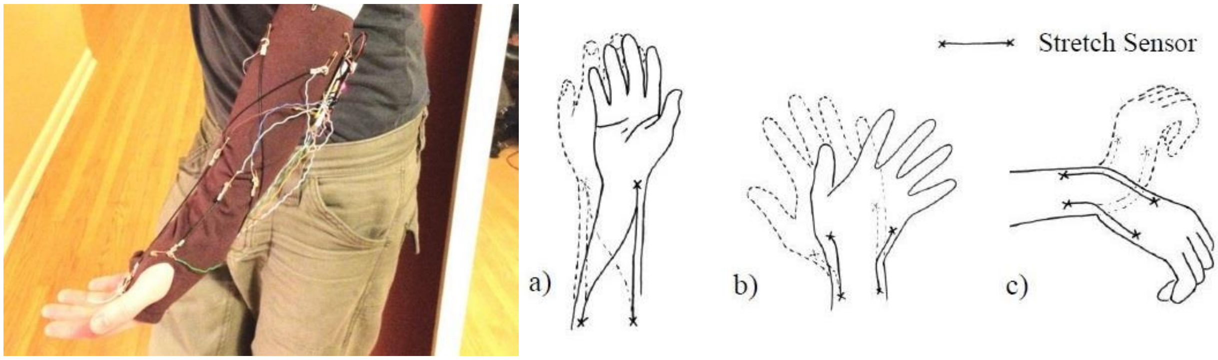


Figure 4.3 - WristFlicker stretch sensors placement: a) pronation/supination; b) ulnar/radial deviation; c) flexion/extension [130]

We used conductive polymer by Images Scientific Instruments [1] as stretch sensors to measure the movements of the wrist. The polymer cable is approximately 2 mm in diameter and can be stretched up to 175%. The sensor’s resistance changes according to the amount of stretch. Once the sensor is relaxed, the signal does not return directly to its baseline, but rather decays in an approximately inverse exponential manner. To minimize this effect, we used two counteracting sensors to measure each set of movement – while one sensor is stretched, the other is relaxed.

Combining the readings from both sensors allowed us to minimize the effects of the slower decay time of the relaxed sensor.

We inferred the rotational motion of the forearm and angular motion of the hand by measuring the distance between fixed anchor points, as indicated in Figure 4.3. This change in distance between the points is analogue to the contraction and relaxation of the muscles involved in pronation, supination [4], flexion, extension and ulnar & radial deviation [9]. While this system was able to capture hand motion with relatively high resolution, the anchor points present a design problem, as they are not always in locations where it is convenient to attach such a sensor. In practice, this approach would require us to build an entire suit for the wearer, so we decided to investigate solutions which were more self-contained.

Optical Detection of Wrist Motion using IR

The second method of measuring wrist motion used IR sensors, inspired by the multi-touch sensor we designed and discussed in Chapter 3. A benefit of using IR sensors over stretch-sensors is that they are easier to integrate in a bracelet as, unlike WristFlicker [130], they do not require a connection to multiple specific locations on the forearm allowing the sensing system to be fully integrated in the wrist-worn device.

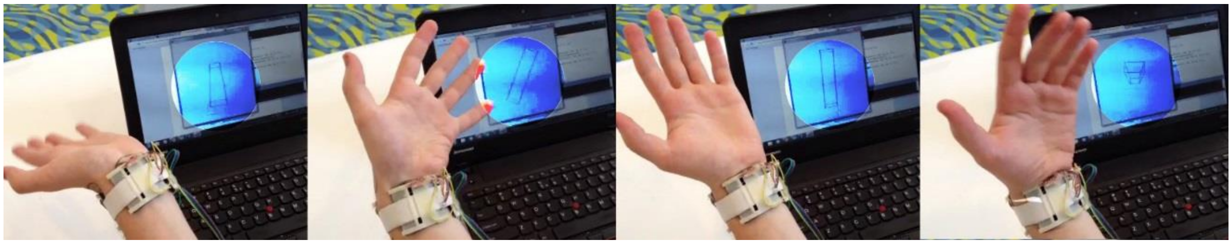


Figure 4.4 - Infrared based pose detection using the QRE1113 IR sensor by Fairchild (visual feedback of hand-position enhanced for clarity)

We augmented a 3d printed bracelet with 4 QRE1113 IR sensor by Fairchild. These sensors are convenient for prototyping IR applications as they contain an IR emitter and IR phototransistor in a single package [129]. The QRE1113's were placed on the bezel of the bracelet, at a 90° angle, pointing towards the hand. The IR emitter shines light towards the hand. Based on the position of the hand, the amount of light reflected back into the phototransistor varies. This enabled us to create a 3D reconstruction of the hands relative position to the arm (Figure 4.4).

While this sensor is promising as it can be integrated in the device itself, it is not possible to detect rotation with this method. Also, while we found it to be useful for discrete gestural input, this approach did not have the precision required for the type of analog input we were interested in.

Kinematic Modelling of the Arm

The resistive and optical methods showed potential for simple gestural input, however, they did not provide the sensing resolution we wanted to achieve for DisplaySkin. We finally decided that to construct a full kinematic model of the user's arm. This would allow us to infer the position and orientation of DisplaySkin relative to the user's face.

To create this kinematic model, we used two Inertial Measurement Units (IMUs). One is worn around the user's upper arm and one is integrated in DisplaySkin. Each IMU contains a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer. Two Arduino boards collect the data, and a sensor-fusion algorithm [84] calculates the absolute orientation of each IMU.

