Effects of Display Sizes on a Scrolling Task using a Cylindrical Smartwatch

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Abstract
With a growing interest in wrist-worn devices, research has typically focused on expanding the available interaction area for smartwatches. In this paper, we instead investigate how different display sizes influence task performance, while maintaining a consistent input area. We conducted an experiment in which users completed a scrolling task using a small display, a large display, and a cylindrical display wrapped around the wrist. We found that the large and cylindrical displays resulted in faster task performances than the small display. We also found that the cylindrical display removed constraints on the participants' body pose, suggesting that cylindrical displays have unique benefits for mobile interactions.

Author Keywords
Wearable Computing; Smart Watches; Display Size; Flexible Displays; DisplaySkin; Organic User Interfaces.

ACM Classification Keywords
H.5.2. Information interfaces and presentation.

Introduction
Over the last few years there has been a growing interest in wrist-worn devices, a movement seen in both the research of novel wearable computers [3,6,7,9,12,13] and in the positive reception of smart-

Figure 1: Wrist-worn device prototype.

Left: Small display
Center: Large display
Right: Cylindrical display

watches by Pebble, Samsung, and Apple. Emerging deformable technologies such as flexible displays, batteries, and circuits can enable innovative form factors for wrist-worn devices. Despite these advances, most currently available smart-watches follow the design of conventional watches: a small display attached to the wrist by a flexible strap. This design has largely gone unquestioned in the past hundred years [1].

The physical limitations of the traditional wrist-watch layout also limit the range of potential interactions. For example, a small display has a reduced area for touch input and is especially susceptible to occlusion. There is a large body of research investigating this issue. One approach decouples the interaction space from the display. Some of these explorations extend the interaction area by embedding a touch sensor directly into the wristband [9], while others do this by detecting a finger's position in the space above and around the watch face [3]. These types of systems facilitate precise and expressive input without increasing the size of the display.

A different sort of question remains: if the restrictions that led to these solutions could be lifted, could a larger display improve interaction even further? In response, we created a wrist-worn device with a large, touch-enabled cylindrical display [2] (Figure 1), which allowed us to investigate the effects of different display sizes. We asked: if the interaction space is kept constant, does a larger display support more efficient or new styles of interactions?

In this paper, we report on an experiment where participants performed a scrolling task on DisplaySkin [2], a prototype interactive wristband. To understand the effects of display size, we varied the active display area, while keeping the input method constant. We also present our observations of user behavior and strategies, as these were affected by display size.

Related Work

Prior work has explored some alternative display sizes and configurations. With Augmented Forearm, Olberding et al. [8] built a prototype wearable consisting of a series of small displays placed along the arm. They diverged from traditional wristwatch conventions, investigating a design space where displays are an extension of the body—an area also studied in projects like Armura [4]. Lyons et al. [6] demonstrated a cylindrical wrist-worn device made of segmented displays, each with separate functionality. Tarun et al. [11] presented Snaplet, a shape-changing wristband. When a user removes Snaplet from their wrist, its flexible E Paper display can be shaped into a tablet or a phone, depending on its context.

Other work has looked at the topic of expanding the interaction space of wrist-worn devices; they are, in part, attempting to overcome the constraints of interacting with small displays. With Abracadabra, Harrison et al. [3] added gestural input in the space above and around the watch. Oakley and Lee [7] and Perrault et al. [9] have similar approaches. They used the edges of a smart-watch and the wristband as touch surfaces, respectively.

In regard to novel display techniques, Xu and Lyons [13] explored different styles of glance based interactions by integrating LED indicators into a watchface. We previously presented DisplaySkin [2], a cylindrical E Paper device, to introduce the concept of a pose-aware display: one that orients content towards a user's face based on their body pose.

Apparatus

Our experimental device consists of a DisplaySkin [2], a 7" Plastic Logic Flexible E Paper Display wrapped around the user's wrist, forming a cylindrical shape (Figure 1). The display has a resolution of 354 by 944 pixels and is controlled by Flexkit [5] to run at 12.5 fps. The device is augmented with an infrared touch sensor that can detect both swipes and discrete taps along the circumference of the cylindrical display [10]. The touch sensor can detect touches with a precision of 3 mm, a sufficient amount of precision for our target size.

Experiment

Task

Our task is similar to the experiment performed by Perrault et al. [9]. Participants were presented with a scrollable list of 184 countries, listed alphabetically. In each trial, an external display prompted the participants with the name of a country and asked them to find it within the list on the wristband. In all conditions, participants used relative touch scrolling with inertia to navigate the list. Once the target item was visible, they tapped it to complete the trial. The task is reminiscent of scrolling through a list of applications on a Pebble or Android Wear devices.

Display Size

We simulated three display sizes using different viewports on the E Paper screen (Figure 2). The small display was a 1.5" rectangle on the top of the wrist, similar to standard smart watches and the display used by Perrault et al. [9]. The large display consisted of a 3.5" rectangle that started at the top of the wrist and covered the visible area of the display, as viewed from above. The cylindrical display condition spanned the entire surface of the prototype.

