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# FoldWatch: Using Origami-Inspired Paper Prototypes to Explore the Extension of Output Space in Smartwatches

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## ABSTRACT
Smartwatches are highly portable, ubiquitous devices, allowing rich interaction at a small scale. However, the display size can hinder user engagement, limit information display, and presentation style. Most research focuses on exploring ways in which the interaction area of smartwatches can be extended, although this mainly entails simple fold-out displays or additional screens. Conversely, added weight and size can hinder the wearable experience. In response, we took inspiration from origami and explored the design space for new types of lightweight, highly foldable smartwatch, by developing complex paper-prototypes which demonstrate novel ways of extending screen space. We collected data on potential input and output interaction with complex folded smartwatch displays during workshops with expert and non-expert users, discovering application ideas and additional input/output functionality. These insights were used to produce and evaluate a concept video for the FoldWatch prototype.

### *ACM Classification Keywords*
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

### *Author Keywords*
Smartwatches; Paper-prototyping; Origami; Wearables

## INTRODUCTION
The introduction of smartphones – especially the release of the iPhone 1st Generation by Apple in 2007 – united phone and PC within a mobile computer with customized applications. In the intervening years, computing hardware has become smaller, faster, cheaper, and better connected [41]. Through wearables, technology is physically and "inextricably intertwined"

with the human body [21] and can be fluently interconnected with users' daily life and activities – even more so than smartphones or other PDAs [63]. Nowadays, the trend for mobile and wearable devices is toward generating less interruption of day-to-day activities, and also providing more integration within the context of use: a closer symbiosis of user and technology.

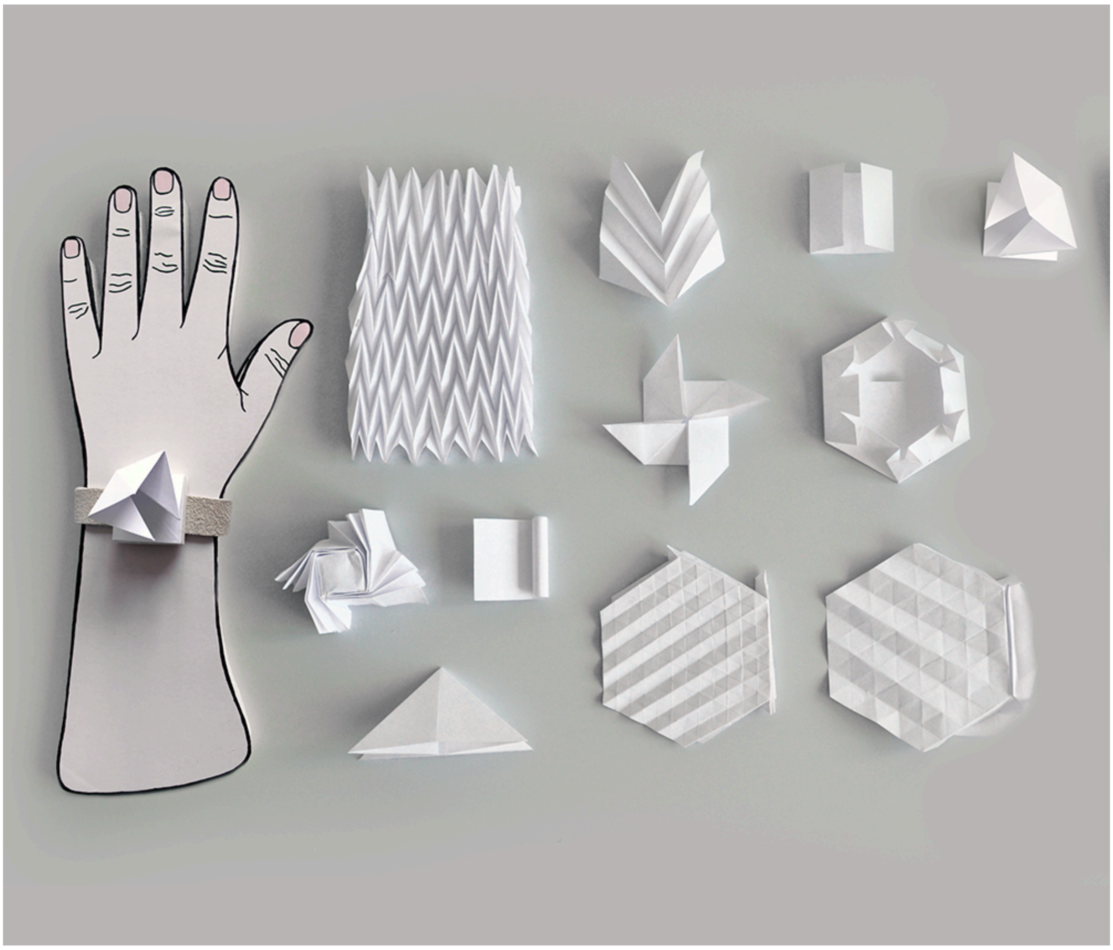

*Figure 1. Investigative origami work to establish the best folding structures to use for the smartwatch concept.*

Consequently, the range of wearable computers is further optimized for special applications, usage scenarios, and special tasks [8], with smartwatches being the most common iteration of such technology. Smartwatches can be broadly defined as "wrist-worn devices with computational power, that connect to other devices via short range wireless connectivity; provide alert notifications; collect personal data through a range of sensors and store them; and have an intelligent clock" [4]. Additionally, they support integration with natural movement [8] and instant availability – compared to smartphones which first have to be retrieved from the pocket. People are used to wristwatches, and this increases acceptance of smartwatches in society [41]. In 2015, the worldwide smartwatch output surpassed that of the Swiss watch industry [46] indicating the increasing popularity of these devices. Smartwatches also have the smallest practical screen size of personal computers [30]. Despite this practicality, the compact screen can limit interaction: the small size is the reason why the interactive surface does not provide space for physical buttons, and can lead to issues such as the fat finger problem [52]. To overcome this, research has examined implementing voice control [35]; adding holographic levels [62]; and even projecting displays directly onto skin [65] – amongst other solutions – such as expanding the smartwatch screen size, which has been shown to have a significant impact on users' satisfaction with mobile services and devices [21]. Additionally, display size and interaction techniques are central characteristics of smartwatches in terms of context-awareness. According to Pascoe [41], context awareness enhances users' acceptance of devices by offering appropriate information or services in a current environment.

Foldable smartwatch screen extensions maintain the discrete nature of the device, and offer a simple solution to manually enlarge the area of interaction, e.g. Doppio [50] or Facet [30], although they can be bulky or heavy additions to the wearable concept – extending the height or width of the initial state of the device. Despite this, the increased screen space offers novel interaction capabilities, a wider range of display data types, and the possibility of merging smartphone and wearable seamlessly into a single device [16]. To further the foldable smartwatch idea, and in response to current research prototypes, we propose to use origami-inspired paper structures in order to explore the design space and potential interactions of lightweight, discrete and highly aesthetic, extended-screen smartwatches. This work has the potential to support the continued uptake in the use of smartwatches, and enhance their range of user interactions.

### Contribution

Smartwatches are highly portable, ubiquitous devices, allowing rich interaction at a small scale. However, the display size can hinder user engagement, limit information display, and its representation. Most research focuses on exploring ways in which the screen and interaction area of smartwatches can be extended, although this mainly entails "around" device interaction and/or additional screens. Conversely, this added weight can hinder the wearable experience. In response, this paper takes inspiration from origami and explores the design space for new types of lightweight, highly foldable smartwatch displays, by exploring paper folding configurations which demonstrate novel ways of extending screen space.

Therefore, the following review and design exploration was conducted: i) A detailed literature review and survey of the current state-of-the art for smartwatch interactions and extensions, with associated visuals; ii) An investigation of origami techniques with the potential for display use; iii) A design exploration using expert (n=10) and non-expert users (n=10) to investigate novel interaction styles and notification outputs with origami-inspired paper smartwatch prototypes; and, iv) A concept video and AttrakDiff survey (n=36) based on findings from the feasibility study. It is hoped that this work can map the way for the development of functional, highly foldable, smartwatch prototypes, in both hardware and interaction methodologies.