Figure 4.5 – Kinematic Model in foreground, Participant conducting experiment in background.

We use these headings to create a direct, forward kinematic model of a user's arm. The model treats the user's shoulder as the base of an open kinematic chain with two links. Each IMU represents one element in this chain and is considered a rigid body [117]. With this, we calculate the position and orientation of the user's wrist relative to their shoulder (Figure 4.5 shows the model in the foreground with the users corresponding pose in the background). The model assumes that a user’s face is in a fixed position relative to their shoulder, an assumption that is sufficiently accurate to calculate the angle and rotation offset between the forearm and face.

Using this model, we can rotate information around the wrist so that it is pointing at the users face (Figure 4.6, left) as well as rotate it relative to the face so that text or objects (or in case of Figure 4.6, right, the north position) remain upright. These two effects together enable an experience described by a user as “a frameless window into another information environment rather than an additional object to interact with“ [69].

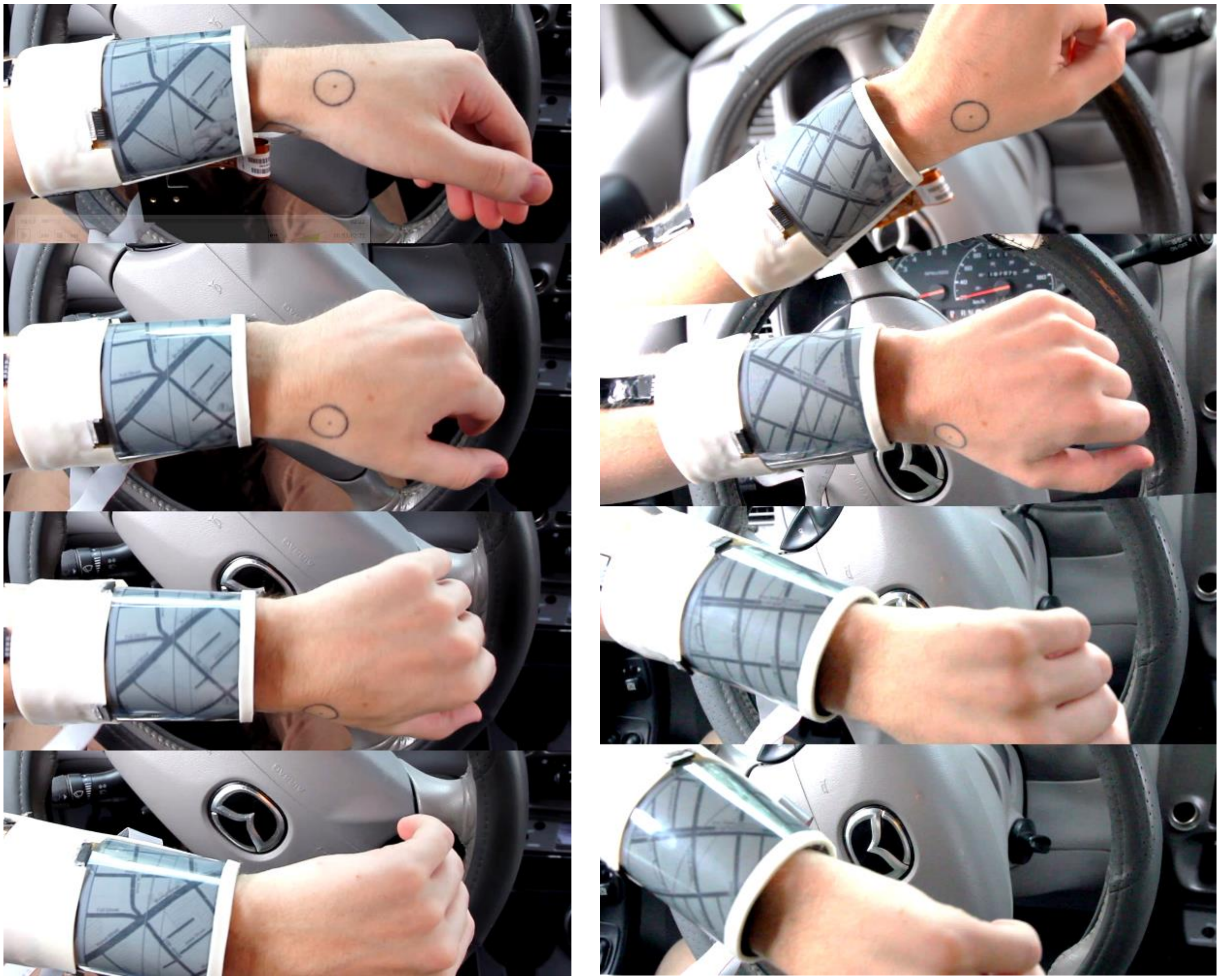


Figure 4.6 - Pose aware display orients content so that it always faces the user (left) and that it is always oriented correctly relative to the user (right)[4]

To test if the pose-aware display has real world benefits, we developed four interaction scenarios and also designed a qualitative experimental evaluation which will be presented later in this chapter.

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[4] This effect is difficult to capture in images, as the cameras location is necessarily offset from the location of the users head. To get a better sense of this effect, please view the video figure which supplements this thesis.

