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Citation for the original published paper (version of record):

Zhu, K., Fjeld, M., Unluer Cimen, A. (2018). WristOrigami: Exploring foldable design for multi-display smartwatch. DIS 2018 - Proceedings of the 2018 Designing Interactive Systems Conference: 1207-1218. http://dx.doi.org/10.1145/3196709.3196713

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WristOrigami: Exploring Foldable Design for Multi-Display Smartwatch

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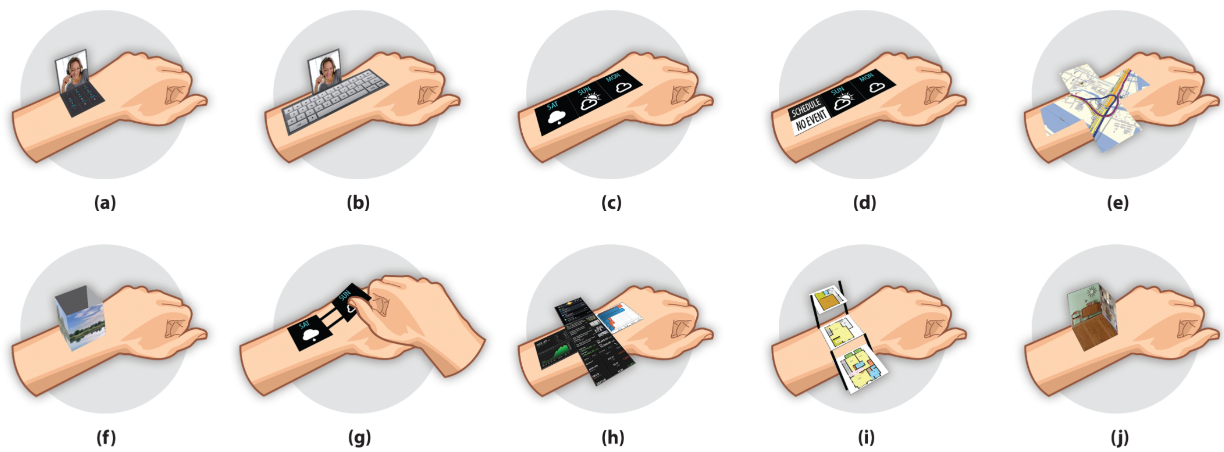


Figure 1: Illustration of WristOrigami application concepts: (a) video call; (b) a large keyboard by unfolding the lower displays; (c) weather forecast using the horizontal combination of three displays; (d) flipping the display to show daily schedule; (e) map view with fully unfolded displays; (f) panorama photo taking with a 3D cube shape; (g) elastic pulling of the display to view weather forecast; (h) multitasking with fully unfolded displays; (i) indoor view in a 3D ladder shape with different displays showing the maps of different floors; (j) VR (Virtual Reality) view with a 3D CAVE (Cave Automatic Virtual Environment) shape.

ABSTRACT
We present WristOrigami, an origami-inspired design concept and system extending the interaction with smartwatches through a foldable structure with multiple on-wrist displays. The current design provides extra affordances via folding, flipping, and elastic pulling actions on a multi-display smartwatch. To motivate the design of WristOrigami, we developed a taxonomy that could be useful for analyzing and characterizing the origami-inspired multi-display smartwatch interaction. Through a participatory-design study with a set of prototypes with different levels of fidelity, we investigated users' perception of WristOrigami in a wide range of applications with the presented features, and summarized a list of common shape configurations. We summarized our findings into seven design recommendations, to inform the future design of foldable smartwatch interactions. We further developed a set of application demonstrations as proofs-of-concept.

DIS '18, June 9–13, 2018, Hong Kong

ACM ISBN 978-1-4503-5198-0/18/0..$15.00
https://doi.org/10.1145/3196709.3196713

Author Keywords
Smartwatch; Foldable; Shape-changing Interface; Organic User Interface.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces

INTRODUCTION
The smartwatch has become increasingly popular for many tasks, such as scheduling, navigation, texting, phoning, and blockchain-based applications [45]. However, its limited display area and the inaccuracy of traditional touch devices [16], sometimes referred to as the "fat finger" problem, may constrain its interaction space. Given that the wrist is a candidate for tasks where hand-eye coordination is naturally required, extending the interaction surface on a wrist device could be a strategy concordant with user preferences. Researchers have proposed various solutions to overcome the limited interaction space of smartwatches, including coordinating interactions between smartwatch and larger interactive surfaces [17], embedding extra sensors in the watch [40], projecting/displaying onto the forearm [28],

equipping an additional and separate display [4,33], or leveraging mid-air input [6].

While previous research extended smartwatch interaction with detached space or functionality, here we present WristOrigami, an integrated on-wrist design with hinged foldable mechanisms, extending the interaction space while keeping the scale of a wristwatch. WristOrigami builds upon the concept of organic user interfaces [14], which have particularly promoted the design principles of *Function Equals Form* and *Form Follows Flow*. While these design concepts have been extensively explored at the scale of desktop- [18] and handheld devices [9], WristOrigami extends them to the emerging area of wrist-worn devices, particularly smartwatches. Inspired by the paper-folding traditions of origami, we followed the idea of cutting, opening and folding a cube with multiple joint faces into the design of WristOrigami. All faces have additional displays and sensors. Fig. 2 illustrates the fully unfolded WristOrigami as worn on the left wrist. Here we show the central (C-display) and corresponding displays at the top (T-display), bottom (B-display), left (L-display) and right (R-display) of the C-display. All faces can be fully folded into the size of a normal wristwatch, and unfolded to form a larger panel. This not only expands the interaction spaces, but also enables new interactions.

A recent trend of organic user interfaces (OUI) with a non-flat display offers a set of classifications and design principles [14] useful in our investigation, given that our work can be classified under *shaped user interfaces* guided by the design principle *form follows flow*. Applied to our work, WristOrigami can physically adapt to the context of a user's multiple activities, e.g., by taking on multiple shapes. In a more traditional sense, our work is also inspired by the accessibility and the flexibility of paper material. These qualities have motivated paper-based or paper-like interface designs such as automated paper-craft [42], paper-like shaped user interfaces [15], origami-inspired desktop-size display [18], and origami-inspired digital fabrication [26].