## RELATED WORK

Pascoe [41] suggested that the smartwatch was the "next step in the evolution of mobile computing devices" , but although these wrist mounted devices are gaining in popularity, they still lack the variable functionality of their larger, cellphone or tablet-sized counterparts. Features such as keyboard integration are a logical addition to the smartwatch display, but the size limitations of the watch face can make it harder to type, or require the user to learn a new, smaller keyboard styles, e.g. splitboard [19], Flexy or Swype [5]. An additional method of extending smartwatch interaction has been by exploring gesture-based input [23, 48] – with varying levels of success – but by far the most utilised methodology is to simply extend the zone of interaction of a smartwatch by utilising the space on and around the arm, or by adding functionality and screen space to the smartwatch itself.

### Smartwatch Interaction Review

Given the breadth of work in increasing input and output functionality of smartwatches and other types of wrist or arm mounted wearable, we conducted a review of all prototypes in this area and identified devices as either having a) enhanced or extended input, or, b) enhanced or extended output. This research work was indispensable in identifying ideas and ways of extending the interaction for smartwatch input and output. The examples are summarized in two tables that can be found at http://www.hci.uni-bremen.de/data/FoldWatchAppendix.pdf .
Foldable Devices.

There has been a surge of interest in shape-changing interfaces in the past decade, with various functional prototypes extending our technical knowledge of how to build, and classify, such devices [17, 20, 54]. However, advances in shape-changing, foldable displays are so far an under-utilised solution for extending the smartwatch zone of interaction: having a variable extendable display would be a logical way of allowing for additional, larger visual input, without compromising on wearability or size (as with the Paddle phone concept [44]. The concept of foldable electronic devices in itself is not new, although advances in thinner display technology and linkages has opened up new possibilities for ultra-thin, multiply folding devices – with the potential for interactions based on the act of folding.

In smartwatches, both Watchthru [62] and Cito [13] make use of folding to augment their watch displays, although the additional space is either display only (Watchthru ) or is not utilised for input/output (Cito ). In larger devices, folding and multiple displays have been utilised to create book-style interfaces such as FoldMe [24] and BookiSheet [61], or make use of interconnected multiple sheets, for example PaperFold [12] and PaperTab [56]. The potential of paper interfaces is further expanded by printable, and even actuated, electronics [38, 37], as well as complex interaction styles with foldable interfaces where creases and folds can be "set" via gestures [9], which also then opens up the possibility to apply this technology to more complex folded interfaces.

### Origami in HCI

Origami is the Japanese art of paper folding. It is often used for technical innovation in engineering to increase portability and storage [31]. In HCI, origami has inspired work both practical and playful in nature, such as Lee et al.'s Foldable Interactive Display [27] where projection is combined with large-scale paper folding to create interactive umbrellas, newspapers and fans, or in the case of Projectagami [55] where practical applications for paper devices are explored. In the same style, more complex origami folds can be seen in Go et al.'s tessellated origami works [10], examining possible interactions with such structures, whereas Jamsheets [40] explores the possibility of self-actuated origami by incorporating jamming technology into air-bladders contained within the folds.

Figure 2. (table) summarizes the current state of the art for foldable devices, interfaces, and concepts in HCI research (in alphabetical order). The aim of this table is to examine current research e.g. to adopt or to extend these concepts to the foldable origami display. The table also helps us exclude concepts that have already been considered in paper-folding research. In addition, and identify gaps in current research – for example – there is no research on a foldable display that unfolds from a small area to a bigger extension, and that is mechanically connected in the unfolded state. Furthermore, the folding principle of the display itself has not been considered so far.

## EXPLORING THE EXTENDABLE ORIGAMI SMARTWATCH

A 4-stage process was employed in order to investigate the extended screen potential for smartwatch displays: 1) Investigation of origami techniques/structures to establish the best formats to enhance smartwatch interactions; 2) Focus Groups [32] with expert and non-expert participants exploring common smart-device interactions using paper prototypes; 3) Creation of a concept video utilising interaction methods taken from the focus groups; and, 4) A survey in response to the proof-of-concept video gathering user opinion on the origami smartwatch prototype using AttrakDiff [14].

| Name | Features | Used Technology |
|---|---|---|
| **Awakened Apparel** (Perovich, Mothersill, & Broutin Farah, 2014) | Shape-changing fashions to employ pneumatically actuated origami, a pneumatic folding, shape-changing skirt | Soft-bodied robotic actuators, combines robotics, folding, and fashion |
| **BookiSheet** (Watanabe, Mochizuki, & Horry, 2008) | Flip pages like a book, set book marks | Two thin plastic sheets and bend sensors |
| **Color-Changing Origami** (Kaihou, & Wakita, 2013) | Color-changing origami using LEDs | Uses thermochromic and conductive ink, it can be folded in the same way as paper origami, it mustn't contain any hard electronic components |
| **Flexpad** (Steimle, Jordt, & Maes, 2013) | Transformed sheets of plain paper into flexible, highly deformable, and spatially aware handheld displays | Depth camera detects deformations of papers' surface and projector projects pictures in real time |
| **Foldable Interactive Displays** (Lee, Hudson, & Tse, 2008) | Four paper folds are introduced: newspaper, scroll, fan, and umbrella | Projection, tracking with infrared (IR) LEDs embedded in the prototypes, the PixArt camera within the Nintendo Wii remote |
| **FoldMe** (Khalibeigi, Lissermann, Kleine, & Steimle, 2012) | Three prototypes: book, partial-fold and dual-fold devices | Snap-in effect with magnefied hinges, Optitrack motion capture system, six infrared cameras, a full HD projector, infrared retro-reflective markers |
| **Gummi** (Schwesig, Poupyrev, & Mori, 2004) | Physical deformation of a hand-held device, bendable device | Layers of flexible electronic components including sensors measuring deformation (2D position sensors) |
| **jamSheets** (Ou et al., 2014) | Technology for designing deformable, stiffness-tunable thin sheet interfaces | Sensor layers, multiple materials used in one jamming unit to get different levels of deformation |
| **MimicTile** (Nakagawa, Kamimura, & Kawaguchi, 2012) | Variable stiffness deformable user interface for mobile devices, haptic feedback, deformation-based, gestures possible | Shape memory alloy (SMA) wires act as actuator and external input sensors |
| **PaperFold** (Gomes, & Vertegaal, 2014) | Foldable thin-film device with multiple detachable flexible display tiles | The tiles consists of a flexible E-Inc display, and a flexible 3D printed substrate with embedded sensors |
| **PaperTap** (Tarun et al., 2005) | Touch sensitive flexible electrophonetic displays | Each displaywindow is an Android computer that shows documents in several resolutions, touch and bend sensors allow to navigate content |
| **PaperWindows** (Holman, Vertegaal, Altosaar, Troje, & Johns, 2005) | Simulates digtal paper displays | Paper is used as an input device by tracking its motion and shape with a Vicon Motion Capturing System |
| **PrintScreen** (Olberding, Wessely, & Steimle, 2014) | Flexible thin display | Digital fabrication of customized flexible displays using thin-film electroluminescence (TFEL) |
| **Projectagami** (Tan, Kumorek, Garcia, Mooney, & Bekoe, 2015) | Foldable mobile device, demo application on a book, online shopping, a board game, street navigation, and a browser | Tracked with a Kinect and uses a projector for visual output |
| **Shape Memory Alloy** (Qi, Jie and Buechley, & Leah, 2012) | Animated paper | The paper is actuated with SMAs to achieve dramatic movement, design quidelines are given |
| **Self-Folding Origami** (Tolley, Felton, Miyashita, Aukes, Rus, & Wood, 2014) | Self-folding shapes that are activated by heating | Folding mechanism based on the in-plane contraction of a sheet of shape memory polymer, four shapes are intruduced |
| **Sticky Actuator** (Niiyama, Sun, Yao, Ishii, Rus, & Kim, 2015) | Object movement | Soft planar actuators enhanced by free-form fabrication, the actuator consists of adhesive-backed inflatable pouches, shapes: squares, circles and ribbons |
| **Tilt Displays** (Alexander, Lucero, & Subramanian, 2012) | Actuatable display, provides visual feedback combined with multi-axis tilting and vertical actuation | 3x3 Tilt Displays (physically mutatable visual feedback devices), components support multi- axis tilting and vertical actuation |
| **uniMorph** (Heibeck, Tome, Della Silva, & Ishii, 2015) | Digital fabrication of customized thin-film shape-changing interfaces | Copper (its thermo- electric characteristics), polyethylene (high thermal expansion rate) |
| **Xpaaand** (Khalilbeigi, Lissermann, Mühlhäuser, & Steimle, 2011) | Rollable display device, dynamically changeable size and form factor with novel interaction possibilities | Thin and lightweight device concept with on-bord power, high resolution display, retro-reflective marker, trackball, projection on display surface |