4.2 Interaction Scenarios using DisplaySkin and a Pose-Aware Display

An advantage of having a display on the wrist is its close proximity to our focus of attention. A dentist, for example, when working on a patient, balances their focus between the activity they are engaged with and supplementary information such as X-Rays or perio charts. Moving this supplementary information closer to their focus of attention reduces the interruptions introduced by glancing at the information. Placing it on the wrist ensures that the information can never occlude something that might otherwise be in view. The cognitive load of accessing the information is further reduced by the pose-aware orientation of the information as well as by our proprioceptive abilities, which enable us to know exactly where the display is located at all times.

4.2.1 Driving a Car

Using a current smartwatch while driving is an activity that could be described somewhere between difficult and dangerous, as they usually require either gestures or bimanual interactions for accessing content. Both our hands are, however, required to fully control the vehicle. If a driver is required to conduct a maneuver which includes rotating their arm, a regular wrist-worn device with might become inaccessible.

Figure 4.7 – Driving a car using DisplaySkin

We imagine that DisplaySkin might display information supplementary to the information already present on the dashboard. DisplaySkin is better suited for this than traditional smart-watches as the content will be visible independent of steering or other driving-related activities which influence body pose. Additionally, information such as map-data would require the user to mentally rotate the image if they were using a traditional wristwatch. As DisplaySkin knows its position relative to the user, it could display a map which maintains its north orientation even when the arm is being rotated (Figure 4.7). Because of our sense of proprioception, the fact that the display is not in a fixed location relative to the rest of the information displays in the car, is not a problem: the user always knows exactly where the display is, as it is linked to the hand.

4.2.2 Preparing Food

Figure 4.8 – Preparing Food using DisplaySkin

Cooking is a bimanual, visceral activity: kneading dough requires both of our hands and provides us with rich feedback in form of textures ranging from smooth and silky flower to rough and sticky dough. We also move throughout the kitchen, because different activities (straining pasta, placing or removing items from the refrigerator, putting food in the oven, kneading dough) require us to be in specific locations. If we wish to follow a recipe we are unfamiliar with, this can be a difficult task as we are regularly changing location and our hands might be moist or dirty. Using DisplaySkin provides users with an always available display that does not require us to modify our behavior to use it, as the pose aware display accommodates the cooking activity we are engaged in (Figure 4.8). A traditional wristwatch would be prone to occlusion based on our activity, while the fact that our hands might be moist or dirty would impede interactions with traditional mobile devices.

4.2.3 Using DisplaySkin to Augment Sports

The kinematic model used by DisplaySkin tracks the movements of the body. This can be used to evaluate and reflect on athletic performances. DisplaySkin could record motion trajectories and play them back for analysis. A user might, for example, compare their batting speed, as well as the entire sequence of arm motions leading up to a hit, with those of famous players such as Derek Jeter, or reconstructions of the performance of baseball legends such as Lou Gehrig or Babe Ruth.

Figure 4.9 – Playing Gold with DisplaySkin

In a sports context, DisplaySkin could take over three functions. It could provide the user with information collected from external sources, it could measure motion sequences and it could provide the users with statistics regarding their personal performance. DisplaySkin might, for example, provide a golfer with contextual information relevant to striking the ball, such as wind speed and direction. Once the user strikes the ball, DisplaySkin measures the angle and speed of the swing. After the ball has been hit, the golfer can access information and statistics of their performance on DisplaySkin (Figure 4.9). In team-sports such as soccer, where the referee is constantly in motion, DisplaySkin could provide the referee with player information in a non-disruptive way. In team games which require complex strategies to be decided upon in the spur of the moment, such as American football, DisplaySkin replace the wristband traditionally worn by quarterbacks.

4.2.4 Supporting Musicians

Different musical instruments require different body poses. A smartwatch could, theoretically, provide a piano player with notation. Playing a guitar, on the other hand, requires a pose in which the display of a smartwatch would not be visible. DisplaySkin on could recognize the pose and the instrument and provide information accordingly. Once the user has selected a song, DisplaySkin could support them by providing cues in the form of chords (Figure 4.10).

Figure 4.10 – Displaying Guitar Chords on DisplaySkin

We believe this to be an increasingly interesting scenario, especially with regards to new instruments combining expressive motion and dance with music. Example of these might be ‘The Hands’ played by Michel Waisvisz [32] and Imogen Heap’s Gloves [143]. DisplaySkin could provide such artists not only with a display for musical notation or cues, but also with expressive input abilities based on orientation of the arms and movement of the body.

4.3 Evaluating the Pose-Aware Display

The examples discussed in the previous section highlight interaction scenarios that would not be possible with traditional wrist-worn devices. We were, however, also interested in assessing if the pose aware display provides a benefit in more basic tasks, for example, acknowledging a notification. We conducted an experiment to understand how pose-aware displays benefit acknowledging a notification on the wrist. Instead of choosing a task that is completely impossible with traditional smart-watches, such as the scenarios above, we chose a task which could be completed with either type of device. We provided users with a primary task, and at certain intervals required users to respond to a notification on a pose aware or static (fixed location on the top of the wrist) display. We measured the participants’ ability to quickly acknowledge notifications presented on DisplaySkin [19].