In this paper, we aim to address two main research questions: Q1) How could origami operations be leveraged to inspire the design of multi-display smartwatch interaction? Q2) How would users perceive the interaction with origami-inspired multi-display smartwatch? To address these questions, we constructed a taxonomy for multi-display smartwatch interaction, and used it to analyze existing work in this area. Motivated by the analysis and a user-centered design session, we developed a hinged foldable structure for multi-display smartwatch interaction. Through a series of participatory design sessions, we derived a set of WristOrigami prototypes in different fidelities probing how users might perceive and utilize this design space, and summarized seven design recommendations for foldable multi-display smartwatch interaction.

To highlight the main characteristics of WristOrigami and to demonstrate how it can help enrich people's daily

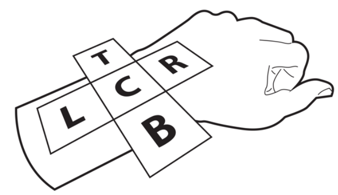


Figure 2: Layout for an unfolded WristOrigami on user's left hand: central (C), left (L), top (T), right (R), and bottom (B).

interactions with a smartwatch, we provide a hypothetical scenario derived from observations and feedback garnered in the of participatory-design sessions.

Scenario: Mary and Kate use WristOrigami to Plan a Picnic

Fig. 1 (a - g) illustrate how WristOrigami is configured, and how it can be used in scenarios such as this: Mary gets a video call from her friend Kate on her WristOrigami to check on her availability for a picnic in the nearby park this week. Mary answers the call by unfolding the fully folded device to a perpendicular shape (Fig. 1(a)), where she can see Kate while dropping notes on the lower display. She then unfolds the other two displays to form a large keyboard to type her notes more easily (Fig. 1(b)). After a short chat, Mary further transforms her WristOrigami into a shape combining three displays horizontally (Fig. 1(c)), to check the weather forecast. The weather for Saturday looks perfect, and Mary flips the left display 360^{o} (Fig. 1(d)), to show her schedule on Saturday, and they agree to picnic on Saturday. On Saturday, she decides to walk to the park and unfolds all the displays in her WristOrigami (Fig. 1(e)) to toggle the map mode showing her the route. During the picnic, Mary and Kate take a panorama photo of themselves and the park by folding the WristOrigami into a 3D cube and using the cameras on each display (Fig. 1(f)). To plan next week's outdoors activities, Mary toggles the weather mode, and pulls the right display to temporarily check the extended weather forecast (Fig. 1(g)). Fig. 1(h – j) show more applications in multitasking, 3D indoor layered map, and on-wrist CAVE VR [5].

RELATED WORK

Our work continues the evolution of academic research and commercial products jointly addressing smartwatch screen placement and smartwatch interaction techniques. The latter have grown out of formative manipulation techniques for surface computing (i.e. detachable screens [24], elastic/retractable interfaces [19, 29], and flipping/folding interaction [13]), which often predates smartwatch-related research. While much current research on handheld organic user interfaces has been strongly inspired by paper-folding, flipping/rotation is also one popular manipulation in this traditional paper art [42], and widely adapted in much OUI research. However, its use and combination with folding in mobile interaction still requires deeper investigation.

Smartwatch Interaction

Seyed et al. [33] provided a comprehensive literature review on the research of extending watch display and enhancing its input. Here we focus on how formative techniques (i.e. detachable screen, flexible interaction, and folding/flipping screen) can be applied to the context of wrist-worn devices with different display configurations.

Next-to-Wrist Interaction

While most smartwatches have been limited to a small screen on the wrist, researchers have investigated the use of the forearm and other areas next to the wrist as a larger input and output space for smartwatch interaction. Olberding et al. developed AugmentedForearm [28], a wearable system with a chain of detachable small displays, leveraging the whole forearm area for content display and interaction. Zadow et al. presented SleeD [36], a touch-sensitive sleeve display that facilitates interaction with wall-size displays. Leveraging the human skin as the flexible interface, Laput et al. developed Skin Buttons [20], using tiny projectors integrated into the smartwatch to render icons on the user's skin, and tracking the on-skin smartwatch interaction.

On-Wrist Interaction with Mobile Phones

A larger interactive surface is another alternative to extend the interaction space of a smartwatch. Duet [33] is an interactive system that "*explores a design space of interactions between a smart phone and a smartwatch*". This device combination turns the watch into an active element enhancing multiple phone-based interactive tasks. Duet also presents a new class of multi-device gestures and sensing techniques. Blasko et al. [2] introduced flexible interaction with a retractable elastic string for dual-display mobile devices. In our research, we did not specifically focus on cross-device interaction. Instead, our results provided important design insights for cross-display on-wrist interaction with multiple congruent screens.

On-Wrist Interaction with Separated Small Displays

While the small screen of a smartwatch can be extended to other parts of the user's body or a larger display surface, researchers also investigated enhancing the interaction space with extra modules directly on the wrist. Weigel et al. developed iSkin [38], a thin, flexible, stretchable, and visually customizable modular touch sensor that can be worn directly on the skin. One of its applications is to be attached to a smartwatch as an input device for the small screen. Recently, Seyed et al. developed Doppio [33], a reconfigurable smartwatch with two display faces: one worn on the wrist; the other separated from or attached on the wrist display. The authors also defined and enumerated possible configurations and manipulations for Doppio, including hinged folding, rotating, and stacking. The proof-of-concept system demonstrated the application of Doppio in various tasks. While our research on WristOrigami was directly inspired by Doppio, WristOrigami distinguishes itself by integrating all the extended displays into one complete device on the wrist, as well as supporting both folding and flipping actions.