Figure 2. Foldable device analysis, with prototypes listed in alphabetical order: Awakened Apparel [42]; Bookisheet [61]; Colour-Changing Origami [22]; Flexpad [53]; Foldable Interactive Displays [27]; FoldMe [24]; Gummi [49]; jamSheets [40]; MimicTile [33]; PaperFold [11]; PaperTab [56]; PaperWindows [18]; PrintScreen [39]; Projectagami [55]; Shape Memory Alloy [43]; Self-Folding Origami [57]; Sticky Actuator [36]; Tilt Displays [1]; uniMorph [15]; Xpaaand [25];.

## Creating Origami Structures for Smartwatch Displays

Following a review of origami patterns in collaboration with an origami professional with over 40 years experience, five were identified to be particularly promising for smartwatch display folding: the Miura-ori , Flasher , Leaf , Preliminary Base and the Triangulation  fold. Miura-ori pattern is used for solar sails on satellites [3] and creates compact and lightweight objects with maximum extension [2]. Some of the investigative folding can be seen in Figure 1. During the folding process and exploration, it became clear that the Flasher and Leaf form were not suitable for purpose because of their thickness, and increasingly complex creases as the size reduced which rendered them unsuitable for compact folded thin displays – this is especially the case when the ultimate goal is to translate the folding techniques into flexible OLED or other display technology. Although Triangulation  fold was promising, it was later rejected by the team as it could only offer a relatively small extension to the smartwatch display, and this would not offer enough increased functionality to significantly improve upon existing solutions.

Preliminary Base and Miura-ori were both chosen by the research team for investigation due to their larger extension area, and simplicity of interaction. Preliminary Base allows for double sided display interaction within multiple fold combinations, whereas Miura-ori offers one type of extension, but offers the user a more flexible surface to work with (see Figure 3). The two completed folds were sized to be correlated with the current average size of smartwatches (when in their initial pre-interaction state) and attached to a foam board base of the same size with a velcro strap. To allow for the different ways in which people choose to wear their watches and preferences of left or right hand, the prototypes were built with a turning mechanism similar to the Cito smartwatch [13].

The reasoning behind choosing a limited number of folding styles before presentation was twofold: firstly, the expertise offered by the origami professional and subsequent discussion of application techniques in relation to the literature review allowed for an informed decision to be made as to the viability of the folds for smartwatch extension; and secondly, including many types of fold in a focus group would be overwhelming and the result would be unfocused and likely to produce only low-level findings. By conducting prior analysis and exploration of folding techniques, the focus groups could produce meaningful interaction ideas and application scenarios.

**Paper Prototyping Focus Groups**

We adapted the dual-workshop and concept video research model used with Cito [13] in order to explore the interaction potential of the origami display extension. Paper prototypes of the two chosen origami-smartwatch interfaces were made, and these were used to stimulate discussion around, and act out commonplace digital-device interaction scenarios (e.g. opening an application or sending a text message).

**Participants**

Twenty participants (11M / 9F) between the ages of 20 and 73 were recruited via email and social media, and offered 10 Euros compensation for taking part. Of these participants, half were classed as “expert” (that is, having high-level computer and HCI skills), and half were classed as “non-expert” (having used smartphones/smartwatches before but with no programming or HCI experience).

**Focus Group**

An hour-long focus group was held with each participant set (expert/non-expert), and each group was supplied with 10 smartwatch paper-prototypes (half Preliminary Base and half Miura-ori fold). Sessions were filmed and the audio recorded. The session format incorporated a 5 minute introduction to the origami smartwatch concept and related research, after which participants were paired up and given one of the prototypes to explore following a set scenario protocol (in order to produce a comparable result between groups for some session items). After 15–20 minutes, participants were asked to write down their responses to the protocol questions, and discuss the smartwatch prototype in an unstructured format as a group, before swapping to the second prototype, which followed the same procedure.

All participants were also provided with extra paper upon which they made notes and sketches to describe their interactions and other ideas, and a final discussion was held where we invited the group to suggest and explore other user-led scenarios and ideas so that the exploration was not limited to pre-defined goals. A post-workshop questionnaire was given at the end of the hour, collecting basic demographic data, and quantifying levels of experience using smartwatches and other digital devices on a 5-point Likert scale. Participants were also asked which of the devices they preferred, which applications would be most desirable on an extended smartwatch, their preferred method of interaction and whether they would consider purchasing such a watch.

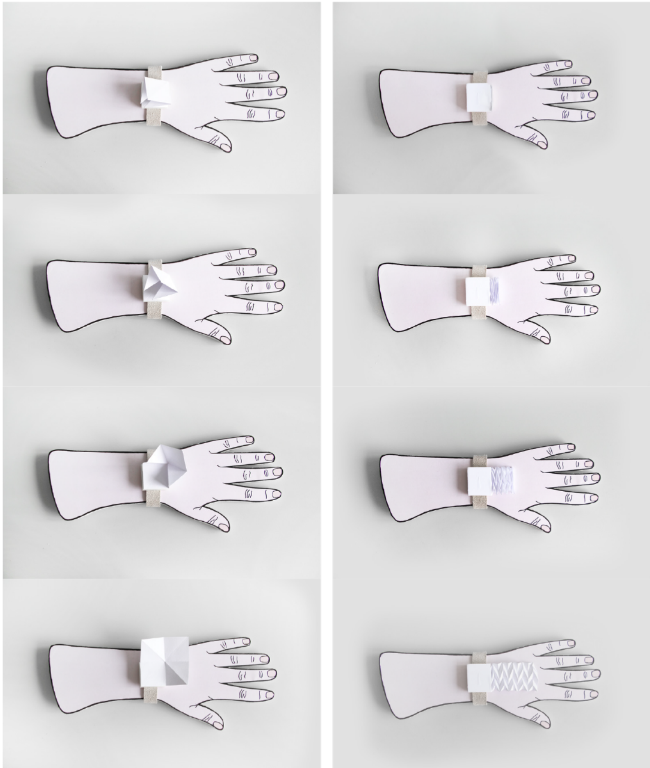

*Figure 3. The chosen origami folds used for the paper prototypes, left: Preliminary Base, right, Miura-ori.*

**Scenario Protocol**
For each focus group session, participants were asked to explore and model the following common smartwatch/smartdevice interactions, utilising the folding properties of the origami prototype (see Figure 3 for an example of the possible folding combinations): 1) Navigating the application screen 2) Receiving a text message or email ; 3) Sending a text message or email ; 4) Making a call ; and, 5) Opening a map application, routing, and navigating to a destination . These popular smart-device interactions were based on those used by Fernandez et al. [7].

**Modelling Interactions as Proof of Concept**
The collected interaction methodologies for each scenario were examined and the most frequently occurring interactions were incorporated into a Wizard-of-Oz proof-of-concept video (i.e. interactive capabilities were manually controlled). These can be seen in the accompanying video submission.