4.3.1 Experiment

Task

As a primary activity, participants performed a targeting task, similar to a one-dimensional Fitts’ law pointing test. Two bars appeared on a desktop monitor and spanned the height of the screen. The bars were fixed in width and were varied in amplitude between conditions. Participants were asked to move a cursor between the two targets as quickly and accurately as possible. They controlled the cursor’s horizontal position with the rotation of their left hand. They selected targets with a button they held in their left hand. This task allowed us to interrupt our participant’s activity with the wrist in a controlled rotational position relative to the user’s body.

As a secondary task, participants performed an acknowledgment task on DisplaySkin. Upon completing selected trials of the primary task, the participant was interrupted by a notification: the monitor flashed red. Participants were instructed to, upon such notification, look at DisplaySkin, find an arrow, and, using their right hand, swipe DisplaySkin in the direction indicated (Figure

4.11). Once the notification was acknowledged, participants returned to the rotational targeting task.

Figure 4.11 – Participant being interrupted by notification. The arrow is pointed towards his face. In the static condition the arrow would be mostly occluded.

By asking the participants to perform a task with wrist rotation, we were provided with a wide variety of wrist angles. This, in consequence, allowed us to control the level of occlusion of the top of the wrist at the moment when a notification occurred. For the pose-aware condition the arrow was always in the participant's field of view, while in the static condition, the arrow was partly occluded, based on the current rotation of the wrist relative to the body. In addition, the demands of the task required the participants' full concentration, ensuring they could not plan for interruptions.

Task Rationale

The motivation behind designing this task was less to prove beyond doubt the benefits of the pose-aware display. Instead we wanted to better understand how users react to such a dynamic display. The task is designed to provide basic information upon which more complex pose-aware applications can be designed. Had we wanted to simply prove the benefits of a pose-aware display, we would have introduced a task where a standard watch-face is fully occluded. Instead we investigated the edge-cases, to better understand at which point a pose-aware device becomes useful.

Conditions

We used two independent variables: display type and angle. The two display types were static and pose-aware. The angles were 0°, 30°, 60°, and 90°. Figure 4.12 shows the position of the arm for each condition, with a watch-face indicating the level of occlusion of the arrow for the static condition. In the pose-aware condition, the arrow was dynamically placed in the participant's field of view.

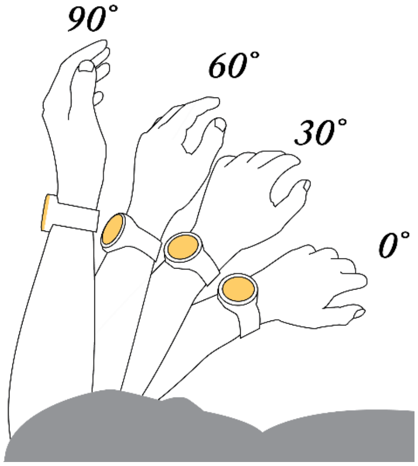

Figure 4.12 – Angles used in our experiment

Controlling Wrist Angle and Hand Position

During a trial, the participant's left elbow and right hand were in a fixed position. The participant controlled the targeting task with their left hand and they held their right hand in a fixed position. This allowed us to specify the rotation of the left forearm when the interruption occurred, as well as ensuring that the distance between the right hand and the display was consistent between participants, as it would influence the time required to complete the acknowledgement task.

Measurements

We recorded two dependent measures: homing time and resume time. *Homing time* is the time from the moment of the interruption until the participant touched the surface of DisplaySkin. *Resume time* is the time between completing the swipe to re-engaging with the targeting task, as indicated by selecting the target that prompted the interruption. To do so the participants had to rotate their left arm back to the orientation in which they were when interrupted and click the button they held in their left hand.

Apparatus

Aside from DisplaySkin, we needed additional hardware to perform the experiment. To make sure the resting position of the right hand remained constant, we instructed participants to place their hand on a capacitive sensor, when not swiping DisplaySkin. To select targets in the primary task, participants pressed a small push button that they grasped with the same hand with which they wore DisplaySkin.

Experiment Design

We used a 2x4 factorial within-subject design with repeated measures. Our factors were: *display type* (static and pose-aware), and *wrist angle* upon notification (0°, 30°, 60°, and 90°). Each participant performed 8 trials of the acknowledgment task per combination of factors, for a total of 64 trials. Condition order was countered-balanced between participants. The experiment lasted 40 minutes, including practice. Participants practiced with each display type until they achieved less than 10% improvement between trials. Participants clicked between the vertical bars for a total of 384 targeting trials. The trials were segmented into blocks of 6, grouped by target distance (each target distance corresponding to a wrist angle). There was one interruption within each block of the targeting trials. It occurred randomly when a participant clicked on the target bar that corresponded to the desired wrist angle.

Participants

The experiment was conducted with the same 12 participants used in our first experiment. Most were male (9/12) and they were between the ages of 17-29. Most participants were right handed (9/12) and only a small number (3/12) wore a wristwatch. They were paid $10 for their participation. Left handed and right handed participants were given the same task.

Hypotheses

We hypothesized that the pose-aware display would have faster homing times than the static display (*H1*). We predicted that participants would be able to home to the wrist faster when the arrow was dynamically placed in their field of view. We also hypothesized that larger wrist angles would result in slower homing times for the static display, while times for the pose-aware display would remain relatively similar (*H2*). We hypothesized that participants would have shorter resume times in the pose-aware display condition (*H3*).

As a control, we expected that targeting times in the primary rotational pointing task would not significantly differ between display types (*H4*), and that larger target amplitudes would result in longer targeting times (*H5*).