On-Wrist Interaction with Integrated Small Displays

Compared to the research that augmented the smartwatch space with separate, small displays, there have been more companies and academic researchers focused on developing new complete/integrated on-wrist watch-like devices with more interaction space. In 2008, Nokia released the concept mobile phone Nokia Morph [27] which can be bent into numerous shapes. Based on a similar concept, Lenovo released the flexible CPlus concept phone [21], a conceptual smartphone that can be bent into the shape of a smartwatch worn on the wrist. By integrating multiple modular displays, Lyons et al. developed Facet [23]; a multi-display wrist-worn system consisting of multiple independent touch-sensitive segments joined into a bracelet, and proposed a set of interactive techniques for separated on-wrist content display. Xiao et al. [40] implemented the tilting interaction with integrated sensors in the smartwatch.

WristOrigami falls into this theme of designing an integrated wrist-worn device with multiple modular displays. More importantly, it stands out by supporting multiple manipulation techniques simultaneously, enabling 2D and 3D shape formation on the wrist. This distinguishes WristOrigami from most published research on integrated multi-display wrist devices, which focus on the fixed 2D configuration for each display module. We also investigated user perception of WristOrigami use, and generated insights into designing origami-inspired foldable on-wrist interaction.

TAXONOMY OF MULTI-DISPLAY ON-WRIST INTERACTION

To analyze and compare our work with existing research, we identified the multi-dimensional taxonomy for classifying multi-display on-wrist interaction, based on the features of previous multi-display wrist-worn devices and the analytical taxonomies used in existing participatory-design studies [39]. As listed in the first column of Table 1, the first dimension is the shape of the device for each designed interaction, which could be 2D or 3D. The next five dimensions involve the use of the five displays, the central square display and the surrounding displays. The four following properties are defined by the use of the supported features in the user-defined interaction, including folding, flipping, elastic pulling, and multi-touch. The following dimension is the display style of the contents, which can either be separated on each display or collated across multiple displays. The next dimension is the interaction style in multi-display on-wrist interaction, which includes within-display interaction, single display controlling single (one-to-one) or multiple other screens (one-to-many), and multiple displays controlling one display (many-to-one).

To demonstrate the applicability of the presented taxonomy, we used it to systematically categorize and compare the capabilities and limitations of previous work on multi-display on-wrist interaction (Table 1, [21, 23, 27, 33, 38, 40]). Dotted lines indicate that the system can only process a single design option at a time; solid lines indicate multiple design options can co-exist in one particular dimension.

Design Dimensions and Options		Design Cases						
Shape	2D	①	②	③	④	⑤	⑥	⑦
	3D							⑦
Usage of display	C-display	①	②	③	④	⑤	⑥	⑦
	T-display		②		④	⑤	⑥	⑦
	B-display		②		④	⑤	⑥	⑦
	L-display	①			④			⑦
	R-display	①			④			⑦
Display style	Separated display	①	②	③	④			⑦
	Collated display		②		④	⑤	⑥	⑦
Feature	Folding		②		④	⑤	⑥	⑦
	Flipping				④			⑦
	Elastic pulling							⑦
	Touch	①	②	③	④	⑤	⑥	⑦
Interaction style	Within-display				④	⑤	⑥	⑦
	One-to-one	①	②	③	④			⑦
	One-to-many							⑦
	Many-to-one							⑦

① iSkin [38]
② Facet [23]
③ Xiao et al. [40]
④ Doppio [33]
⑤ Nokia Morph [27]
⑥ Lenovo CPlus [21]
⑦ WristOrigami

Table 1: Taxonomy of multi-display on-wrist interaction, here used to juxtapose and contrast seven design cases: compared with alternative systems (1 - 6), WristOrigami (7) supports a larger range of movements. (dotted-line connection: the system can only process a single design option at a time; solid-line connection: multiple design options can co-exist under one particular dimension.

Going over Table 1, we find all the existing work explored 2D shape formation only, while the form factor of multi-display foldable wrist-worn device could support the folding manipulation to form 3D shapes. Secondly, most of the existing work [21, 23, 27, 38, 40] did not fully leverage the input/output space around the center display, while Doppio [33] could not support all the peripheral displays simultaneously. Aiming to leverage these unexplored affordances, we designed WristOrigami, which falls into this theme of designing an integrated wrist-worn device with multiple modular displays. At the same time, it stands out by supporting multiple manipulation techniques simultaneously (i.e. fulfilling more features in Table 1), enabling 2D and 3D shape formation on the wrist as shown in Fig. 1. This distinguishes WristOrigami from most published research on integrated multi-display wrist devices, which focus on the fixed 2D configuration per display module. We also investigated user perception of WristOrigami usability, and generated insights into designing origami-inspired on-wrist interaction.

FOLDABLE STRUCTURE DESIGN

The mechanical structure of WristOrigami was strongly inspired by the paper-folding manipulation, which has also inspired various industries, including packaging, defence, and aerospace engineering. More specifically, the designs of solar panels and space telescopes have adopted the form of origami to fold a large panel into a small volume, which can fit into a compact space. Here we see the on-wrist interaction

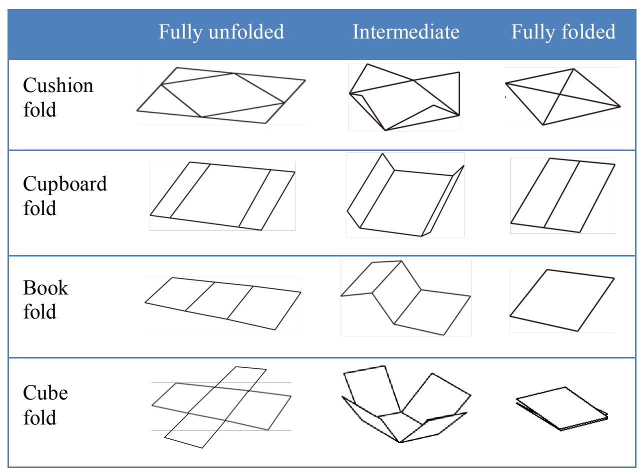


Figure 3: Four primitive paper-folding patterns.

space as a compact space which can benefit from origami-inspired design. It appears that both (finite) folding and (infinite) flipping play significant roles in origami practice; both have inspired our work. While origami could easily involve complex combinations of folding and flipping, we identified four primitive patterns from the literature related to paper folding [43], as shown in Fig. 3.