**Video Survey Methodology**
Twenty new participants were recruited via email and social media and asked to review the concept video and rate the device using the AttrakDiff framework which measures the usability and design of interactive products [14] (e.g. examining intended product quality; perception of quality; evaluation of quality; independent pragmatic/hedonic qualities; behavioural/emotional consequences ). The survey was also sent to 16 of the 20 original focus group participants for comparison. The online video elicitation study was conducted to present a finished product to the user so that they could grasp the concept of the foldable origami smartwatch as a product, its features, to gain insight into novel interaction techniques, and also to find out whether the study participants could imagine using such a product in their everyday lives.

## ANALYSIS & RESULTS

This section presents the results of the focus group and concept video. For simplicity during the focus groups, the origami folds were renamed PullWatch (Miura-ori ) and FoldWatch (Preliminary Base). Both focus groups had a mixed response to and the watch display types, although the interactions used with the FoldWatch model were more consistent with novel, extendable smartwatch displays and offered a planar screen to work with upon unfolding. In contrast, the PullWatch prototype did not offer as much extension and therefore limited the interactions available, whereas the behaviours observed were consistent with basic smartphone interactions, albeit on a smaller scale. Another issue with PullWatch was that the complex folds would make the screen content difficult to see, and could possibly get in the way of using keyboards. FoldWatch ultimately emerged as the favoured model, and was used to generate the concept video.

### Focus Group Overview

For both focus groups all participants preferred to wear their watch on their non-dominant arm with the display facing outwards (out of 20 participants only one was left-handed), although they were given the option to engage with the device in other ways. The primary reason for this was that participants said if there was a keyboard function they would find it difficult to type with their non-dominant hand. Only one participant across both groups actually owned a smartwatch, although all owned normal watches.

### Screen Ranges & Interactions

Figure 4 shows the range of foldable screen interactions utilised by the participants within the constraints of the prototype hardware: Figure 4.1-4 show the Foldwatch display interactions (fully extended display at 2 angles of rotation, half-size screen option; method of using the flaps like reading a book, and '3D box' style). Figures 4.5-8 show the PullWatch interactions (simple extension, fan-fold, 90 degrees and full bracelet extension). In addition to the folding interactions, participants also explored existing smartdevice interactions to accompany the novel folding structure. Swiping away from the leading corner of Foldwatch or tapping on the home screen on either prototype was discussed as a possibility to activate the self-actuated unfolding movement, although one participant preferred there to be a 'home' button as with the current edition iPhone . Several participants also considered how gestures could activate the unfolding mechanism, e.g. shaking the arm, although the chances of accidental activation would be high. The subsections below discuss the scenarios of use.

*1) Navigating the application screen*

The chosen application home screen was either the fully extended version of both prototypes (Figure 4.1 & 4.5) or the simple folded outer screen as is the case with current smartwatches, although one participant thought the half screen of Foldwatch would be enough (4.2). Navigation would then occur as with current smartdevices (swipe/tap). Another participant felt that using the folds from corner to corner on the Foldwatch prototype ('flip-flap') as with a book would allow to move between screens of applications – in this case the smartwatch screen hardware would need to be fully double-sided to take advantage of this.

*2) Receiving a text message or email*

For receiving a notification of either type of message, participants felt that there should be a preview on the folded home screen, and then you would either pull out the side to read with PullWatch (Figure 4.5) or unfold the Foldwatch either fully for an email, or into half-view for a text message (Figure 4.1-2). Some felt however, that a text message is usually so short it could scroll across the home-screen, only needing to be opened if it was particularly lengthy.

*3) Sending a text message or email*

To send a text or email, all participants preferred the pulled out/unfolded versions as these would allow a full keyboard at the same scale of a smartphone. The full extension of Fold-Watch was also thought to be useful for browsing the contact list, or other types of listed data (e.g. web page information).

*4) Making a call*
The majority of participants said that they would prefer not to use a smartwatch for making a call, and felt that the watch was not private enough unless you held it to your ear in an awkward manner (although if the watch was worn on the inside of the wrist this was less of an issue). If a call was to be made, they felt that they would prefer that no folding or unfolding occurred to enable this, however they did feel that the half-fold of FoldWatch  (Figure 4.2) would be helpful for video calling, and that the unfolding for receiving a call, and folding down to end that call would be apt interaction styles.

*5) Opening a map application, routing, & navigating*
The map scenario was found to be the application type best supported by the folding methodology, as all participants felt that current smartwatch screens do not have the space to allow viewing the map in sufficient detail, or pan and move around the screen to get an idea of location. Either the full fold out for both watch types (Figure 4.1/4.5) or the 3D box (Figure 4.4) were given as the preferred extensions (3D Box view for map applications is discussed below).

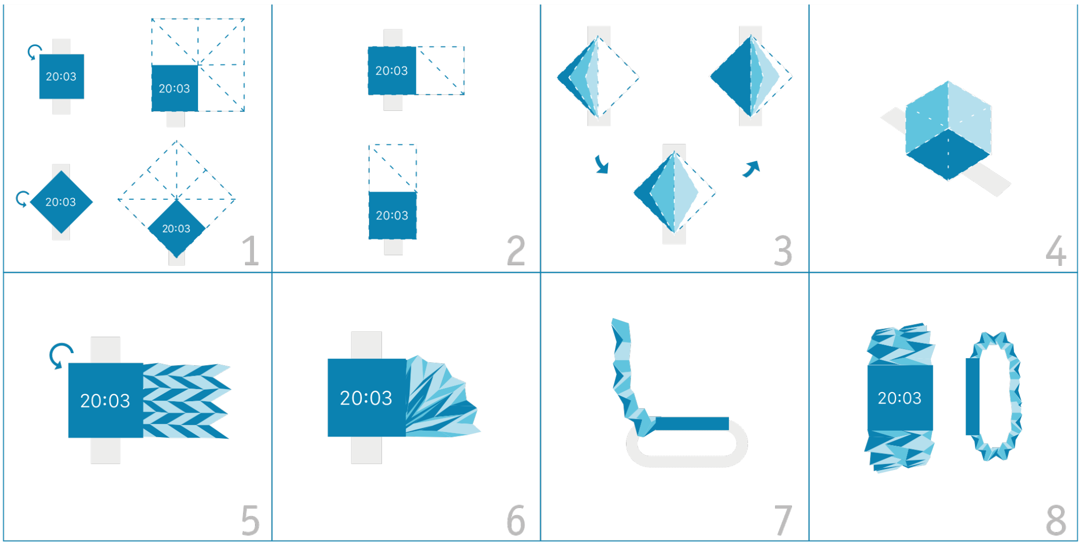


*Figure 4. Illustration of types of fold identified during the focus groups for preliminary base (top) and miura-ori (bottom).*

Other scenarios/questions arose during the focus group sessions and emerged organically during the process, for example, one participant query was whether all interactions required unfolding or whether the single home screen would work as with current watches, and what the exact format of that homes screen would be. Device personalisation was also considered: participants felt that the folding action and usage should be customisable, and were worried that accidental activation would be an issue whilst the watch was obscured by clothing, and therefore the auto-unfolding would need to be turned off or include obstruction sensors. It was also decided that the fold-action itself must not be too sensitive to avoid having to reset if it was set off accidentally, and that the folding should be controlled with no moving parts during tasks.

