Investigating Current Techniques for Opposite-Hand Smartwatch Interaction

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ABSTRACT

The small display size of smartwatches creates a challenge for touch input, which is still the interaction technique of choice. Researchers and producers have started to investigate alternative interaction techniques. Apple and Samsung, for example, introduced digital versions of classic watch components such as the digital crown and the rotatable bezel. However, it remains an open question how well these components behave in terms of user interaction. Based on a self-built smartwatch prototype, we compare current interaction paradigms (touch input, rotatable bezel and digital crown) for one-dimensional tasks, i.e. scrolling in a list, two-dimensional tasks, i.e. navigation on a digital map, and a complex navigation/zoom task. To check for ecological validity of our results, we conducted an additional study focusing on interaction with currently available off-the-shelf devices using our considered interaction paradigms. Following our results, we present guidelines on which interaction techniques to use for the respective tasks.

ACM Classification Keywords

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

Author Keywords

Input techniques; opposite-side interaction; smartwatches.

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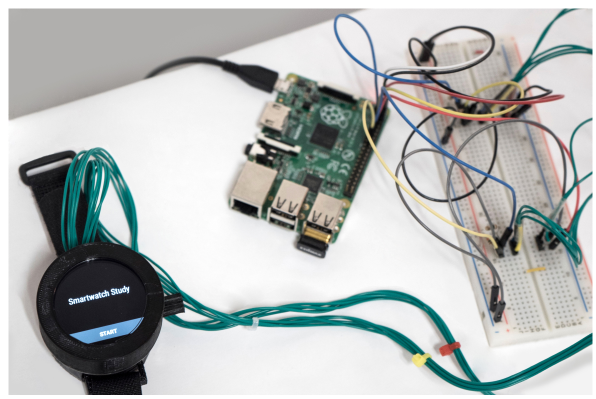


Figure 1. Smartwatch prototype consisting of our 3D-printed housing including the mechanical components for the digital crown and the rotatable bezel, a Moto 360 and the attached Raspberry Pi B+.

INTRODUCTION

In the last few years, the importance of smartwatches, i.e. wrist-worn watch-shaped devices with added features similar to a smartphone, has rapidly increased. The size of the smartwatch market is expected to grow to 32.9 billion USD in 2020[1]. In terms of accessibility, Ashbrook et al. [4] demonstrated that a wrist-mounted device can be reached significantly faster than e.g. a smartphone which is carried in the user's pocket. Also with reference to social acceptability, the wrist and the forearm are the most desirable areas for wearable devices [31]. These findings underpin the current trend, but smartwatches are still evolving and their appearance and use cases should be, among other things, informed by use patterns of former and current (digital) watches [23]. Furthermore, cultural concepts and fashion will ultimately influence the development [24, 36].

[1]https://goo.gl/K71yoY, last accessed 24/05/2017

The increasing miniaturization of technological components is an important factor for the success of wearable devices. However, the small size is challenging for touch input. Hence, researchers started to investigate alternative interaction methods. Possible solutions include utilizing the wristband [1, 11, 29], integrating additional sensors [22, 28, 37, 38] or using gestural input [33]. Besides these scientific investigations, commercial manufacturers also presented their approaches, e.g. by including mechanical input components. The Samsung Gear S2 integrates a rotatable bezel which surrounds the watch face, whereas Apple utilizes the crown, a small knob at the side of the watch. Both approaches are inspired by classic watches and do not require complex and possibly power- and space-consuming hardware components, as is the case for some of the scientific approaches. The mechanical controls are mainly used to navigate through list-like or grid-like structures, such as menus for example. However, it remains an open question how well these digital counterparts of classic watch components behave in terms of user interaction. We contribute to this research by building a smartwatch prototype (see Figure 1) including the three input methods touch, rotatable bezel, and digital crown to conduct two user studies to compare the input methods w.r.t. perceived usability, task completion time and error rate. We further provide a comparison using currently available off-the-shelf devices employing the aforementioned input methods. We conclude our paper with guidelines that should be kept in mind when designing interaction for typical tasks such as scrolling/searching in a list (one-dimensional), navigation/searching on a digital map (two-dimensional) or doing more complex tasks such as navigation/zoom. Our results show that the rotatable bezel as well as the digital crown represent usable alternatives to touch.

RELATED WORK

Input techniques for wearable devices have been investigated for more than a decade. Raghunath and Narayanaswami [32] examined touch input and developed guidelines which can be found nowadays in wearable operating systems such as Android Wear. Blaskó et al. [7, 8] investigated the utility of passive haptics for eyes-free numeric entry as well as bi-directional strokes and tactile landmarks as an input system. In contrast, Ashbrook et al. investigated touch interaction on a round wristwatch without tactile landmarks [5] and derived a mathematical model for error rate based on movement type and angular as well as radial button widths.