Prior to the current implementation of WristOrigami, we conducted three focus-group discussions with nine smartwatch users (two females, averagely aging 27.3 years old), three users per group, to investigate the feasibility of different paper-folding patterns (Fig. 3 (a - d)) as the form factor of wrist-worn device. The focus-group discussion was facilitated by one researcher, and lasted one hour. The facilitator first introduced the paper-based structural prototypes of the four wrist-worn origami primitive patterns. In these paper-based prototypes, the side panels are connected to the center panel (1.5 inch on the diagonal) by rotary hinges and rubber strings, giving the flexibility of folding the displays on the sides into the center. Users can thus fully fold the structure into the size of a standard square-shape smartwatch, and expand the display and the interaction space by unfolding different combinations of the displays. In addition, considering the capability of displaying when folded and to reduce the thickness of the display panels, we designed the mechanism of the flipping hinge at the middle of the side display panel, allowing the flip operation to show the display while folded. The flipping operation was also inspired by conventional watch design with multiple faces [30, 31], which leverage flipping to switch the watch panel.

We then instructed the participants to imagine these were the fully-functioning on-wrist smart devices which contain touch-sensitive displays and built-in sensors (e.g. accelerometer, gyroscope, GPS, etc.) on each panel. The participants were then asked to freely manipulate the prototypes on the wrist, rank the four prototypes of origami-based wrist-worn foldable devices based on their preference, and elaborate the rationale behind their ranking.

According to the focus-group discussions, the pattern of cube fold (Fig. 3 (d)) was ranked in the first place for the shape of multi-display foldable smartwatch. The participants of the focus-group discussions commented the advantages of cube fold as “enabling layered display”, “supporting 2D and 3D combinations of panels that can be easily mapped to different applications”, “enabling separated content display”, “larger input and output space” and “offer more possibility of manipulation”.

Based on the participants' feedbacks in the focus group discussion, we developed the first low-fidelity prototype of WristOrigami as shown in Fig. 4. WristOrigami provides common features available in current smartwatches, such as multi-touch and communication with other devices. Inspired by the previous design recommendations for foldable handheld multi-display devices [9] and the design considerations for dual-face smartwatches [33], we also included a set of new features based on the designed affordances in WristOrigami, such as folding, flipping, and elastic pulling. Firstly, the device can sense the folding and the flipping operations of all side displays, and has sensors for detecting the angle, direction, and speed of movement. Secondly, the rotary hinges on the side displays are attached to the C-display by magnets, allowing the side display to be detached. In addition, we designed an elastic string-based connection between each side display and the C-display to ensure all displays are integrated into the whole, and that the side display cannot be completely detached and act as a separate device. Along with this structure, we designed elastic pulling as an interaction feature to sense the detachment of the side displays.

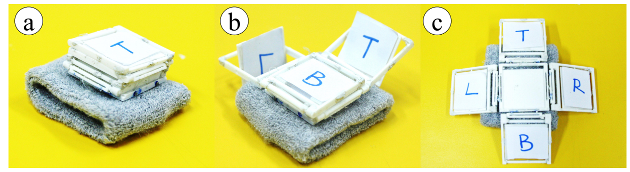


Figure 4: Three different folded/unfolded stages of the 3D-printed WristOrigami model: (a) fully folded, (b) two displays unfolded and flipped, (c) all displays unfolded. The panels with written letters indicate the side displays.

While the preliminary focus-group discussions revealed the the importance of form factors of WristOrigami on user preference, it is unknown how users would perceive the usage of the cube-fold shape in different smartwatch applications, including context and input and output features. To address this question, we adopted the participatory-design/elicitation-based method, which has been used to understand users' mental model towards new interfaces [39].

PARTICIPATORY-DESIGN STUDY

We ran a number of open-ended, user-elicitated design sessions to examine display configurations and functionalities preferred by users, and to investigate possible user motivations and perceptions for WristOrigami.

Participants

There were twenty participants (indexed P1-P20; 8 males and 12 females; all right-haned; 5 Caucasian and 15 Chinese) from diverse backgrounds were recruited for our study. 17 were university students from different disciplines: computer science and electrical engineering (8), civil engineering (1), biology (2), business & management (4), and public policy (2), while three were working professionals from different industries: pharmacy (2), and public health (1). Participants had various degrees, ranging from undergraduate (15), master (4), and PhD (1)). The average age was 22.95 years (SD=0.72). Five participants were smartwatch owners for more than 6-months.

Apparatus

In order to provide economic yet sufficient fidelity in the design apparatus, we adopted McCurdy's research suggestion on the combination of low-fidelity and high-fidelity prototypes as a good predictor of eventual user performance and perception with the final application in the participatory design process [44]. We developed three prototypes of WristOrigami at different levels of realization, including a 3D-printed model without any interactive features, a screen-free interactive prototype with accelerometers attached on the backs of all displays but without any screen in a 3D-printed model, and a fully interactive prototype with capcative touch screens, accelerometers, and OLED screens integrated into a 3D-printed model (Fig. 5).

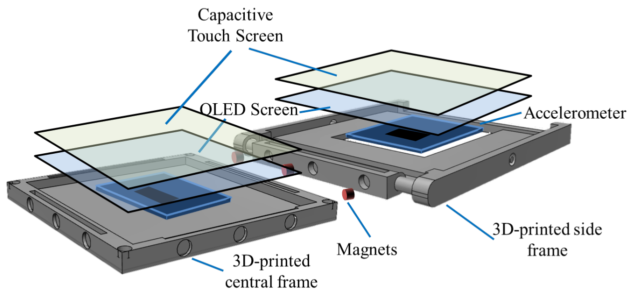


Figure 5: Assembly of fully interactive prototype.