4.3.2 Results

For the secondary acknowledgement task, we analyzed the collected measures by performing a repeated measures ANOVA using *display type* (2) x *wrist angle* (4) on homing time and resume time. Table 4.1 outlines the means and standard errors for homing and resume times.

	Homing Time		**Resume Time**	
	Static	**Pose-Aware**	**Static**	**Pose-Aware**
Overall	1.84 *(0.04)*	1.5 *(0.02)*	1.75 *(0.02)*	1.69 *(0.03)*
0°	1.69 *(0.04)*	1.55 *(0.03)*	1.74 *(0.04)*	1.90 *(0.05)*
30°	1.82 *(0.07)*	1.52 *(0.03)*	1.60 *(0.04)*	1.85 *(0.07)*
60°	1.88 *(0.10)*	1.46 *(0.04)*	1.81 *(0.05)*	1.42 *(0.05)*
90°	1.90 *(0.07)*	1.47 *(0.03)*	1.88 *(0.06)*	1.59 *(0.03)*

Table 4.1 - Homing and resume times and their standard deviations in seconds

For homing time, the analysis showed that *display type* was a significant factor ($F_{1,11}=67.99$, $p < 0.001$), with the pose-aware display resulting in shorter times than the static display. We also found a significant interaction effect between *display type* and *wrist angle* ($F_{3,33}=3.29$, $p < 0.05$).

With respect to resume time, we observed a main effect of *wrist angle* ($F_{3,33}=5.14$, $p < 0.05$). Pairwise post-hoc tests, with Bonferroni corrected comparisons, revealed that 0° was significantly different from 90°. The analysis also showed an interaction effect between *display type* and *wrist angle* ($F_{3,33}=15.12$, $p < 0.001$).

For the rotational pointing task, we analyzed the movement times by performing a repeated measures ANOVA using *display type* (2) x *target amplitude* (4). The analysis showed that *target amplitude* was a significant factor ($F_{3,33}=219.48$, $p < 0.001$). The analysis of the pointing task did not show an effect of *display type*.

4.3.3 Discussion

Our results suggest that pose-aware displays reduce interruption times in interactions with a wrist mounted display when attending to a primary pointing task. Resume times were faster larger angles, and homing times were more efficient throughout. Swiping in the pose-aware condition was more efficient, since the right hand travels a shorter distance to meet the left hand and there is no need to explicitly rotate the left wrist to re-orient the arrow.

As hypothesized, our pose-aware display obtained significantly faster homing times than the static display (*H1*). We believe this result is because the pose-aware display presented the arrow directly in the participant's field of view, regardless of their wrist angle when the notification occurred. In addition, we confirmed our hypothesis (*H2*) that there would be an interaction between *display type* and *wrist angle*. With the static display, larger angles resulted in larger homing times. The observed effects are most easily understood looking at the difference in target times for each angle. Table 4.2 indicates how much the pose-aware display was faster for each wrist angle.

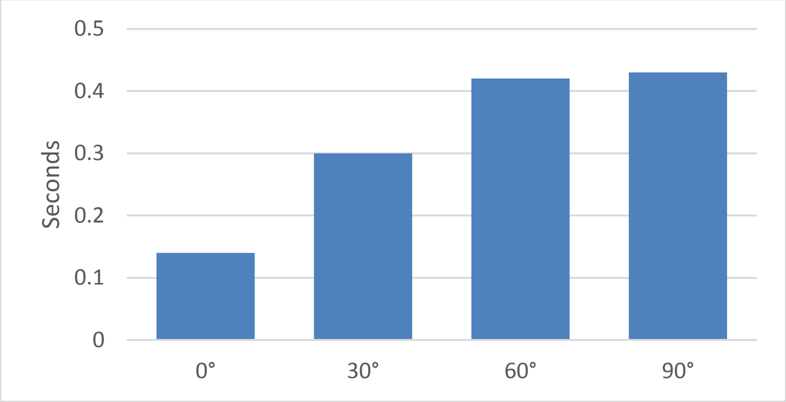

Table 4.2 – Advantage of pose-aware display for homing times in seconds

In our analysis of resume time we did not find a main effect of *display type*, rather we found an interaction effect between *display type* and *wrist angle.* Again, the result is best understood when we look at the differences in resume times. Table 4.3 shows that for small angles, the static display actually was faster than for the larger angles.

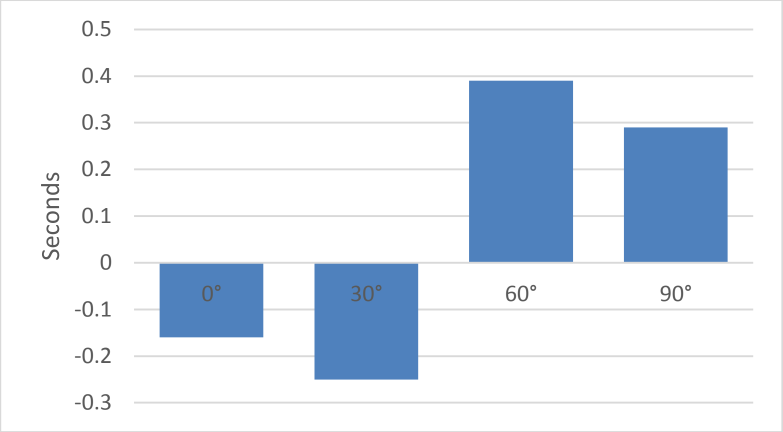

Table 4.3 - Advantage of pose-aware display for resume times in seconds

In the pose-aware condition, participants typically swiped with a bimanual gesture. We observed that participants often let their left and right hands meet in the middle, a comfort permitted since DisplaySkin did not need to be at a specific angle. For the 0° and 30° condition this more comfortable and ergonomic strategy of swiping lead to the left hand moving from the target orientation. In the static condition participants left their left hand static, which was less comfortable for swiping, but lead to faster task resume times.