To deal with the problem of screen occlusion, Baudisch and Chu presented four concepts based on back-of-device interaction [6]. They derived guidelines from a user study in which they used a prototype with a capacitive trackpad on the back. Perrault et al. [29] built a wrist-worn device that extends the interactive surface of a watch to the wristband. With a user study they showed that their developed interaction techniques are effective in eyes-free usage scenarios, and avoid occlusion. Ahn et al. [1] also bring up a prototype which utilizes the smartwatch's wristband to address the problem of occlusion. They show several example applications where their technique would help users to interact more easily and comfortably. Whereas these two prototypes focus mainly on scrolling, Funk et al. [11] use the touch-sensitive wristband for text entry on a smartwatch. They developed keyboard layouts which they compared in a controlled experiment. Utilizing the skin nearby was also considered to remedy occlusion problems. Laput et al. [21] propose to expand the interactive region by integrating infrared proximity sensors in combination with tiny projectors into the smartwatch in order to render touch-sensitive icons on the user's skin. Lim et al. [22] provided a system consisting of infrared line image sensors in combination with a gyroscope to detect touches on the back of a user's hand. Their prototype, built upon a commercial smartwatch, showed that the sensed finger position is accurate enough to control the smartwatch's graphical user interface.

The prototype of Ogata and Imai [27] notices the deformation of the skin under the smartwatch and interprets this as gestures to which the smart device is able to react. Zhang et al. [40] presented a wearable system providing continuous touch tracking on the skin based on a high-frequency AC signal emitted by a ring, with corresponding sensors in a wristband. The sensed finger movements can then, for example, be used to control a smartwatch. Oakley and Lee tackle the occlusion problem with a prototype that allows for touch sensing on the edge of the device [26], ensuring the device screen remains clearly and continuously visible for an interacting user. Darbar et al. [9] attached four pressure sensors to the sides of a smartwatch to enable control based on different levels of pressure, e.g. for bi-directional navigation such as zooming or scrolling.

Techniques for around-device interaction have also been investigated. Kim et al. [20] used an array of infrared proximity sensors to detect gestures which are performed above the watch. Participants of a user study achieved a good recognition accuracy and agreed that the Gesture Watch operated well. The zSense system [37] provides a shallow depth gesture recognition based on infrared LEDs and corresponding sensors to enable gestures in mid-air. Another design utilizes magnetically driven inputs. The prototype of Ashbrook et al. [3] allows input via a finger ring. Users can "click" items by sliding the ring along the finger, while they select them by twisting it. Harrison et al. [12] also created a magnetically driven input. For interaction, the user only has to wear a magnet on the fingertip, which is then sensed by a magnetic sensor within the watch. Ketabdar et al. [19] also used a magnetic sensor within a device to enable 3D around-device interaction. The gestures performed by the user with a magnet are interpreted as commands which are then processed by the mobile device.

The problems of occlusion as well as the fat-finger problem [35] can also be solved by techniques which belong to the category of same-side interactions [17], i.e. the user only uses the arm that is wearing the device for interacting. To detect movements of the forearm and the hand, Rekimoto [33] embedded capacitive and acceleration sensors in a wristband. The gesture-based commands are designed to be as unobtrusive as possible to be usable in everyday life. The problem of involuntary input could be solved by a delimiter gesture such as the one presented in [18]. Fukui et al. developed a device to recognize hand shapes based on photo reflector sensors [10], an approach that has also been used by Aoyama et al. to control a smartwatch based on thumb movements [2].

Other approaches in the field of same-side interaction are built upon surface electromyography (EMG). Saponas et al. [34] used EMG to enable always-available input for interactive systems by classifying gestures in real-time. Nowadays available consumer hardware for EMG such as the Myo armband[2] no longer requires special preparation of the skin or special medical training of the operator. With such a device, Kerber et al. [16] investigated eyes-free, same-side hand interactions. In terms of task completion time as well as user preference, the traditional touch input was preferred by the majority of their participants. The system developed by McIntosh et al. [25] uses a combination of EMG and pressure sensors to sense expressive data at the user's wrist, thereby enabling an integration into devices that are worn there anyway – instead of requiring an additional device. Based on their technique, a set of 15 gestures was detected with an accuracy of about 96%.

In the approach of Xiao et al. [38], the face of the watch is used as a multi-degree-of-freedom, mechanical interface. The prototype allows continuous 2D panning and twisting as well as binary tilt and click, which are illustrated in combination with a set of example applications. In recent work, Yeo et al. presented a similar approach based on typically available sensors such as the IMU [39] instead of adding additional ones, but require touching the display to activate the recognition process. Pasquero et al. [28] enabled the rotatable bezel of a smartwatch to interact with a paired mobile device. Furthermore, the face of their prototype supports capacitive sensing and haptic feedback, which allows eyes-free interaction. Houben and Marquardt presented a prototyping toolkit called WatchConnect [14] that allows for rapid testing of cross-device interactions and smartwatch interaction techniques.

To sum up, it can be stated that many interaction techniques were developed and evaluated in the past. The motivations of the respective scientific works range from occlusion and the fat-finger problem, over the problem of discrete interaction, to the possibility of interacting in situations that do not allow for opposite-side hand interactions. However, only a very few are available in current off-the-shelf smartwatches, since most of them may not be suitable yet, e.g. because they require additional sensors resulting in increased power and space demands. Most of the smartwatches which are currently available on the market use touch as the primary input technique – resulting in the aforementioned problems. Samsung decided to add a rotatable bezel – a rotatable rim on the watch which surrounds the dial – in their Gear S2[3], which is very similar to the prototype developed by Pasquero et al. [28]. In the context of analog watches, the rotatable bezel is mainly used to indicate certain data such as elapsed time. The Apple Watch utilizes the "digital crown" as a mechanical input control[4]. This "digital crown" is inspired by the crown of analog watches, a small knob that can be used to adjust the time. Almost always, the crown is located on the right-hand side of the watch, since most people wear watches on the left wrist. The digital counterpart of the crown as well as of the rotatable bezel are mainly used for navigation and scrolling purposes on smartwatches.