Extra features were also considered during the user-led discussion. Alongside including a camera (discussed below), participants also suggested including voice control [60] and/or a voice activated assistant like Siri on iPhone . Apple  innovations like Apple Active Corners . The Rotation feature for the watch face was seen as a positive addition to the screen extension methodology (as seen in [64]), although this had originally only been intended as a means to adjust the watch for left or right-handed people, it allowed the extended watches to be angled for easier viewing, and enabled the ‘book reading’ mode (Figure 4.3). For practical reasons, participants felt that this should be limited to a set number of angles (e.g. 8) and click into place, to avoid accidentally losing the position, and to give developers set positions to integrate into actions (expert group suggestion). Finally, participants felt that the smartwatch and its contents should be kept as simple as possible in terms of display and extension, to enable a more positive user experience – especially for novice users (non-expert group).

| EXPERTS | | NON-EXPERTS | |
|---|---|---|---|
| Device | Average Experience | Device | Average Experience |
| PC | 4.6 | PC | 4.3 |
| Notebook | 4.6 | Notebook | 4.4 |
| Tablet | 3.8 | Tablet | 3.6 |
| Smartphone | 4.5 | Smartphone | 4.3 |
| Smartwatch | 1.3 | Smartwatch | 1.2 |
| Google Glass | 1.4 | Google Glass | 1 |

*Figure 5. Likert ratings for technology experience between participants*

**Between Groups Differences**

The levels of experience Likert rating between groups was similar, with both the expert and non-expert group self-rating as familiar with interactive technologies such as smartdevices and modern computers, although expert users rated slightly higher. Both groups provided detailed notes and analysis of the types of interactions they would expect to see, although the expert group also provided questions about the build quality and software design of the devices. The expert group were also more likely to elaborate on their findings, and held lively group discussions in between tasks to consider positive aspect such as possible applications, problems or limitations. Figure 5. shows the Likert results for between-groups expertise with interactive technology.

**Specific Usage Scenarios**

The FoldWatch prototype generated ideas for applications not currently in wide use for smartwatches, such as Alternative Reality (AR) gaming (using the 3D box display – see Figure 4.4), holography (also utilising the three sided display to project figures into the remaining space), or reading longer texts such as e-books (using the Flip-Flap method, Figure 4.3). The fold out screen also could be utilised for a versatile camera, as current devices utilise a lens placed within the watch face [59] or within the strap [64] which offers limited angles without uncomfortable twisting of the arm. The 3D Box display type was also suggested as a novel way of interacting with mobile map applications as you can see a street view , navigation and an overview of the map at the same time within the different panes, and map the street view to your current point of view.

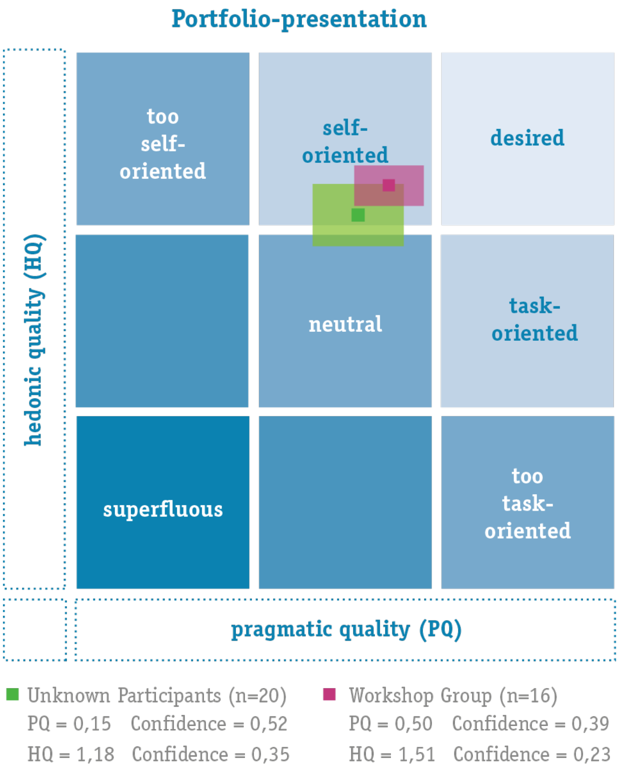


*Figure 6. AttrakDiff results for the focus group (purple) and new participant group (green).*

**Concept Video**

The FoldWatch fold-styles in Figure 4. were used to model the interaction scenarios from the focus group questionnaire in a concept video (see accompanying video submission). Twenty new survey participants and 16 of the original focus group members completed the AttrakDiff questionnaire to establish the validity of the FoldWatch prototype as a future product. The video submission shows: opening the FoldWatch screen, reading and sending a message, browsing the application screens, and opening/using the map application. The examples shown by the video were specifically chosen from the most interesting and detailed results from the focus groups, and included some of the novel ideas (e.g. 3D map-view). Varied results were not included as the intent of the video survey was to gauge interest for potential product development, rather to to evaluate specific interactions.

**AttrakDiff Findings**

AttrakDiff is an evaluation tool developed for rating the usability and design of a product based on theory that describes how user experience is influenced by pragmatic and hedonic qualities, and both qualities contribute equally to the appeal of attractiveness [14]. The model separates four aspects (www.attrakdiff.de/sience-en.html#arbeitsmodell): The product quality intended by the designer; The subjective perception of quality and subjective evaluation of quality; The independent pragmatic and hedonic qualities; and Behavioural and emotional consequences. The AttrakDiff e-survey is built up of 28 contrasting adjective word pairs (confusing-clear, good-bad etc.) and these are combined into a scale. The average value of an item group creates a scale value for Pragmatic Quality of survey or analysis as it was appropriate for the conceptual, design-focused exploration that we have presented. We chose AttrakDiff over other types over other types of survey or analysis as it was appropriate for the conceptual, design-focused exploration that we have presented.

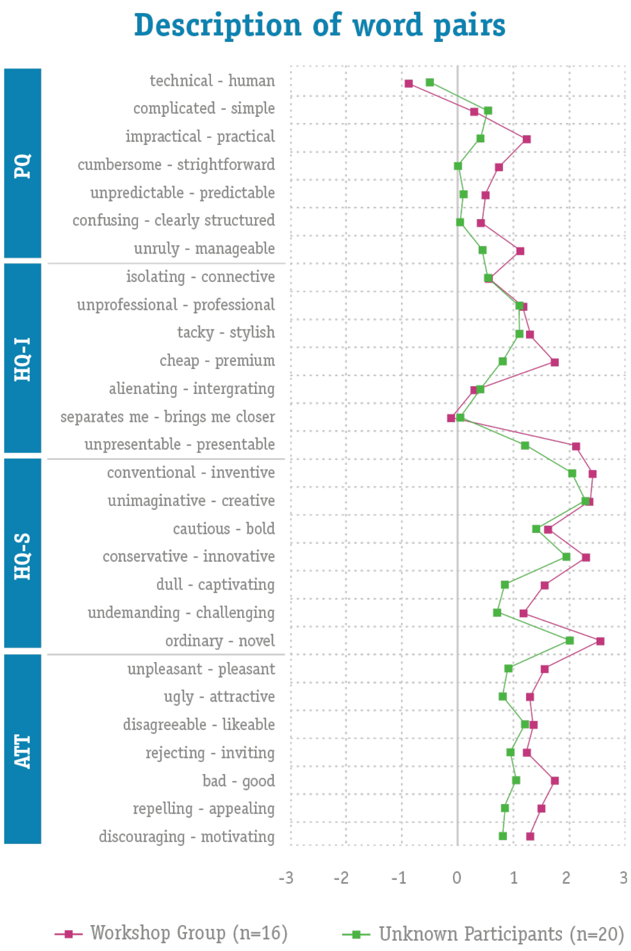


*Figure 7. AttrakDiff word-pair between groups comparison. (PQ), Hedonic Quality (HQ, including HQ-I/HQ-S), and Attractiveness (ATT).*

According to the results generated by AttrakDiff for the focus group participants, the prototype has a higher hedonic than pragmatic quality so there are possibilities for improvement, though the overall result is positive (Figure 6). The Confidence Rectangle shows a higher agreement between the users in the hedonic rather than in the pragmatic quality, and the product is seen as self-orientated (e.g. self-directed goals are mostly more persistent and personally relevant) rather than task-orientated , with a tendency toward being a desirable product.