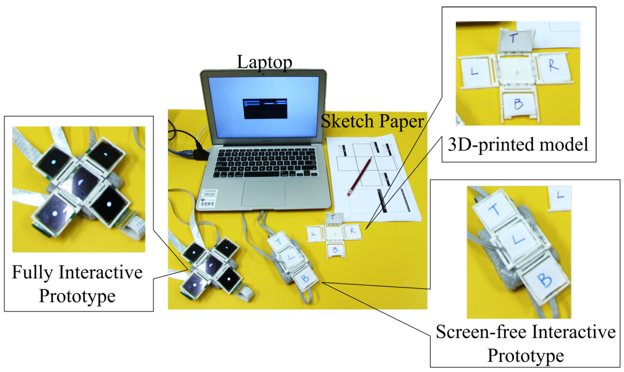


Figure 6: Setup of the user-elicitation design session.

During each design session, the participant was provided with these three prototypes (Fig. 6). The OLED screens only showed circles, to avoid any bias. The two interactive prototypes were connected to a laptop which recorded the sensor data. The purpose of presenting three different prototypes was to clearly explain the shape and the concept of the end-product WristOrigami with the 3D-printed model, and to stimulate the ideation and the future uses with the interactive prototypes. We also provided paper, pencil, and erasers to facilitate the ideation process.

Task

Each design session included one participant and one moderator. Participants were asked to design potential applications for WristOrigami by sketching display content and writing a brief description of the application and the interaction procedure, while wearing the screen-free interactive protoype on their left wrists. Each participant was asked to design at least 10 applications within one hour, given the form factor and affordances of WristOrigami. During the design session, the participant could freely manipulate all the prototypes presented, including the one worn on the wrist and the other two on the table. To understand the applications and context where users would use WristOrigami, we did not fix the type of application as a controlled factor. Instead, the participant could freely propose any application he/she would like to use WristOrigami for. Furthermore, the participant could end the session at any time if he/she had run out of ideas.

Procedure

Twenty 90-minute design sessions were conducted in an open-space classroom in a design school of a university, with the following five steps:

1) Introduction (~5 mins). The moderator introduced the purpose of the study, and the participant finished the prequestionnaire to provide their demographic information and previous knowledge on smartwatches;

2) Warm-up (~6 mins). Inspired by the concept of priming effects [25], we had the participant carry out a *paper folding test* (Vz-2-BRACE) [7]. The purpose of this was to prepare them for paper-folding manipulations;

3) Introduction to WristOrigami (~10 mins). The moderator introduced the concept of WristOrigami and demonstrate the feasible affordances and functionalities;

4) User-elicitated Design (~1 hour). A design session was held in which the participant designed as many applications with WristOrigami, with a minimum of 10 designs/participant, and described the design in detail with the think-out-aloud protocol;

In case participants were stuck for longer than one minute and considered giving up on reaching 10 interactions, they were briefly shown some potential ideas (as shown in the supplementary image) to trigger own designs.

5) Summary and debriefing (~10 mins). Upon finishing all designs, the participants were asked to choose their top three favorite and least favorite designs, and provide brief rationales for their choices.

After these five steps, the participant finished a post-questionnaire to review his/her experience with foldable multi-display smartwatches (ease of learning/usage and comfort of use). Each participant received a USD10 shopping voucher.

Analysis

The twenty design sessions generated a total of 192 designs (Max = 10, Min = 8, Median = 10), 15 of which were generated after the participants referred to the supplementary image. Two independent coders assigned values of the taxonomy to every application designed by the participants. They first coded data from three participants and compared results to remove possible differences in interpretation. They then proceeded to code all the rest of the data. We used Cohen's Kappa statistic to determine the consistency of ratings given by the two coders. The two coders achieved almost perfect agreement over 192 user-designed WristOrigami applications, with a Cohen's Kappa score of 0.81 ($p<0.01$). A third coder resolved the disagreement between the two coders.

RESULTS

In this session, we present findings on user perception of WristOrigami from the data collected during the participatory-design study, with a focus on affordance and interaction. Results are presented by taxonomic breakdown followed by statistical analyses, including an illustration of user-defined shapes.

Taxonomic Breakdown

We found that the taxonomy in Table 1 could appropriately summarize the nature of the user-defined WristOrigami

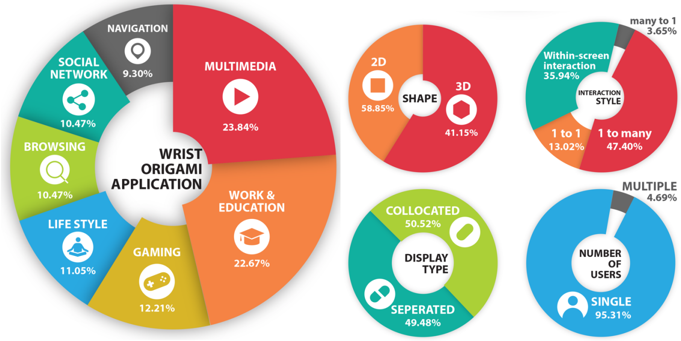


Figure 7: Taxonomic breakdown of user-defined WristOrigami applications.

applications. Fig. 7 shows the breakdown of these user-defined applications according to the taxonomic dimensions of application type, shape, display style, interaction style, and number of users.

One application can involve multiple displays, forming the various configurations. In the coding process, we treated the displays folded above the central panel as the usage of C-displays, regardless of the order of folding and stacking. Fig. 8 shows a heat map to illustrate the usage of each display when the device was worn on the left hand. The most frequently-used display in user-defined applications (95.83%) used the C-display; in contrast, the B-display was used in only 71.88% of the same applications. Similar to display usage, multiple interaction techniques can be involved in one application. Fig. 9 shows that touch was used in 64.06% of the elicitated applications. Both flipping and pulling were required in less than 10% of the applications.

While the taxonomy clearly shows the distribution of the user-defined applications across different dimensions, a series of design questions could be investigated more deeply to generate insights for designing WristOrigami applications. How did the shape, display style, interaction modes and the type of application affect each other? How were different displays and interaction techniques used across different designs? We will present the statistical analysis as follow, aiming to address these questions.