[2] http://www.myo.com,, last accessed 24/05/2017

[3] http://www.samsung.com/gears2/, last accessed 24/05/2017

[4] http://www.apple.com/watch/, last accessed 24/05/2017

The question arises whether the interaction with small screen sizes is better achieved with the integration of an (additional) mechanical input control or if touch is best suited for this purpose. For example, Kerber et al. showed that touch input outperforms dynamic peephole interaction in a map navigation task [15]. Can the problems that occur in combination with a small screen be avoided by using the mechanisms that were introduced recently by manufacturers of commercial smartwatches? We answer these questions by investigating and comparing the three most commonly used input types for smartwatches as of today with a prototype that combines them in a single device. Moreover, we also directly compare the Apple Watch – with its digital crown – and the Samsung Gear S2, which employs the rotatable bezel.

SMARTWATCH PROTOTYPE

For traditional watches three possible mechanical input components are predominant, namely buttons/knobs, the crown and a rotatable bezel, that could be (and were) transferred to the digital world. As we are mainly interested in interactions that are comparable to touch interactions, we excluded a button-only solution from further investigations as it would only allow for selection. To ensure the internal validity of our comparison of the interaction paradigms, we decided to build a single device that is capable of all input modalities we want to investigate. This approach ensures that otherwise present differences between devices such as the Apple Watch or the Samsung Gear S2, such as display shape, do not influence the investigation. For our prototype study, we opted for internal validity instead of ecological validity, and therefore decided to keep things like the list representation or properties of the mechanical controls, such as light rotational feedback due to snapping in, constant across the conditions.

With regard to touch input and display properties, we decided to rely on an existing device due to its sophistication in this respect. Hence, we constructed a 3D-printable housing (see Figure 2) for a Moto 360 smartwatch that enables us to incorporate the additional mechanical input controls as well as the necessary components to operate them. We modeled the case in Rhino[5] and printed it using an Ultimaker 2[6]. The resulting housing has a diameter of 52 mm and a height of 39 mm. Due to the included rotary encoders to sense the movement of the rotatable bezel and the digital crown, the height of our prototype is remarkably larger than that of typical consumer smartwatches as of today (around 10–12 mm). However, with regard to the properties we want to examine, this does not have an effect. Considering the diameter of the device, which is of interest for the required motion when operating the bezel, we ensured compatibility with existing smartwatches, e.g. the LG G Watch R with a diameter of 54 mm.

We used two 24-step rotary encoders (BOURNS PEC11R) to transfer the analog motion of the rotatable bezel and the digital crown into a digital signal. Both rotary encoders were connected to a Raspberry Pi B+ using 90 cm long wires to ensure that the arm wearing the device could be freely moved. In addition to the digitization of the rotary encoder signals,

[5] http://www.rhino3d.com, last accessed 24/05/2017

[6] http://www.ultimaker.com, last accessed 24/05/2017

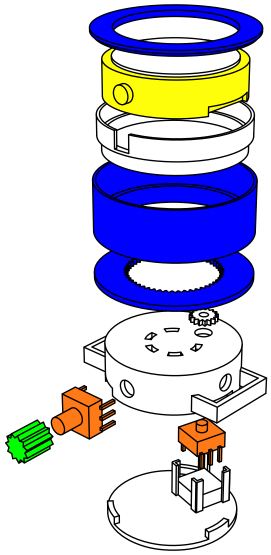


Figure 2. Exploded view of the self-built smartwatch housing with the Moto360 (yellow) and the mechanical components: crown (green), rotatable bezel (blue) and the corresponding rotary encoders (orange).

the Raspberry Pi also handles all logging tasks during the study and provides a wireless network for both the smartwatch as well as the computer we used to operate the study. Here, the communication between the Raspberry Pi B+, the smartwatch prototype and the computer is realized with UDP socket connections and a simple custom message protocol.

Before conducting the actual user study, we empirically made sure that the three considered input mechanisms provide comparable properties in terms of the physical to digital movement ratio. For the one-dimensional task, this resulted in a ratio of 1:1 and 1:3 for the digital crown and the rotatable bezel, respectively. For the two-dimensional tasks, one step on the rotary encoders resulted in 40-pixel (rotatable bezel) and 80-pixel (digital crown) movement of the digital map. For the zoom task, a 1:1 ratio was chosen.

Both the rotatable bezel and the digital crown provide rotational continuous movements that can be transferred to input. While both provide bi-directional rotations, the input is still only one-dimensional. An informal analysis of the user interface structures on smartwatches revealed that scrolling through lists (e.g. selecting a contact or changing settings) is a common task. Lists are especially dominant in Android Wear where not only are all applications sorted in a vertical list, but notifications are also vertically aligned. Hence, we decided to focus on vertical list scrolling as one specific task in our studies. While the interaction with a digital crown affords a vertical scrolling motion, for the rotatable bezel this is more ambiguous. But either way, both techniques could be mapped to vertical or horizontal movements, so we also aimed to integrate a task that would use both mappings at the same time. We decided to investigate map navigation, as it is a very promising use case for users on the go checking their location, and has been employed in prior research as a task as well [15, 38].