The Confidence Rectangle in the workshop group is smaller than in the new participant group: means users converge more in their opinion about FoldWatch . The new participants rated FoldWatch more as a neutral product with only a tendency toward self-orientation, although the larger Confidence Rectangle means there was a greater judgement range between participants. Despite these group differences, the overall agreement for the word pair ratings was high (Figure 7.), suggesting that the new participants were also able to easily grasp and understand the concept and implications of the product despite having never been exposed to it before. The inter-rater agreement and tendency toward positive descriptions here also provides assurances that the FoldWatch concept has potential for development as a functioning product.

**DISCUSSION**

The combined output from the focus groups and the video survey provides a promising outlook for the FoldWatch smartwatch concept. Users expressed a preference for the simpler screen surface of preliminary base, and larger screen extensions for complex interaction, which supports the original hypothesis. The focus groups also allowed us to discover novel use-cases and features that were not included in the original scope of the study. FoldWatch offers an apparently simple solution to the smartwatch screen interaction space problem, avoiding 'fat finger' issues or the need to redesign existing application interactions to fit the hardware. This means developers would only have to make minor adaptations to existing applications in order to extend them to the smartwatch market (no 'miniature' versions), the implication being the range of applications available for smartwatches would also increase.

**Advantages of the FoldWatch Concept**
Other advantages of having a foldable screen are that the interior surface is unlikely to get scratched (which is an issue with smartwatches as they are not kept in protective cases whilst not in use). The folding mechanism also can be used as a novel interaction style if desired, such as for games or gesturebased interaction (as suggested by the folding-down to end a call). The map-view scenario also explored the possibility of multiple viewing planes, and this is something that could be extended to the other fold-styles – such as a different view in each square of the fully extended watch, or utilising theouter facing squares in 3D Box mode for multi-user view. This would be especially interesting in gaming scenarios for two FoldWatch users, or if two people wanted to see a map or image at the same time.

**Manual VS Self-Actuation**
The FoldWatch idea was originally designed with a selfactuation capability in mind (for both the miura-ori and preliminary base designs), that is, the smartwatch would be able to change shape and extend by itself in response to stimuli such as receiving messages, or user gestures. This facility was met with a mixed response from the users. Whilst the novelty of a shape-changing smartwatch was exciting, it was felt that the automatic action may cause issues with unwanted movement or damage to the watch if it unfolded whilst obstructed (as mentioned in the analysis). The element of control was therefore important for users, they were keen to either have completely manual control over the folding interaction, or at least have the option to customise which types of movement were allowed at specific times.

**Smartwatch Text Input**
Text-entry for smartwatches is a challenge due to the small screen size, and research has examined novel screen keyboards such as Fleksy and Swype [5], by optimising the text layout [6], but also whether voice could be used instead of keyboards, e.g. WearWrite [34]. There has also been an investigation of miniature QWERTY keyboards with zoom function to assist in typing on smartwatches [29], amongst other proof-of-concept studies for text entry interaction. The breadth of research in this area makes it clear that users expect to be able to use keyboards for tasks such as sending messages or using search functions within applications such as browsers. The FoldWatch concept removes the need for novel keyboards by allowing the smart watch to expand to provide a full size keyboard, which is larger even than some existing smartphone keyboard options.

**Limitations**
Use-cases that came up during the focus groups that were not explicitly examined were the web-browser and social media. The reasoning behind this is that the folding screen extension would work in the same way for most applications, and adding further scenarios to the focus groups would involve extending the duration of the study, cause fatigue in participants, and also generate repetitive results. The messaging scenario explored the browsing function (contact list) and the application screen navigation supported multi-screen interaction. Additionally, the map application elicited the most novel foldinteraction (3D Box view) and this could be relatable to the multi-screen/window approach for other applications. Another case is that of fitness applications, which are the most common use for smartwatches [45] as they can track heart rate and activity through built in sensors and report back basic results, as well as link to users' smartphones and other devices. We chose not to look at this scenario as it is already well represented in smartwatch research, and it is not clear at this stage how screen extensions could support this data in a meaningful way outside of the interactions we have

already modelled – although future work with a functioning prototype could explore this option (the latter is discussed below).

## FUTURE WORK

The next stages for this work would be to further the extendable FoldWatch concept by making a functional prototype for user testing. This could be produced using Smart Material Alloy (SMA) wires such as in the Morphee Couture prototype [47], and combining with thin-film electro-luminescence [39] and Flexy technologies [58] or OLED [26, 51] – however, the materials used must make use of full closure [47], i.e. bend completely back on themselves. With currently available hardware, we believe it would be possible to make a functional prototype. This would require materials testing, stress testing of joining structures and programming to change screen views to map onto the extended areas in user-friendly fashion. With a working prototype in place, there would also then be the opportunity to look at specific application functions for foldable smartwatches, such as the tri-map view scenario, or investigating if this type of screen extension is of use for fitness bands. With the utilisation of a working model, we can then explore the potential of the interaction types and folds to generate agreement ratings to best develop the device to user-specifications [28]. The addition of physiological data or 3D projected objects would also be an exciting avenue of investigation for subsequent work. The FoldWatch concept offers the potential for extended interaction styles, novelty in application usage, and improving the overall user experience for smartwatches, we therefore hope to continue this exciting line of work and extend our knowledge in this area.

## CONCLUSION

Smartwatches offer highly accessible device interactions, but have been shown to have limited usable screen size. We have analysed methods for extending smartwatch interactions, and suggested a novel, origami-based extension to the smartwatch concept. Via research with focus groups, we have shown that utilising the preliminary base folding technique can support more application types and interaction styles than miura-ori , and also enhance the user experience for smartwatches. By creating and surveying a proof-of-concept video, we have also collected data which suggests that the FoldWatch is a desirable product, with the potential to support rich and varied user-interactions.

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## REFERENCES

1. Jason Alexander, Andr´es Lucero, and Sriram Subramanian. 2012. Tilt displays: designing display surfaces with multi-axis tilting and actuation. In Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services . ACM, 161–170. DOI: http://dx.doi.org/10.1145/2371574.2371600

2. Hani Buri and Yves Weinand. 2008. ORIGAMI – Folded plate structures, architecture. In 10th World Conference on Timber Engineering . 2–5.

3. Hatje Cantz, K Hatori, and P Jackson. 2005. Masters of Origami. Ostfildern-Ruit: Hatje Cantz Publishers (2005), 21–43.

4. Marta E Cecchinato, Anna L Cox, and Jon Bird. 2015.

Smartwatches: the Good, the Bad and the Ugly?. In Proceedings of the 33rd Annual ACM Conference extended abstracts on human factors in computing systems . ACM, 2133–2138. DOI: http://dx.doi.org/10.1145/2702613.2732837

5. Barbara S Chaparro, Jibo He, Colton Turner, and Kirsten Turner. 2015. Is touch-based text input practical for a smartwatch?. In International Conference on Human-Computer Interaction . Springer, 3–8. DOI: http://dx.doi.org/10.1007/978-3-319-21383-5_1

6. Mark D Dunlop, Andreas Komninos, and Naveen Durga. 2014. Towards high quality text entry on smartwatches. In CHI'14 Extended Abstracts on Human Factors in Computing Systems . ACM, 2365–2370. DOI: http://dx.doi.org/10.1145/2559206.2581319

7. Mireia Fern´andez-Ard`evol and Andrea Rosales. 2017. My interests, my activities: Learning from an intergenerational comparison of smartwatch use. In International Conference on Human Aspects of IT for the Aged Population . Springer, 114–129. DOI: http://dx.doi.org/10.1007/978-3-319-58536-9_10

8. Danny Fundinger. 2013. Der Aufstieg der Smartwatch. Die Bank 10 (2013), 64–67.

9. David T Gallant, Andrew G Seniuk, and Roel Vertegaal. 2008. Towards more paper-like input: flexible input devices for foldable interaction styles. In Proceedings of the 21st annual ACM symposium on User interface software and technology . ACM, 283–286. DOI: http://dx.doi.org/10.1145/1449715.1449762

10. Kentaro Go, Yuichiro Kinoshita, Kohei Kaneko, and Reiji Kozono. 2014. Creating Interactive Flexible Surfaces with Origami Tessellations. In International Conference on Collaboration Technologies . Springer, 119–126. DOI: http://dx.doi.org/10.1007/978-3-662-44651-5_11