Input Area

Although the viewport size varied between trials, participants were free to navigate using the entire touch surface of the display for all conditions. In other words, the available input area remained constant throughout all conditions. This setup ensured that the measurable effect is a consequence of the display size and not confounded by different input methods.

Target Distance
We used 4 target distances, a subset of those evaluated by Perrault et al. [9]: 5 items, 20 items, 80 items, and 160 items. Each item had a height of ~1 cm. In the small display condition, the 5th item is not visible at the start of the trial. It is, however, immediately visible in the large and cylindrical conditions.

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

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

Questionnaires
We asked participants three questions, to rate each display size if it was: efficient for searching, allowed an overview of data, and useful for bimanual interactions. Each question was structured using a 5-point Likert scale of agreement (1: Strongly Disagree-5: Strongly Agree).

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

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

Results

Experiment Results
We analyzed the collected measures by performing a repeated measures ANOVA using *display size* (3) x *target distance* (4) on navigation time. Table 1 outlines the means and standard errors for list navigation time.

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

Questionnaire Results
Table 2 summarizes the median scores of the questionnaire responses. We analyzed the data using a Friedman's one-way ANOVA by Ranks on the

Small	Large	Cylinder
The display enabled bimanual interaction		
2	3	4
The display supported task efficiency		
2	4	4
The display provided an overview of the data		
2	4	4

Table 2: Questionnaire Results (Median response. All different values are also significantly different. The Cylindrical display trended towards a higher result than the Large display for all questions. 1 = Strongly Disagree, 5 = Strongly Agree).

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

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

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

Discussion

The results of our experiment suggest that there is a benefit of increasing the display size for list navigation tasks. Results confirm our hypothesis (H1) that display size has a significant effect on navigation time: the large and cylindrical display sizes allowed for faster task completion. These results show that the current display sizes of smart watches limit the ability to

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

Table 1: Mean *(SD)* navigation times (s).

efficiently navigate through information, even if the interaction space is larger than the display. As expected, we confirmed our control hypothesis (H2) that larger target distances would result in longer navigation times.

Participants took advantage of the larger interaction area. For the small display condition many participants used a non-active area below the viewport for scrolling. This allowed them to scroll without causing any occlusion of the active area. This demonstrated that our results are not confounded by the known input issues of small displays. It also suggests that for most currently available devices that do not have the extended input area, the drawbacks of a small display could be more prominent than the ones we found.

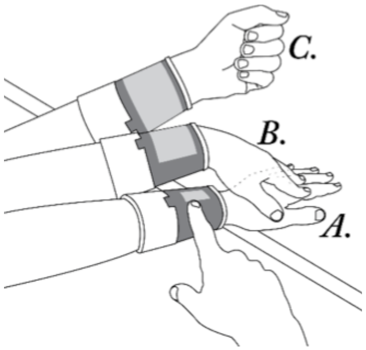

Figure 2: Typical hand-positions for different display sizes

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

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

We would like to point out that the absolute navigation speeds are different from those observed by Perrault et al. [9]. This difference in task completion times was likely due to implementation differences in the scrolling physics model, which in our case was constrained by the slower refresh times of the E Ink display. This led to a slower scrolling behavior, which affected absolute task completion times. Relative task completion times (the ratio between times to scroll through different list lengths) are, however, in agreement with their results.

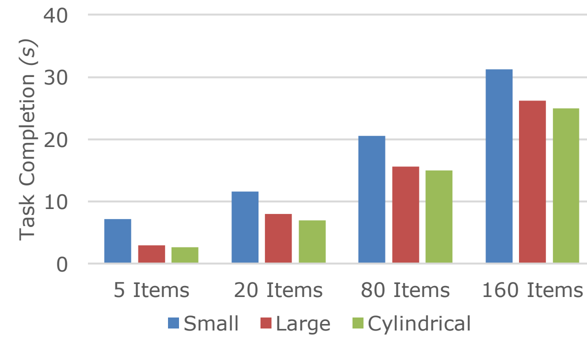

Table 3: Task completion times for target distance and display types

Effects of a Cylindrical Display

Bimanual Interactions

During our experimental evaluation, we observed distinct strategies in how participants interacted with different display sizes (Figure 2). Many participants chose to support their left hand on the table, as our experiment required them to scroll through lists for an extended period of time, which they reported to be tiring—even with breaks. With the small display size, participants often rested their entire palm on the table (Figure 2 - A). In the large display size condition, participants often lifted their hands, supporting the weight with their fingers (Figure 2 - B), while orienting the active display area towards their face. In the cylindrical display condition, participants usually lifted their hand from the table (Figure 2 - C) to leverage bimanual interactions.

We noticed three ways in which participants used bimanual interaction with the cylindrical display.


Figure 3: Bimanual swipe gesture

Bimanual swiping was generally used to enable faster scrolling (Figure 3). When participants were close to the target, but it was not immediately visible, they would rotate their wrist to bring it into view. In addition, participants also used the rotation of their left hand to correct for the actions of the right: to accommodate for the inertial scrolling, they commonly rotated their wrist to respond to an overshoot or in anticipation of an upcoming target.

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

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

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

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

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