USER STUDY I – LIST AND MAP INTERACTIONS

To compare perceived usability, task completion time and error count of the three input methods under investigation, we conducted a user study. We provided two one-dimensional list selection tasks (unsorted/sorted list) as well as two two-dimensional navigation tasks on a map.

Participants and Tasks

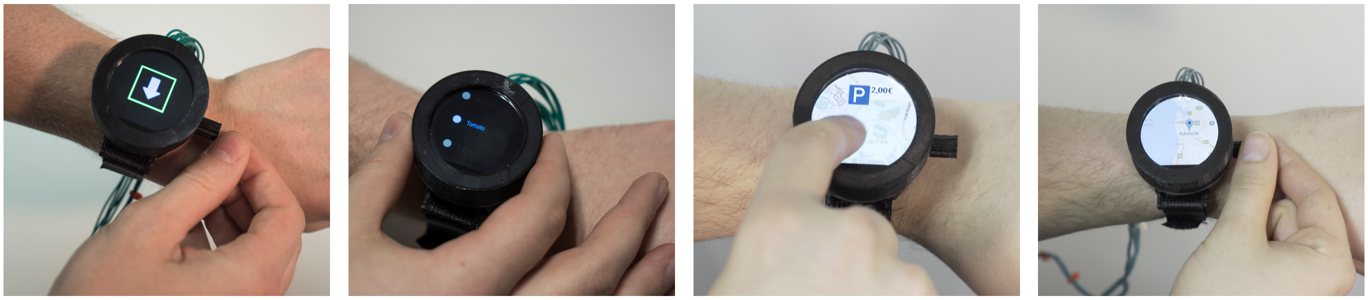
We recruited 14 participants (7 female) with an average age of 23.6 years. All participants are daily smartphone users, but none of them uses a smartwatch in their daily life.

For the one-dimensional list tasks, we provided a list of 50 names (sorted) and 50 shopping items (unsorted), respectively. For each trial, participants were given an item to look up in the list and select. During the trial, the experimenter could be asked for the item again if the participants forgot it. After choosing a list entry (either the correct one or an incorrect one), the next item was presented for selection. We thereby defined three conditions for how the scrolling had to be executed: via **touch (T)**, or using the **rotatable bezel (RB)** or the **digital crown (DC)**, respectively. We executed ten repetitions per condition resulting in 14 (participants) $\times$ 3 (conditions) $\times$ 2 (list types) $\times$ 10 (repetitions) = 840 one-dimensional trials.

For the two-dimensional map navigation tasks, we provided a city map, unfamiliar to all participants, on which parking lot symbols are displayed (similar to [15]). Each parking symbol showed the parking rate and participants were instructed to find and select the cheapest parking lot. We restricted the map to one zoom level and were only interested in the panning process. For this task, we examined four conditions: two-dimensional panning via **touch (T)**, panning via **rotatable bezel (RB)** or **digital crown (DC)** and the **combination (C) of rotatable bezel and digital crown**. As RB and DC are one-dimensional in nature, the two-dimensionality was achieved by successive movements in the single dimensions. Switching between the two directions could be achieved by pressing the digital crown. In the combined condition, the RB was used for horizontal movements, whereas DC was used for vertical movements. We provided two different numbers of parking lots (4 and 8) and repeated each condition five times, resulting in 14 (participants) $\times$ 4 (conditions) $\times$ 2 (lot amounts) $\times$ 5 (repetitions) = 560 two-dimensional trials.

Before the study started, all interaction methods were presented and the participants could test them. As we saw in a pre-study with 12 participants, there is no clear preference for scrolling/navigation direction, i.e. whether rotating the bezel or digital crown clockwise should move the selection/map up or down and left or right, respectively. Hence, we first asked the participants to define their desired directions.

To ensure that the participants were familiar with the interaction methods, they had to perform several trainings. In those for the list tasks, a blue rectangle was placed virtually above or under the currently visible display space. A blue arrow in the middle of the screen pointed up or down to indicate in which direction the participant had to move. For these one-dimensional training tasks, the movement was restricted to the vertical direction. When the arrow was in the middle of



(a) Training with digital crown interaction **(b) 1D list selection task with rotatable bezel** **(c) 2D map navigation task with touch interaction** **(d) Complex map zoom task with digital crown interaction**

Figure 3. Training task as well as the three task groups we investigated in our user studies.

the rectangle, it turned green (see Figure 3a) to indicate that the final position was reached. To ensure that participants did not simply pass over the target, it had to be in the center position for 1.5 seconds. We ensured that each direction was tested at least twice, which results in a minimum of four repetitions. These repetitions had to be finished in less than six seconds each to complete the training phase. In the trainings for the map tasks, the blue arrow could additionally point left and right, so that training was two-dimensional. Again, the participants had to move in the direction of the arrow until the rectangle was placed around the arrow. We again ensured that every direction was tested at least twice, resulting in a minimum of eight trials. For switching between the vertical and horizontal movement for the DC and RB condition, the user had to press the DC. In the C condition, the DC enabled vertical whereas the RB allowed horizontal movement. Again, the rectangle had to be around the arrow for 1.5 seconds to complete the iteration. After finishing eight repetitions in a row, each in less than ten seconds, the training was completed.