Statistical Results

Shape vs Application

The Pearson Chi-Square Test indicated a significant dependent relationship between the type of the application and the shape of the device ($\chi^2_{(6,\ N=192)} = 14.19$, $p < 0.05$, Cramer's V = 0.271). In particular, 60% of multimedia applications were linked to more 3D WristOrigami shapes. For instance, the 3D-cube shape formed by four displays folded upwards was used by nine participants for 3D content display, including taking/viewing panorama photos and videos with the assumption that each display contains a camera. VR exploration was another typical application (as shown in Fig. 1(j), having common points with CAVE VR [5]) on the wrist. Another interesting example of 3D shapes

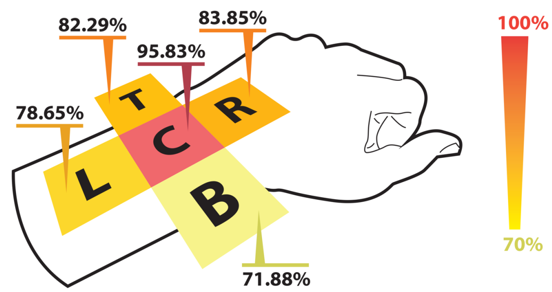


Figure 8: Usage of display: percentages of applications that involved a particular display.

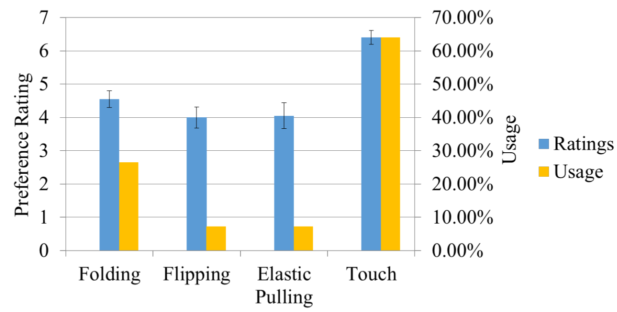


Figure 9: Users' subjective rating of interactive features and usage of feature (percentages of applications that involved a particular feature).

is the ladder shape (Fig. 1(i)) presenting a smartwatch version of lens-enabling layered map information, similar to metaDESK [35]. For the applications often involving multitasking (e.g. life style, work & education, social network, and navigation), 2D shapes were predominant. For example, we observed eight designs for group chatting, where each chat thread is shown on different displays, five for checking time while scheduling events on a calendar, five for note-taking while viewing online lectures and communicating with classmates online, and three for navigation with different map views and a compass. Fig. 10 shows the common shapes produced by participants across different applications and display styles.

Display Style vs Application

The display style also differed significantly by application type (Pearson Chi-Square Test: $\chi^2_{(6,\ N=192)} = 22.67$, $p < 0.001$, Cramer's V = 0.344). Specifically, the collated display style was more associated with applications for multimedia, browsing, gaming and navigation, which involved a large amount of visual content. On average more than 65% of these applications (i.e. multimedia, gaming, browsing, and navigation) adopted the collated display style. For instance, webpages, video, photo, and maps were often displayed by combining multiple displays into one large full-screen display. The separated display style was used more in applications for work & education, social network, and life style. These applications often involved showing multiple dimensions of information or multitasking in different

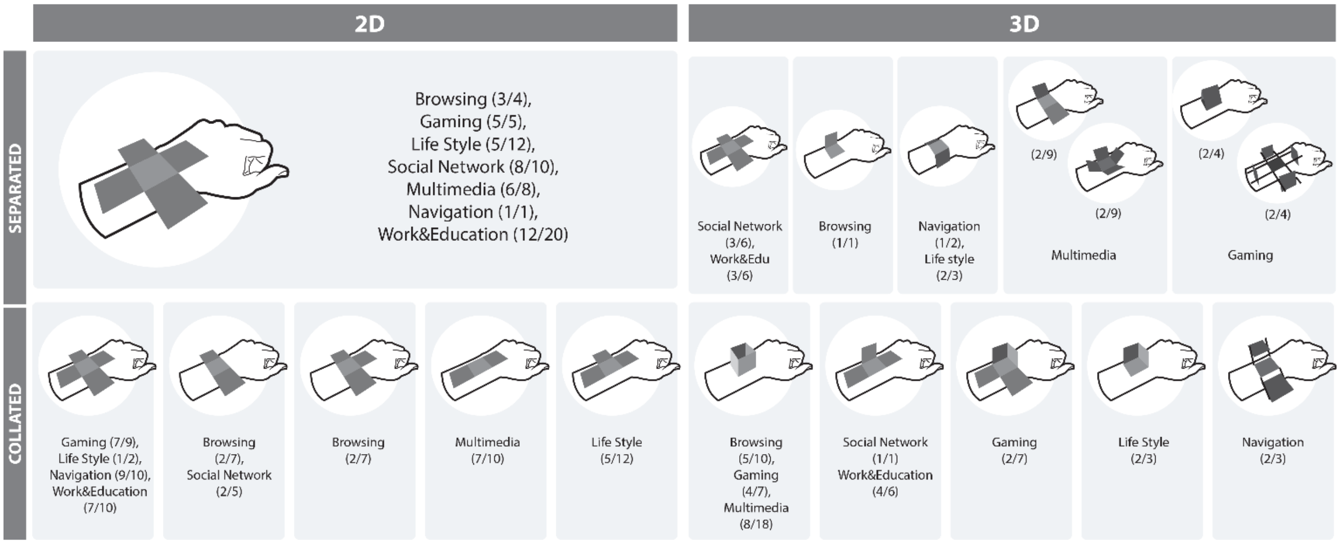


Figure 10: Illustration of user-defined WristOrigami configurations by display style, by shape, and for each cell, by type of application. Numbers (x/y) indicate number of times a configuration appeared in one particular combination of display style, shape, and type of application. For example, "Gaming (7/9)" in the first gray cell of the second row means that the configuration of four fully-unfolded displays appeared 7 times in a total of nine 2D shapes using the collated display style for gaming applications.

displays, such as showing different health indicators, displaying the current time in different cities, chatting with different people simultaneously, and taking notes while having an online group meeting/lecture.