11. Antonio Gomes and Roel Vertegaal. 2014. Paperfold: a shape changing mobile device with multiple reconfigurable electrophoretic magnetic display tiles. In CHI'14 Extended Abstracts on Human Factors in Computing Systems . ACM, 535–538. DOI: http://dx.doi.org/10.1145/2559206.2574770

12. Antonio Gomes and Roel Vertegaal. 2015. PaperFold: evaluating shape changes for viewport transformations in foldable thin-film display devices. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction . ACM, 153–160. DOI: http://dx.doi.org/10.1145/2677199.2680572

13. Jun Gong, Lan Li, Daniel Vogel, and Xing-Dong Yang. 2017. Cito: An Actuated Smartwatch for Extended Interactions. In Proceedings of the 2017 CHI Conference

on Human Factors in Computing Systems . ACM, 5331–5345. DOI: http://dx.doi.org/10.1145/3025453.3025568

14. Marc Hassenzahl. 2006. Hedonic, emotional, and experiential perspectives on product quality. In Encyclopedia of human computer interaction . IGI Global, 266–272. DOI: http://dx.doi.org/10.4018/978-1-59140-562-7.ch042

15. Felix Heibeck, Basheer Tome, Clark Della Silva, and Hiroshi Ishii. 2015. uniMorph: Fabricating thin film composites for shape-changing interfaces. In Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology . ACM, 233–242. DOI: http://dx.doi.org/10.1145/2807442.2807472

16. Horace Henley Jr. 2008. Combination watch and cell phone foldable onto each other for use around a wrist of a user. (March 3 2008). US Patent App. 12/074,491.

17. David Holman and Roel Vertegaal. 2008. Organic user interfaces: designing computers in any way, shape, or form. Commun. ACM 51, 6 (2008), 48–55. DOI: http://dx.doi.org/10.1145/1349026.1349037

18. David Holman, Roel Vertegaal, Mark Altosaar, Nikolaus Troje, and Derek Johns. 2005. Paper windows: interaction techniques for digital paper. In Proceedings of the SIGCHI conference on Human factors in computing systems . ACM, 591–599. DOI: http://dx.doi.org/10.1145/1054972.1055054

19. Jonggi Hong, Seongkook Heo, Poika Isokoski, and Geehyuk Lee. 2015. SplitBoard: A simple split soft keyboard for wristwatch-sized touch screens. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems . ACM, 1233–1236. DOI:http://dx.doi.org/10.1145/2702123.2702273

20. Hiroshi Ishii, D´avid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical atoms: beyond tangible bits, toward transformable materials. interactions 19, 1 (2012), 38–51. DOI: http://dx.doi.org/10.1145/2065327.2065337

21. Yoonhyuk Jung, Seongcheol Kim, and Boreum Choi. 2016. Consumer valuation of the wearables: The case of smartwatches. Computers in Human Behavior 63 (2016), 899–905. DOI: http://dx.doi.org/10.1016/j.chb.2016.06.040

22. Tatsuya Kaihou and Akira Wakita. 2013. Electronic origami with the color-changing function. In Proceedings of the second international workshop on Smart material interfaces: another step to a material future . ACM, 7–12. DOI:http://dx.doi.org/10.1145/2534688.2534690

23. Keiko Katsuragawa, James R Wallace, and Edward Lank. 2016. Gestural text input using a smartwatch. In Proceedings of the International Working Conference on Advanced Visual Interfaces . ACM, 220–223. DOI: http://dx.doi.org/10.1145/2909132.2909273

24. Mohammadreza Khalilbeigi, Roman Lissermann, Wolfgang Kleine, and J¨urgen Steimle. 2012. FoldMe: interacting with double-sided foldable displays. In Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction . ACM, 33–40. DOI:http://dx.doi.org/10.1145/2148131.2148142

25. Mohammadreza Khalilbeigi, Roman Lissermann, Max M¨uhlh¨auser, and J¨urgen Steimle. 2011. Xpaaand: interaction techniques for rollable displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems . ACM, 2729–2732. DOI: http://dx.doi.org/10.1145/1978942.1979344

26. Sunkook Kim, Hyuk-Jun Kwon, Sunghun Lee, Hongshik Shim, Youngtea Chun, Woong Choi, Jinho Kwack, Dongwon Han, MyoungSeop Song, Sungchul Kim, and others. 2011. Low-Power Flexible Organic Light-Emitting Diode Display Device. Advanced Materials 23, 31 (2011), 3511–3516. DOI: http://dx.doi.org/10.1002/adma.201101066

27. Johnny C Lee, Scott E Hudson, and Edward Tse. 2008. Foldable interactive displays. In Proceedings of the 21st annual ACM symposium on User interface software and technology . ACM, 287–290. DOI: http://dx.doi.org/10.1145/1449715.1449763

28. Sang-Su Lee, Sohyun Kim, Bopil Jin, Eunji Choi, Boa Kim, Xu Jia, Daeeop Kim, and Kun-pyo Lee. 2010. How users manipulate deformable displays as input devices. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems . ACM, 1647–1656. DOI: http://dx.doi.org/10.1145/1753326.1753572

29. Luis A Leiva, Alireza Sahami, Alejandro Catala, Niels Henze, and Albrecht Schmidt. 2015. Text entry on tiny qwerty soft keyboards. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems . ACM, 669–678. DOI: http://dx.doi.org/10.1145/2702123.2702388

30. Kent Lyons, David Nguyen, Daniel Ashbrook, and Sean White. 2012. Facet: a multi-segment wrist worn system. In Proceedings of the 25th annual ACM symposium on User interface software and technology . ACM, 123–130. DOI:http://dx.doi.org/10.1145/2380116.2380134

31. Jun Mitani. 2011. A Method for Designing Crease Patterns for Flat-Foldable Origami With Numerical Optimization. J. Geom. Graphics 15, 2 (2011), 195–201.

32. David L Morgan. 1997. The focus group guidebook . Vol. 1. Sage publications.

33. Yusuke Nakagawa, Akiya Kamimura, and Yoichiro Kawaguchi. 2012. MimicTile: a variable stiffness deformable user interface for mobile devices. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems . ACM, 745–748. DOI: http://dx.doi.org/10.1145/2207676.2207782

34. Michael Nebeling, Alexandra To, Anhong Guo, Adrian A de Freitas, Jaime Teevan, Steven P Dow, and Jeffrey P Bigham. 2016. WearWrite: Crowd-assisted writing from smartwatches. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems . ACM, 3834–3846. DOI: http://dx.doi.org/10.1145/2858036.2858169

35. David Nield. 2017. OK Google: Useful voice commands for your Android Wear smartwatch. Web article. (23 June 2017). Retrieved July 16, 2017 from http://www.wareable.com/android-wear/ how-to-use-voice-commands-on-android-wear .

36. Ryuma Niiyama, Xu Sun, Lining Yao, Hiroshi Ishii, Daniela Rus, and Sangbae Kim. 2015. Sticky actuator: Free-form planar actuators for animated objects. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction . ACM, 77–84. DOI:http://dx.doi.org/10.1145/2677199.2680600

37. Hyunjoo Oh, Jeeeun Kim, Cory Morales, Mark Gross, Michael Eisenberg, and Sherry Hsi. 2017. FoldMecha: Exploratory Design and Engineering of Mechanical Papercraft. In Proceedings of the Tenth International Conference on Tangible, Embedded, and Embodied Interaction . ACM, 131–139. DOI: http://dx.doi.org/10.1145/3024969.3024991

38. Simon Olberding, Sergio Soto Ortega, Klaus Hildebrandt, and J¨urgen Steimle. 2015. Foldio: Digital fabrication of interactive and shape-changing objects with foldable printed electronics. In Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology . ACM, 223–232. DOI: http://dx.doi.org/10.1145/2807442.2807494

39. Simon Olberding, Michael Wessely, and J¨urgen Steimle. 2014. PrintScreen: fabricating highly customizable thin-film touch-displays. In Proceedings of the 27th annual ACM symposium on User interface software and technology . ACM, 281–290. DOI: http://dx.doi.org/10.1145/2642918.2647413

40. Jifei Ou, Lining Yao, Daniel Tauber, J¨urgen Steimle, Ryuma Niiyama, and Hiroshi Ishii. 2014. jamSheets: thin interfaces with tunable stiffness enabled by layer jamming. In Proceedings of the 8th International

Conference on Tangible, Embedded and Embodied Interaction . ACM, 65–72. DOI: http://dx.doi.org/10.1145/2540930.2540971

41. Jason Pascoe. 2006. The smartwatch. In Proceedings of the Conference on Mobile and Ubiquitous Systems (CSMU), Guimaraes Portugal . 203–206.