Somewhat surprisingly, we found that in the 0° condition, the pose-aware display had faster homing times than the static display, a scenario where performance should be equivalent. We believe this difference is due to the dynamic nature of the pose-aware display and these differences in acknowledgement strategies. Even though the target is initially located at the same place, the swiping motion is more efficient when the arrow adjusts position during the interaction: the arrow appears at an angle that is easier to reach.

In the pose-aware conditions, it appears that the 60° angle resulted in the shortest times for both homing and resume times. The result suggests that users may be naturally inclined to touch at that angle of the wrist for interactions that are not constrained by a fixed target. This result might be relevant to the design of wrist worn devices that are not pose-aware. It also suggests that the unorthodox design of early solar watches such as the Synchronar or Nepro Alfatronic may in fact be ergonomically preferable to the traditional watch face orientation, as our results suggest that there may be a benefit to having the display and interaction area slightly rotated facing the body, away from the 0° position, and towards the 60° position.

Although the targeting task was not the focus of this experiment, we conducted a statistical analysis of the task to ensure that the conditions were consistent across both display types. We confirmed our hypothesis that movement times did not differ between display types (*H4*) and larger amplitudes resulted in longer times (*H5*). Even though non-significant difference is not equivalence, these results are enough to suggest that the participants' focus was on the primary task.

A question commonly raised was if the moving images of the pose-aware display might not confuse the user. This was not the case. In fact, the movements were so subtle and so well in sync with the activity the user was performing, that most of our participants did not notice that the device was pose-aware. In casual discussions after the experiment many of the participants were surprised when we described how the pose-aware display worked. Subjectively, they simply experienced one condition as more convenient that the other, without having any explanation, why this was. Even more, they did not even consider it something to be curious about. Only once we explained the mechanism to them, did they actively notice the effects of the pose-aware display. This demonstrates that our prototype was true to our intent to design a glance-based interface for non-focal interactions: in fact it did not draw the users' attention at all.

4.4 Concluding thoughts to the Pose-Aware display

The most important difference between the various wearable watches popular from the 16th to the 20th century and the modern wristwatch is one of access. The bracelet watch, just as watch-pendants and rings was designed as lockets. The user was required to open them to tell the time. These devices required to user to interrupt their activity and engage with them for accessing information. The wristlet on the other hand was designed with an open face. Users could tell the time simply by glancing at it. This small change in design enabled the wristwatch to be used as a contextual tool for non-focal, glance based, interactions. While the bracelet watch was jewelry designed to draw attention, the wristlet was designed as a tool, intended to recede from attention. This change in design philosophy lead to the popularity of the wristwatch as we know it today.

This affordance of the watch is lost in devices such as the Hamilton Pulsar. Requiring the user to press a button to access the time, draws their attention away from their primary activity and instead bringing the device into focus. The Apple Watch and many of the Android Wear smartwatches have a similar design flaw. A user, for example, describes that they would usually use their wristwatch to time how long they have been grinding their coffee. Because the display of their new smartwatch needs to be explicitly turned on, and then set into a setting in which it does not time out, this is no longer possible. In fact, the effort required to time the duration of grinding coffee has become greater than that of grinding the coffee in the first place [140].

This example demonstrates the importance of designing wrist-worn devices as glance-based interfaces, if they are to support the user in casual, day to day activities. Only few smartwatches, for example the Pebble products, provide this opportunity. The pose-aware display is an attempt to not only preserve this affordance of the wristwatch, but to improve upon it. We have received criticism that our results, while significant, may not be relevant, as they only demonstrate minor improvements in reaction times over a regular smartwatch. These minute improvements, however, may result in the difference between requiring the user to actively attend to the device, or not. These minute improvements allow the device to recede from attention, providing more opportunities to present the user with information, while distracting less from the task at hand. This is further supported by how unremarkable participants in our experiment felt the pose-aware display to be: even as a novel technology, it did not draw any attention to itself.

Chapter 5

Limitations, Future Scenarios & Conclusion

5.1 Future Work

5.1.1 Ornamental use of DisplaySkin

This thesis has not explored any of the ornamental qualities of wearable technology, however, looking at early technologies, such as the Drum Watch or Hamilton Watch Companies digital wristwatch, one sees that their ornamental design was important. While the scope of this project did not allow us to further pursue ornamental aspects of interactive wrist-worn devices, we find that interaction space to be both fascinating and important. Interactive ornamental devices could change their appearance on the fly, adjusting dynamically to suit the occasion. An interesting concept device that explores this idea is *the tago* arc by liber8 (Figure 5.1) [75]. The tago arc is a piece of wearable technology which explicitly serves an ornamental purpose. Its appearance can be updated on the fly via a smartphones NFC system. It collects parasitic power for updating its display via the NFC system as well.