The basic procedure for all tasks was the same: The attendees were able (but not required) to redo the training for the upcoming interaction type. To exclude carryover effects we balanced the tasks using a Latin square. In the sorted list task, we presented one out of 50 names in a dialog, whereas in the unsorted task one out of 50 shopping items was shown (see Figure 3b). After users confirmed the dialog by touching, the list was shown. To allow for easy readability of the entries, we limited the amount of simultaneously shown items to three. Once the user started to interact, the time measurement started. This ensured that the period the user needed to start interacting was not considered. The participants then had to scroll to the desired list entry and select it by pressing the digital crown (in the RB and DC condition) or touching it (in the third condition). After selecting an entry, the time measurement was stopped and the process was started over again, thereby randomizing the list anew in the unsorted condition. After completing ten trials, participants were requested to fill out a questionnaire consisting of the NASA Task Load Index (NASA TLX) as well as the System Usability Score (SUS).

In the map tasks, the participants initially started in the exact middle of the map. The time-keeping started as soon as the participant began to interact. It was up to the user which strategy they used to find the cheapest spot. Most of them explored the map systematically line by line from top to bottom with alternating horizontal direction, whereas others searched the map without a recognizable strategy. As soon as the participant thought that he found the cheapest spot (see Figure 3c), it could be selected by double tapping it. Then, the time measurement stopped and the user got feedback on whether the selected spot was the cheapest one or not. The next trial started again in the middle of the map. The spots were displayed again at new random positions on the map and with new randomized costs. This procedure was repeated five times. Again, after completing all trials, participants were requested to fill out a questionnaire consisting of the NASA TLX as well as the SUS. At the end of the study, participants were asked to rate the interaction techniques. Since there were three conditions in the list task, users could rate from most preferred (rating 3) to least preferred (rating 1) for each of the two tasks. In the two map tasks with four conditions, the rating from most preferred (rating 4) to least preferred (rating 1) was applied.

Measures

- *Task completion time*: Time between starting the interaction and selecting a target (also including trials with incorrectly selected targets).
- *Error rate*: Percentage of selected items/parking lots that were not the target ones.
- *Perceived usability/popularity*: NASA TLX and SUS questionnaire assessing subjective information as well as personal ranking.

Hypotheses

We expect touch to be significantly faster (*H1*) as people are most used to it, but we do not expect any difference in error rate (*H2*) between the interaction techniques as we target a very simple task. For a typical – vertical – list task, we expect the rotatable bezel to be less usable than the other input techniques (*H3*) as its movement is not vertically oriented in the first place. For a two-dimensional map navigation task, we expect touch interaction to be more usable and preferred over the single mechanical input methods, since the digital crown and the rotatable bezel are one-dimensional in nature (*H4*).

	Median/*Mean* task completion times				Statistical analysis		
	T	RB	DC	C	Friedman test/ANOVA	T vs. DC	T vs. RB
Unsorted list	11,224	13,793	12,922	–	$\chi^2(2) = 8.143$ $p < 0.05$	n.s.	$Z = -2.668$ $p < 0.05$
Sorted list	4,320	6,036	5,038	–	$\chi^2(2) = 10.429$ $p < 0.01$	n.s.	$Z = -3.233$ $p < 0.01$
Map (4 lots)	24,419	34,412	36,196	29,546	$\chi^2(3) = 13.114$ $p < 0.01$	$Z = -2.731$ $p < 0.05$	$Z = -2.542$ $p < 0.05$
Map (8 lots)	*27,901*	*41,911*	*39,290*	*34,475*	$F(2.242, 29.152) = 6.866$ $p < 0.01$	$t(13) = -3.431$ $p < 0.05$	$t(13) = -5.901$ $p < 0.001$

Table 1. Task completion times (in milliseconds) and statistical significances w.r.t. the examined tasks and interaction methods. n.s. refers to a non-significant result.

Results

If normality was not violated, we used a repeated-measures ANOVA with the interaction techniques, digital crown (DC), rotatable bezel (RB), their combination (C) and touch (T) as factors for task completion time and error rate. Otherwise, as well as for personal preference/perceived usability, we utilized Friedman tests. For post-hoc analysis, we used Wilcoxon signed-rank tests/t-tests with a Bonferroni correction applied, resulting in a significance level set at $p < 0.017$ and $p < 0.0125$ for the list and the map tasks, respectively.

Task completion time

For all four tasks, there were statistically significant differences in task completion time with respect to the interaction methods (see Table 1). In both list tasks, T is significantly faster than RB. However, we could not find statistical significance regarding T vs. DC and RB vs. DC. In the case of the two-dimensional map navigation tasks, T is significantly faster than RB and DC. Again, we could not find any statistical differences between RB and DC, or for the combinations C vs. RB, C vs. DC and C vs. T.

Error rate

For both list tasks, there were no statistically significant differences in the number of errors depending on the input technique. For both map navigation tasks, we found a statistically significant difference in the number of errors, but for the smaller task (4 parking lots), none of the pairwise comparisons revealed any significance. For the other map task ($\chi^2(3) = 10.107, p < 0.05$), a pairwise comparison showed that the error rate when using DC (min = 0, max = 3, Mdn = 1) is significantly higher ($Z = -2.640, p < 0.05$) than is the case when using C (min = 0, max = 1, Mdn = 0). None of the other pairwise comparisons revealed any significant difference.