Use of Displays

The C-display was widely used across all user-defined interactions. The Pearson Chi-square Test suggested that the L-display was significantly more likely to be used in the collated display style than the separated display style ($\chi^2_{(1, N=192)} = 6.59$, $p < 0.01$, Cramer's V = 0.185). The same was true for the R-display ($\chi^2_{(1, N=192)} = 8.29$, $p < 0.005$, Cramer's V = 0.208). This could be related to the result that the separated display style involved within-display interaction significantly more than the collated display style (Fisher's Exact Test: $p < 0.001$, Cramer's V = 0.310). Additionally, six participants (P2, P5, P6, P11, P19, P20) commented that it was difficult to manipulate the L-display with their right hands only while wearing WristOrigami on their left hands.

The shape of the device could also affect the usage of the display. A Pearson Chi-square Test showed that the T-display was significantly more used in 3D shapes than 2D shapes ($\chi^2_{(1, N=192)} = 7.21$, $p < 0.05$, Cramer's V = 0.194), with all 3D shapes using the T-display. When an application used a collated display style, the R-display was more likely to be used than the other displays. Fisher's Exact Test ($p < 0.01$, Cramer's V = 0.305) showed that the R-display was significantly more used in applications for multimedia, browsing, gaming, and navigation, which tended to be more visually intensive and yield more collated formats.

Usage of Interaction Features

One-way ANOVA ($F_{(3, N=192)} = 53.20$, $p < 0.001$, $\eta^2 = 0.53$) showed that touch input was significantly more used in all user-designed applications than the other interaction features, and that folding was used more significantly than flipping and elastic pulling. Nonetheless, even if the formative features (i.e. folding, flipping, and elastic pulling) were less used, we observed different usage patterns for these features. We observed a total of 14 usages of flipping, four of which flip the display 360º to change content without affecting other displays, i.e., five for changing the map view, three for changing the shopping items, two for changing the browsing pages, and four for game control.

We observed a different usage pattern for folding. Within the 51 usages of folding, 24 were used in the collated format to control the overall content across different displays, including camera panning/zooming (9), fast forward/backward for video (6), previous/next viewing items (5), and adjusting display parameters (4, e.g. brightness, contrast, etc.). The elastic pulling had the same number of usages as flipping (14), and it was mostly related to quick actions, such as capturing screen (4), shooting in games (5), and sending messages (5). Fig. 9 shows overall user preferences for different interaction features indicated in the post-workshop questionnaire. One-way ANOVA ($F_{(3, N=192)} = 18.25$, $p < 0.005$, $\eta^2 = 0.19$) suggested that the touch was significantly preferred over other interaction features. As stated by all participants, they are more familiar with this input method. P10 commented, "*It is easier to touch than fold with only one hand*". While it is difficult to statistically analyze the formative features (folding, flipping, and pulling) individually due to their imited numbers of usages, participants (8/20) who used these features commented that it was fun to use these features, and that "*they are similar to daily paper-craft manipulations, such as page flipping and folding*" [P5]. In addition, this group of participants rated these features higher than those who did not use them.

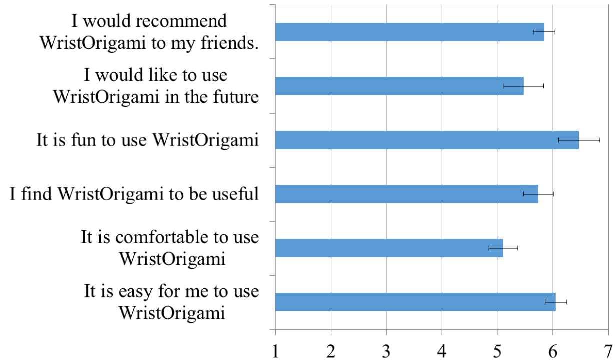


Figure 11: Results of post-session questionnaire.

Ease-to-learn/use, Comfort-of-Use, and Preference

Fig. 11 shows the participants' ratings on their experience of using WristOrigami, including ease of learning, ease of use, comfort of use, and future preferences. All of the questionnaire statements had an overall average of more than 5 out of 7 on the Likert scale. The lowest rating was linked to comfort (Mean: 5.2, SD: 0.37), and some participants commented that it was not natural to manipulate the L-display with single hand.

DESIGN RECOMMENDATIONS (R1-R7)

We summarized the above findings (i.e. taxonomic breakdown, statistical analysis, and users' comments) into a set of design recommendations for foldable multi-display smartwatch interaction (R1-R7):

R1: Based on the statistically significant association between the display style and the type of the application, we recommend toggling the collated full-screen display style for visually-intensive multimedia contents such as videos, games, and maps, where the shape of the device is a function of how all displays are combined.

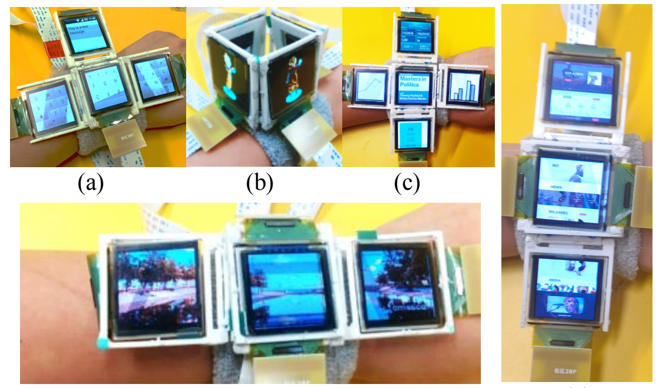
R2: Based on the statistical results on the relationship between the interaction style and the usage of the input features, we suggest using folding for changing the view of the content in other displays, and flipping for the changing the display content in the same display. For example, folding can be used for panning the camera while viewing panorama photos, while flipping can be used for changing between the weather forecast and the schedule for the day.