Figure 5.1 - tago arc by Liber8 [75]

A pose aware device would enable dynamic interactive ornaments. Patterns could adopt based on the pace at which the user is moving, for example, synchronizing to dance movements. Patterns could also adjust dynamically based on the activity, for example, displaying subtle images during activities where the wearer does not wish to draw attention to their hands, while otherwise allowing them to present extravagant animated patterns.

5.1.2 Separation of Public and Private viewing areas

Ornaments have both a public and a private function. DisplaySkin could present directional ornaments. For example, a picture of a loved one could be presented so as to face the viewer, while a less intimate image, intended for public viewing could be pointed outwards. Such a mechanism could be used together with functional content. Notifications, contextual information or interactive elements could be presented towards the user, while viewed from an external space, DisplaySkin would appear as an ornamental device. A similar mechanic has been suggested by Olberding et al. [100], however, using DisplaySkin, private and public areas could be dynamically defined based on current body pose.

5.1.3 Removing the device

DisplaySkin was in part inspired by design probes such as Kinisi by Katia Vega [66] (Figure 5.2, center) and interactive tattoos by Phillips Design [120] (Figure 5.2, left). These design probes remove the concept of device, instead considering the whole body as an interactive canvas.

Figure 5.2 - Interactive tattoo concept by Phillips [120]**, interactive makeup by Vega** [66] **and photography by Baran** [35]

We like to think of DisplaySkin as a medium that is not only used to explore the future of the wrist-worn device, but rather the future of ‘on-body-interaction’. Investigating the ornamental opportunities of DisplaySkin will provide designers with valuable lessons applicable to more radical designs for the interactive body: what if touch leaves a trace not only in our minds, but also in visible form on our bodies, similar to the artistic depiction by Rachal Baran (Figure5.2, right) [35]? We would like to see future work with DisplaySkin explore this intimate and expressive design space.

5.1.4 Skin

Our skin is both a sensory, as well as a protective organ. Idioms like ‘to get under one’s skin’ or the German ‘to be in someone else’s skin’ (in English ‘to be in someone else’s shoes’) highlight the multiple roles of the skin, and how close it is bound to our identity. In fiction we commonly find characters who can ‘change their skin’, literally transforming into other people (Figure 5.3). What other functions might an augmented skin perform? While our exploration does not specifically engage with the human skin, we hope it can serve as a point of reference for future work on interactive skin and augmented bodies.

Figure 5.3 – X Men's Mystique transforming from an adopted skin into her own [161]

5.2 Current Limitations

Our prototype was tethered to a dedicated driver board. When given the opportunity to explore DisplaySkin before the experiment, some users noted the cables restricted their movement. Later, they commented that for the more limited motion required in our experiments, the cables did not interfere with their activities.

In our current prototype, our forward kinematic model requires users to wear, in addition to DisplaySkin, a small (8 x 36 x 2mm) secondary IMU on their upper arm. Future research in tracking algorithms may allow us to create an inverse kinematic model to remove this IMU. Trends in wearable technology and tracking technology seen in systems such as NOTCH [59] suggest however that the second IMU may actually be a feasible solution in the long term as well.

The chosen display technology suffers from a slow refresh rate. This was mainly noticeable when implementing the physics model for scrolling. The slow refresh rates made very fast motion difficult to visualize and was a constraining factor on scrolling speed, leading to longer scroll times than expected. A display technology with higher refresh rate would mitigate this issue and would also make the pose-aware aspects of the display appear smoother.

5.3 Conclusion

In this thesis we presented a variety of contributions to the design of wrist-based devices. We initially presented a historic analysis of the development of the wrist-watch: we start with the first portable mechanical devices of the 15th century, showing how technologies such as the mainspring and fusee acted as catalyst for a generation of devices. These devices started out as vanity products commissioned by the rich and powerful. The introduction of the wristlet moved the design space of wearables away from a focus on fashion, towards a greater focus on utility. The main innovation of the wristlet over previous wearable technology is its open face design. This enabled glance-based interactions and lead to the transformation of the wristwatch into a non-focal interface. With this transition of wearables from pure fashion accessories to contextual interfaces came a broad adoption of wristwatches by the general public.

Many of the observations made on the development of the wristwatch can also be observed in the evolution of the digital watch. Introduced as a limited edition extravaganza, the digital watch eventually became useful as a tool. The new generation of smartwatches, however, introduces design constraints similar to those found in the original Hamilton Pulsar or the first Drum Watches: they require focal attention. By doing so, they neglect one of the key affordances that lead to the wristwatches popularity.

While this key affordance appears to be lost in newer designs, the form factor of most smartwatches constrain themselves to the traditional shape and size of the wristwatch. However, the interactive elements of smartwatches are clearly inspired from tablet and phone interfaces. We believe these to be arbitrary design choices. Instead, we suggest looking back at the factors that made the wristwatch successful in the first place. Rather than implementing computers which can be worn on the wrist, we suggest focusing the design of wrist-worn devices on non-focal, glance-based interactions.

Based on these considerations we presented DisplaySkin: a pose-aware device with a large cylindrical touch display worn on the forearm. DisplaySkin implements a kinematic tracking system that enables it to be pose-aware. Its pose-aware display orients content towards the user’s face, enabling fast glance-based interactions.