Perceived usability/popularity

To assess the perceived usability, we evaluated the NASA TLX questions without the additional weighting process (Raw TLX [13]). For both list tasks, we did not find significant differences when considering pairwise comparisons for the NASA TLX questions. For the two-dimensional map navigation task with four parking lots (see Table 2 for the relevant numbers), we found T to have significantly better ratings when compared to RB for all but the fourth question, i.e. T is considered less mentally ($Z = -2.555, p < 0.05$), physically ($Z = -2.573, p < 0.05$) and temporally demanding ($Z = -2.701, p < 0.05$), requires lower effort ($Z = -2.547, p < 0.05$) and results in less frustration ($Z = -2.687, p < 0.05$) than RB. Further, T was also considered significantly less frustrating than DC ($Z = -2.539, p < 0.05$).

In the case of the two-dimensional map navigation task with eight parking lots (see Table 2 for the relevant numbers), C is ranked significantly less mentally demanding than DC ($Z = -2.716, p < 0.05$); T is significantly less temporally demanding than RB ($Z = -2.859, p < 0.05$) and DC ($Z = -2.701, p < 0.05$), requires significantly less effort than RB ($Z = -2.544, p < 0.05$) and is significantly less frustrating than DC ($Z = -2.701, p < 0.05$). No other pairwise comparisons revealed any significant differences.

Considering the scores of the System Usability Scale, there was a significant difference for all tasks w.r.t. the input methods (see Table 3). For the unsorted list tasks, T and DC were perceived as significantly more usable than RB; in the sorted list task, T was perceived as significantly more usable than RB. However, we could not find a statistical significance regarding T vs. DC and DC vs. RB in the sorted condition. Regarding both map tasks, we found T to be significantly more usable than DC and RB, whereas the larger map task (8 parking lots) also showed a significant difference in favor of T when compared to C. All other pairwise comparisons did not reveal significant differences.

	Mental Demand	Physical Demand	Temporal Demand	Effort	Frustration
Map with 4 spots					
Touch	2	1.5	2.5	2	1
Dig. Crown	2	2	3.5	3	3
Rot. Bezel	2.5	2.5	4	4	3
Combination	2	2	3	3	2
Map with 8 spots					
Touch	1.5	1.5	2.5	2.5	2
Dig. Crown	3	2	3.5	4	3
Rot. Bezel	3	3	3.5	4	2
Combination	2	2	3.5	3.5	2

Table 2. Median ratings of the NASA TLX questions 1, 2, 3, 5 and 6 for the map navigation tasks in study I on a scale from very low (1) to very high (7).

	Median SUS scores				Statistical analysis				
	T	RB	DC	C	Friedman test	T vs. RB	T vs. DC	DC vs. RB	T vs. C
Unsorted list	92.5	80	92.5	–	$\chi^2(2) = 9.102$ $p < 0.05$	$Z = 2.435$ $p < 0.05$	n.s.	$Z = -2.816$ $p < 0.05$	–
Sorted list	98.75	87.5	97.5	–	$\chi^2(2) = 11.455$ $p < 0.01$	$Z = -2.847$ $p < 0.05$	n.s.	n.s.	–
Map (4 lots)	91.25	76.25	75	85	$\chi^2(3) = 21.545$ $p < 0.001$	$Z = -3.186$ $p < 0.01$	$Z = -3.204$ $p < 0.01$	n.s.	n.s.
Map (8 lots)	93.75	75	67.5	82.5	$\chi^2(3) = 23.705$ $p < 0.001$	$Z = -3.078$ $p < 0.01$	$Z = -3.184$ $p < 0.01$	n.s.	$Z = -2.773$ $p < 0.05$

Table 3. Perceived usability ratings and statistical significances w.r.t. the examined tasks and interaction methods. n.s. refers to a non-significant result.

Regarding desired ranking (popularity), we found significant differences for all four tasks. DC is ranked significantly higher than RB for the sorted ($Z = -2.635, p < 0.05$) and the unsorted ($Z = -3.090, p < 0.01$) list task, but for the other pairwise comparisons, no significance could be revealed. Overall, 8 (9) of 14 participants ranked DC first for the sorted (unsorted) list selection task. T is ranked significantly higher than RB and DC for the two-dimensional map navigation task with four parking lots (RB: $Z = -3.003, p < 0.05$, DC: $Z = -3.154, p < 0.01$) as well as with eight parking lots (RB: $Z = -3.003, p < 0.05$, DC: $Z = -3.154, p < 0.01$), but we found no significant differences between RB and DC nor for comparisons with C. Overall, 8 of 14 participants preferred T over all other input methods for both map navigation tasks.

Discussion

Although we found a significant difference in the task completion time between RB and T for the list tasks, we cannot fully confirm *H1* as we do not observe a significant difference in the task completion times of DC and T. Similar results could be observed for the two-dimensional map navigation tasks: T is significantly faster than DC and RB, but there was no significant difference when compared to their combination.

In accordance with our expectations, we did not observe significant differences in the error rate for the one-dimensional list tasks or the two-dimensional map navigation task with four parking lots. However, for the map navigation task with eight parking lots, a significant difference between DC and C could be observed. This partially rejects *H2*.