Based on our analysis of users' feedback on the display content, such as preferring customizable contents on different displays, and their concern regarding single-hand operation, we derived the following two design recommendations (R3, R4):

R3: Provide user customization for the content shown on different displays when the separated display style is used.

R4: Consider the side of the watch hand when using the folding/flipping/pulling features. For example, it is easier to fold/flip/pull the R-display than the L-display while wearing the watch on the left wrist and operating with the right hand.

As we observed that WristOrigami stands out by supporting 3D-shape formation, we distilled the final three recommendations (R5 – R7) based on the analysis of 3D-shape applications:



(a) (b) (c) (d) (e)

Figure 12: Examples of WristOrigami applications: (a) keyboard, (b) cube, (c) multitasking, (d) panorama view, (e) vertical webpage browsing. Flat ribbon cables connect to a microcontroller communicating with a host computer. In a marketable version, all components could be intergraded into the form-factor of a smartwatch.

R5: Consider the smart-watch applications containing the graphical-user-interface elements, such as buttons and keyboards, for the function presented in the B-display/the combination of lower displays.

R6: Consider showing a 3D view of the content when users fold the device into a 3D cube shape.

R7: Consider showing layered/leveled information (e.g. indoor navigation in a building) when users fold the device into a 3D ladder shape.

We note that our R5 and R6 are aligned with Gomes' and Vertegaal's guidelines (5) and (7) for handheld foldable devices [9], indicating that these guidelines can be adapted for both handheld and wrist-worn devices. On the other hand, R1 to R4 and R7 are unique to the focus of our work on multi-display foldable smartwatch interaction.

APPLICATION DEMONSTRATION

To demonstrate the design recommendations, we built five applications to show how different design characteristics and affordances can be applied.

Keyboard: Fig. 12(a) shows a larger keyboard than the current design in smartwatches. The B-display is folded and stacked on the C-display, forming a large keyboard with the L-display, and the R-display in the collated display style. Gomes et al.'s design guidelines for foldable display devices [9] suggested showing a keyboard on the lowest display when the device is folded into a perpendicular shape. Our participatory-design study revealed that users tended to adapt a similar metaphor for the wrist-worn devices. As commented by most participants (except P2, P4, and P10 who did not explicitly state the details), the enlarged keyboard across the displays can increase the typing accuracy in smartwatches, and might be a solution to the "fat finger" problem.

Wrist Stereo Display: The most observed 3D shape during the participatory-design study was the cube with four side-displays folded up perpendicularly to the C-display. This mode has been proposed for panorama image/video taking and viewing, and 3D virtual-reality content display. Fig. 12(b) shows the proof-of-concept implementation for a stereo display on the wrist, with each side-display showing a 3D view of the virtual object. One potential application in the future could be teleconferencing on the wrist. This application also suggests that the previous design guideline of showing 3D view with 3D hull shapes can be transferred to wrist-worn devices.

Multitasking: Fig. 12(c) shows an example of multitasking with WristOrigami for financial officers. While the stock market involves multi-dimensional information, a user can fully access this information and leverage the multiple displays in WristOrigami by showing different information such as curves, news, and international market activity separately in different displays.

Multimedia viewer: Combining the L-display, C-display, and R-display (Fig. 12(d)), landscape images/videos can be shown in WristOrigami in the collated display style. In addition, our participants also proposed the application of viewing 360^{o} videos, with the folding manipulation of the side-displays to pan the camera.

Web browser: The webpage can be displayed across three vertically collated displays (Fig. 12(e)), forming a large display with a height comparable to standard smartphone displays. This could facilitate an easy transition of the waterfall-style webpage design from smartphone usage to smartwatch interface.

DISCUSSION AND FUTURE WORK

In this section, we discuss limitations of our work and suggest future research to better explore shape-changing wrist-worn interfaces.

Shape Manipulation with Single Hand

During the study, we observed most participants had difficulties in manipulating the display tiles with a single hand, especially for the L-display when the device is worn on the left wrist. Furthermore, some participants suggested implementing the mechanism of automatic shape actuation to reduce the demands of forming shapes with one hand. In addition, we did not specify the order of folding in the current WristOrigami design, which was a question posed by some participants. As the next step, we will investigate new designs of WristOrigami with automatic actuation, involving spring-based mechanical designs and smart shape-changing materials [22]. While the displays in the current WristOrigami design were divided by the mechanical parts, we believe that it will be feasible to minimize these physical gaps with the advancement of smart material technology, achieving seamless cross-display interaction (e.g. swiping).

Evaluation in Different Contexts

Due to the requirement of wire connections in the current interactive prototype, the participatory-design study was conducted with only one participant at a time sitting in an indoor environment, while the participants were encouraged to brainstorm on possible applications of WristOrigami in different contexts. However, we observed only limited cases of applications that involved multiple users, which could be due to the study design. As smartwatches are designed for different levels of mobility, we still need to investigate and compare how users would interact with shape-changing wrist-worn devices in different contexts, such as indoors, outdoors, still, moving, single user, and multiple users.

CONCLUSION

In conclusion, we presented WristOrigami, an origami-inspired concept and prototype for foldable multi-display smartwatches. WristOrigami extends the display and the interaction space of the current smartwatch design, and demonstrates how the simultaneous availability of extra shape-changing affordances could support new interactions with multi-display smartwatches. We conclude that based on early user feedback, origami-inspired, hinged foldable structures for multi-display smartwatch interaction justified further effort. A participatory-design study showed that users adapt different shapes in different contexts according to the form follows flow principle. A set of design recommendations (R1-R7) derived from our findings could be used as a preliminary and ready-to-use framework for designing origami-inspired, foldable, multi-display smartwatch interaction. Our research presents an important and necessary step towards future product-oriented work on foldable wearable devices.

ACKNOWLEDGEMENT

This work was partially supported by grants from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. CityU 21200216), City University of Hong Kong (Project No. 7005021), ACIM-SCM, and the Wallenberg AI, Autonomous Systems and Software Program (WASP) funded by the Knut and Alice Wallenberg Foundation. We appreciate the language consultation by Maria Pamela Dobay, Erik Tobin, and Philippa Beckman.

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