In implementing DisplaySkin we explored a number of novel sensing methods: infrared touch sensors, infrared motion capturing sensors and elastic stretch sensors. These are documented to facilitate the prototyping and design process of other designers. In addition to the sensing mechanisms we demonstrate a novel method of creating 3D structures, by 3D printing a flat object which is then thermoformed to achieve its final 3D structure.

Further contributions of this thesis are the two experimental evaluations of the prototype device. We initially focused on the physical display of DisplaySkin, investigating the effects of display size on wrist-interaction. The experiment demonstrates that larger displays enable faster list-scrolling than smaller ones. At a certain size however, the visible are does not increase, as part of the display is occluded. Once this occurs the additional display size does not make list searching more efficient, however it enables participants to be more flexible in their body poses, enabling bimanual interactions. This suggests that, in the wild, a cylindrical display would have additional benefits, as it allows the device to be used in a larger range of poses.

This affordance of the cylindrical shape lead us to develop the pose-aware display. To evaluate whether a pose-aware display helps users access information more efficiently, we designed an experiment in which users performed a rotational pointing task that was interrupted by a task on DisplaySkin. Results suggest that pose-aware displays reduce the time taken to acknowledge notifications: if a user wishes to access contextual information, the pose-aware display minimizes the interruption of a primary task. Our results also suggest that some areas on the wrist might be more natural to touch than others and that pose-aware displays may be a useful method of further exploring ergonomics of body-worn devices.

In summary, this thesis provides the following contributions to design research for wrist-worn devices: (i) a historic analysis of related technology, (ii) design suggestions derived from this analysis, (iii) three novel sensor designs, (iv) a novel rapid prototyping method, (v) a prototype device, and (vi) two experimental evaluations of the prototype device.

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Appendix

August 29, 2013

Mr. Jesse Burstyn
Ph.D. Candidate
School of Computing
Queen's University
Kingston, ON K7L 3N6

GREB Ref #: GCISC-071-13; Romeo # 6010722
Title: "GCISC-071-13 Wrist-Based Flexible Display Interactions"

Dear Mr. Burstyn:

The General Research Ethics Board (GREB), by means of a delegated board review, has cleared your proposal entitled **"GCISC-071-13 Wrist-Based Flexible Display Interactions"** for ethical compliance with the Tri-Council Guidelines (TCPS) and Queen's ethics policies. In accordance with the Tri-Council Guidelines (article D.1.6) and Senate Terms of Reference (article G), your project has been cleared for one year. At the end of each year, the GREB will ask if your project has been completed and if not, what changes have occurred or will occur in the next year.

You are reminded of your obligation to advise the GREB, with a copy to your unit REB, of any adverse event(s) that occur during this one year period (access this form at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Adverse Event Report). An adverse event includes, but is not limited to, a complaint, a change or unexpected event that alters the level of risk for the researcher or participants or situation that requires a substantial change in approach to a participant(s). You are also advised that all adverse events must be reported to the GREB within 48 hours.

You are also reminded that all changes that might affect human participants must be cleared by the GREB. For example you must report changes to the level of risk, applicant characteristics, and implementation of new procedures. To make an amendment, access the application at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Amendment to Approved Study Form. These changes will automatically be sent to the Ethics Coordinator, Gail Irving, at the Office of Research Services or irvingg@queensu.ca for further review and clearance by the GREB or GREB Chair.

On behalf of the General Research Ethics Board, I wish you continued success in your research.

Yours sincerely,

Joan Stevenson

Joan Stevenson, Ph.D.
Chair
General Research Ethics Board

c: Dr. Roel Vertegaal, Co-Principal Investigator

Mr. Paul Strohmeier, Co-investigator
Mrs. Karilee Whiteway, Research Coordinator

July 29, 2014

Mr. Jesse Burstyn
Ph.D. Candidate
School of Computing
Queen's University
Kingston, ON, K7L 3N6

GREB Romeo #: 6010722
Title: "GCISC-071-13 Wrist-Based Flexible Display Interactions"

Dear Mr. Burstyn:

The General Research Ethics Board (GREB) has reviewed and approved your request for renewal of ethics clearance for the above-named study. This renewal is valid for one year from August 29, 2014. Prior to the next renewal date you will be sent a reminder memo and the link to ROMEO to renew for another year.

You are reminded of your obligation to advise the GREB of any adverse event(s) that occur during this one year period. An adverse event includes, but is not limited to, a complaint, a change or unexpected event that alters the level of risk for the researcher or participants or situation that requires a substantial change in approach to a participant(s). You are also advised that all adverse events must be reported to the GREB within 48 hours. Report to GREB through either ROMEO Event Report or Adverse Event Report Form at http://www.queensu.ca/ors/researchethics/GeneralREB/forms.html.

You are also reminded that all changes that might affect human participants must be cleared by the GREB. For example you must report changes in study procedures or implementation of new aspects into the study procedures.
Your request for protocol changes will be forwarded to the appropriate GREB reviewers and/or the GREB Chair. Please report changes to GREB through either ROMEO Event Reports or the Ethics Change Form at http://www.queensu.ca/ors/researchethics/GeneralREB/forms.html.

On behalf of the General Research Ethics Board, I wish you continued success in your research.

Yours sincerely,

Joan Stevenson

Joan Stevenson, Ph.D.
Chair
General Research Ethics Board

c.: Dr. Roel Vertegaal, Co-Principal Investigator
Mr. Paul Strohmeier, Co-investigator
Mrs. Karilee Whiteway, Research Coordinator