For both list tasks, participants rated interactions with the RB as significantly less usable than T and in the unsorted case also significantly less usable than DC. As the movement of the RB is not vertically oriented in the first place, it is not surprising that it is perceived as less usable for a vertically oriented task; this is in compliance with *H3*. For the map tasks, T is considered significantly more usable than RB and DC. In the condition with eight parking spots, that potentially required even more scrolling, the combination of both mechanical input techniques is also considered less usable than touch. Hence, *H4* can be seen as confirmed w.r.t. usability.

Overall, we see that the mechanical input techniques are perceived as usable alternatives to touch with an average SUS score of 82.3 and 92.3, respectively, for the list tasks. However, the rotatable bezel does not seem to be well-suited for a vertically oriented task, while the digital crown is the preferred interaction method for the majority of our participants. For the two-dimensional map task, touch outperforms both mechanical techniques and is also the preferred interaction method for most of our participants (confirms *H4* w.r.t. popularity).

USER STUDY II – COMPLEX NAVIGATION/ZOOM TASK

The first study provides insights into both one-dimensional and two-dimensional interaction with the mechanical input controls. However, there are situations in which this is not sufficient, e.g. when navigating on a map or browsing some larger view. Typically, some kind of third dimension, most often in terms of zoom, is in place. To get additional insights, we conducted a second user study that investigates a combination of touch with one of mechanical input techniques to cover this case as well. We provided a search task on a map that requires zooming as well as panning. Based on the results from our first study, we decided to realize panning via touch, whereas zooming was done either via **touch (T)**, **rotatable bezel (RB)** or **digital crown (DC)**.

We recruited twelve volunteers (six female) aged 22 to 32 (average age 27.3) all of whom were used to working with touch-enabled devices. None of the participants was familiar with the Apple Watch or the Samsung Gear S2 beforehand. To exclude sequence effects, we balanced the three conditions using a Latin square. In all conditions, participants were presented a world map with 15 red markers (five markers each in North America, the United Kingdom and Australia). When zooming in far enough (zoom level 8 on a scale from world view (level 1) to building view (level 20)), one of the markers, randomly selected for each trial, was marked blue.

To ensure familiarity with the interaction methods as well as the required level of zooming, we included a training task with our prototype and a given target marker before the actual study. For the direction of zooming, we adopted the choices from Apple and Samsung respectively, i.e. rotating the bezel to the left/the digital crown down zooms out and rotating to the right/up zooms in. For touch, we used the implementation of the Google Maps API, i.e. zooming in is possible via a double tap or pinch gesture, while there is no equivalent of the double tap for zooming out.

Each task started at lat./long. position 0,0 (Atlantic ocean, left of Africa) and zoom level 1 (world view). The participants then had to find the target marker by panning the map to the marker positions and zooming in. When zoomed in far enough, all markers become selectable while the target marker also turns blue (see Figure 3d). For each condition, three trials were executed in a row, resulting in nine trials per participant. After all trials of one condition were completed, a questionnaire consisting of the NASA TLX as well as the SUS was handed over to the participant. After a short break, the procedure was repeated for the other conditions. After completing all nine trials, we asked the participants for their personal preference from most preferred (rating 3) to least preferred (rating 1).

Measure and Hypothesis

In this study, we were interested in *perceived usability/popularity* measured via NASA TLX and SUS questionnaires assessing subjective information, as well as by the personal ranking of the interaction methods.

We expect the RB and the DC condition to be perceived as significantly more usable and to be preferred by the participants, mainly due to the fact that the interaction space for pinch-to-zoom is very limited.

Results

A Friedman test with the interaction techniques digitial crown (DC), rotatable bezel (RB) and touch (T) determined that the median SUS score differed statistically significantly between the different interaction methods ($\chi^2(2) = 16.174, p < 0.001$). Median SUS scores for DC, RB and T were 85 (62.5 to 100), 87.5 (57.5 to 100) and 56.25 (32.5 to 75), respectively. Post-hoc tests using the Bonferroni correction did not show significant differences between DC and RB. However, there were statistically significant differences in SUS scores with DC vs. T trials ($Z = -2.981, p < 0.01$) and with RB vs. T trials ($Z = -3.066, p < 0.01$). In summary, DC and RB were perceived as significantly more usable than T for the combined zoom/navigation task.

Regarding the ratings for the NASA TLX questionnaire (see Table 4 for the relevant numbers), Friedman tests with the aforementioned factors revealed significant differences for physical demand ($\chi^2(2) = 13.867, p < 0.01$), performance ($\chi^2(2) = 16.27, p < 0.001$), effort ($\chi^2(2) = 12.474, p < 0.01$) and frustration ($\chi^2(2) = 10.606, p < 0.01$). Pairwise comparisons with Wilcoxon signed-rank tests using Bonferroni correction showed that using T results in significantly more physical demand than using RB ($Z = -2.981, p < 0.05$). Also, the performance of T is significantly lower when compared to DC ($Z = -2.831, p < 0.05$) or RB ($Z = -2.825, p < 0.05$). The effort to accomplish the level of performance was significantly higher for T than for DC ($Z = -2.79, p < 0.05$), and the frustration when using touch was significantly higher than for DC ($Z = -2.446, p < 0.05$) or RB ($Z = -2.555, p < 0.05$).