42. Laura Perovich, Philippa Mothersill, and Jennifer Broutin Farah. 2014. Awakened apparel: embedded soft actuators for expressive fashion and functional garments. In Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction . ACM, 77–80. DOI:http://dx.doi.org/10.1145/2540930.2540958

43. Jie Qi and Leah Buechley. 2012. Animating paper using shape memory alloys. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems . ACM, 749–752. DOI: http://dx.doi.org/10.1145/2207676.2207783

44. Raf Ramakers, Johannes Sch¨oning, and Kris Luyten. 2014. Paddle: highly deformable mobile devices with physical controls. In Proceedings of the 32nd annual ACM conference on Human factors in computing systems . ACM, 2569–2578. DOI: http://dx.doi.org/10.1145/2556288.2557340

45. Felix Richter. 2014. Activity Tracking Is The Most-Wanted Smartwatch Feature. Web article. (9 September 2014). Retrieved July 16, 2017 from http://www.statista.com/chart/2682/ most-wanted-smartwatch-features/ .

46. Felix Richter. 2015. Smartwatches Push Past Swiss Watches for the First Time. Web article. (19 February 2015). Retrieved June 5, 2017 from http://www.statista. com/chart/4386/smartwatches-vs-swiss-watches/ .

47. Anne Roudaut, Abhijit Karnik, Markus L¨ochtefeld, and Sriram Subramanian. 2013. Morphees: toward high shape resolution in self-actuated flexible mobile devices. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems . ACM, 593–602. DOI: http://dx.doi.org/10.1145/2470654.2470738

48. Stefan Schneegass and Alexandra Voit. 2016. Gesturesleeve: Using touch sensitive fabrics for gestural input on the forearm for controlling smartwatches. In Proceedings of the 2016 ACM International Symposium on Wearable Computers . ACM, 108–115. DOI: http://dx.doi.org/10.1145/2971763.2971797

49. Carsten Schwesig, Ivan Poupyrev, and Eijiro Mori. 2004. Gummi: a bendable computer. In Proceedings of the SIGCHI conference on Human factors in computing systems . ACM, 263–270. DOI: http://dx.doi.org/10.1145/985692.985726

50. Teddy Seyed, Xing-Dong Yang, and Daniel Vogel. 2016. Doppio: A Reconfigurable Dual-Face Smartwatch for Tangible Interaction. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems . ACM, 4675–4686. DOI: http://dx.doi.org/10.1145/2858036.2858256

51. HongShik Shim, InSeo Kee, SunKook Kim, YoungTea Chun, HyukJun Kwon, YongWan Jin, SangYoon Lee, DongWon Han, JinHo Kwack, DongHun Kang, and others. 2010. 18.4: A new seamless foldable OLED display composed of multi display panels. In SID Symposium Digest of Technical Papers , Vol. 41. Wiley Online Library, 257–260.

52. Katie A Siek, Yvonne Rogers, and Kay H Connelly. 2005. Fat finger worries: how older and younger users physically interact with PDAs. In INTERACT , Vol. 5. Springer, 267–280. DOI: http://dx.doi.org/10.1007/11555261_24

53. J¨urgen Steimle, Andreas Jordt, and Pattie Maes. 2013. Flexpad: highly flexible bending interactions for projected handheld displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems . ACM, 237–246. DOI: http://dx.doi.org/10.1145/2470654.2470688

54. Miriam Sturdee and Jason Alexander. 2018. Analysis and Classification of Shape-Changing Interfaces for Design and Application-based Research. ACM Computing Surveys (CSUR) 51, 1 (2018), 2. DOI: http://dx.doi.org/10.1145/3143559

55. Dominique Tan, Maciej Kumorek, Andres A Garcia, Adam Mooney, and Derek Bekoe. 2015. Projectagami: A foldable mobile device with shape interactive applications. In Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems . ACM, 1555–1560. DOI: http://dx.doi.org/10.1145/2702613.2732801

56. Aneesh P Tarun, Peng Wang, Audrey Girouard, Paul Strohmeier, Derek Reilly, and Roel Vertegaal. 2013. PaperTab: an electronic paper computer with multiple large flexible electrophoretic displays. In CHI'13 Extended Abstracts on Human Factors in Computing Systems . ACM, 3131–3134. DOI: http://dx.doi.org/10.1145/2468356.2479628

57. Michael T Tolley, Samuel M Felton, Shuhei Miyashita, Daniel Aukes, Daniela Rus, and Robert J Wood. 2014. Self-folding origami: shape memory composites activated by uniform heating. Smart Materials and Structures 23, 9 (2014), 094006. DOI: http://dx.doi.org/10.1088/0964-1726/23/9/094006

58. Nirzaree Vadgama and J¨urgen Steimle. 2017. Flexy: Shape-Customizable, Single-Layer, Inkjet Printable Patterns for 1D and 2D Flex Sensing. In Proceedings of the Tenth International Conference on Tangible, Embedded, and Embodied Interaction . ACM, 153–162. DOI:http://dx.doi.org/10.1145/3024969.3024989

59. Wouter Van Vlaenderen, Jens Brulmans, Jo Vermeulen, and Johannes Sch¨oning. 2015. Watchme: A novel input method combining a smartwatch and bimanual interaction. In Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems . ACM, 2091–2095. DOI: http://dx.doi.org/10.1145/2702613.2732789

60. Armando Vega and Sandi Ljubic. 2015. Smartwatch as a remote server monitoring device: implementation and interaction design. In Information and Communication Technology, Electronics and Microelectronics (MIPRO), 2015 38th International Convention on . IEEE, 566–571. DOI:http://dx.doi.org/10.1109/MIPRO.2015.7160336

61. Jun-ichiro Watanabe, Arito Mochizuki, and Youichi Horry. 2008. Bookisheet: bendable device for browsing content using the metaphor of leafing through the pages. In Proceedings of the 10th international conference on Ubiquitous computing . ACM, 360–369. DOI: http://dx.doi.org/10.1145/1409635.1409684

62. Dirk Wenig, Johannes Sch¨oning, Alex Olwal, Mathias Oben, and Rainer Malaka. 2017. WatchThru: Expanding Smartwatch Displays with Mid-air Visuals and Wrist-worn Augmented Reality. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems . ACM, 716–721. DOI: http://dx.doi.org/10.1145/3025453.3025852

63. Hendrik Witt. 2007. Human-Computer Interfaces for Wearable Computers. PhD thesis (2007).

64. Robert Xiao, Gierad Laput, and Chris Harrison. 2014. Expanding the input expressivity of smartwatches with mechanical pan, twist, tilt and click. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems . ACM, 193–196. DOI: http://dx.doi.org/10.1145/2556288.2557017

65. Cheng Zhang, AbdelKareem Bedri, Gabriel Reyes, Bailey Bercik, Omer T Inan, Thad E Starner, and Gregory D Abowd. 2016. TapSkin: Recognizing On-Skin Input for Smartwatches. In Proceedings of the 2016 ACM on Interactive Surfaces and Spaces . ACM, 13–22. DOI: http://dx.doi.org/10.1145/2992154.2992187