Regarding popularity of the interaction methods for zoom, five of the participants preferred the digital crown, whereas seven chose the rotatable bezel first. For all but one participant, touch was ranked lowest. Again, a Friedman test with the interaction methods as factor revealed a significant difference ($\chi^2(2) = 15.5, p < 0.001$). Post-hoc tests using Bonferroni correction showed that T is ranked significantly lower than DC ($Z = -2.83, p < 0.01$) or RB ($Z = -3.145, p < 0.05$).

	Physical Demand	Performance	Effort	Frustration
Dig. Crown	2.5	6	2	2
Rot. Bezel	2	6	2	2
Touch	4.5	3	4	5.5

Table 4. Median ratings of the NASA TLX questions 2, 4, 5 and 6 in study II on a scale from very low (1) to very high (7). Note that the desired value for performance is at the high end of the scale, while it is at the low end for all other questions.

Discussion

In accordance to our expectations, both mechanical input methods received significantly better usability scores than touch interaction, resulted in higher perceived performance as well as less frustration and were preferred by the participants. The qualitative feedback confirmed our assumption that the limited screen space of a smartwatch is considered a problem for touch interaction. While zooming in is considered feasible via the double tap gesture, there is no suitable alternative to the inappropriate pinch gesture for zooming out. Several participants stated that touch interaction might be more appropriate given an option to change the physical to digital movement ratio, i.e. if one pinch gesture on the display would result in a larger zoom change. While larger movements are easily achievable for the mechanical inputs by moving faster, this is not so easy for touch interaction. Although changing the zoom speed is technically possible, it would require an additional control – either as physical input or on the screen – to be able to adjust the zoom speed. Otherwise, choosing a larger zoom change by default would hinder detailed adjustments on the map.

USER STUDY III – OFF-THE-SHELF IMPLEMENTATIONS

As previously described, our prototype and the studies conducted with it targeted internal validity by keeping as many aspects as possible constant across the conditions – even when implemented differently in currently available commercial devices that employ the respective technology. However, we were also interested how people perceive these current implementations. To cover this aspect as well, we conducted a study using the Apple Watch with its digital crown and the Samsung Gear S2 with the rotatable bezel. Again, we provided two one-dimensional list selection tasks (unsorted/sorted) and compared perceived usability, task completion time and error count of the three input methods. As the properties of the devices most likely have a non-negligible effect, we conducted the touch-related tasks on both devices, resulting in a total of four examined input methods.

Participants and Tasks

We recruited 16 participants (7 female) with an average age of 27.9 years, all of whom are daily smartphone, but not smartwatch users. The tasks we provided were the ones already used in our first study: a list of 50 names (sorted) or 50 shopping items (unsorted) was provided from which one entry should be selected. The experimenter could be asked for the item if it was forgotten, and choosing a list item (whether correct or incorrect) triggered the next repetition, up to a total number of ten repetitions per condition. All selections had to be made via a touch of the respective list item, whereas four conditions for scrolling were considered: $\text{touch}_{\text{Apple}}$ (TA), $\text{touch}_{\text{Samsung}}$ (TS), digital crown (DC) and rotatable bezel (RB). We examined all input methods for the unsorted as well as the sorted list, resulting in 16 (participants) × 4 (conditions) × 2 (list types) × 10 (repetitions) = 1280 trials. To exclude carryover effects we balanced the tasks using a Latin square of size 8. To ensure familiarity with the interaction methods and tasks, participants could test all conditions prior to the actual study.

In the study, participants were presented an item to select directly on the respective smartwatch and after tapping a start button, the corresponding list to select from was shown and the time measurement started. After selecting an entry via touch, the time measurement was stopped and the procedure was repeated again. After completing all ten repetitions, participants were requested to fill out the same questionnaire as used in the first study – consisting of the NASA Task Load Index (NASA TLX) as well as the System Usability Score (SUS). After the study, we asked the participants to order the four considered input techniques according to their preference from most preferred (rating 4) to least preferred (rating 1).

Measures

We used the same measures as in our first study:

- *Task completion time*: Time between starting the interaction and selecting a target (also including trials with incorrectly selected targets).
- *Error rate*: Percentage of selected items that were not the target ones.
- *Perceived usability/popularity*: NASA TLX and SUS questionnaire assessing subjective information as well as personal ranking.

Results & Discussion

If normality was not violated, we used a repeated-measures ANOVA with the interaction techniques, digital crown (DC), rotatable bezel (RB), $\text{touch}_{\text{Apple}}$ (TA) and $\text{touch}_{\text{Samsung}}$ (TS) as factors for task completion time and error rate. Otherwise, as well as for personal preference/usability, we utilized Friedman tests with the same factors. For post-hoc analysis, we used t-tests/Wilcoxon signed-rank tests with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0125$.

Task completion time

Regarding the task completion time, a direct cross-device comparison is not really sensible, e.g. due to different list loading behaviors. We therefore consider the respective task completion times for touch interaction as a baseline for both devices and compare the times of the mechanical controls with respect to these baselines.

Paired t-tests revealed a statistically significant difference in task completion time with respect to the interaction methods for all but one pairwise comparison. In the sorted list condition, TA (M = 6,135 ms) is significantly faster ($t(15) = -2.396, p < 0.05$) than DC (M = 6,813 ms) as well as in the unsorted condition (M = 9,085 ms vs. M = 10,533 ms, $t(15) = -3.972, p < 0.01$). In the sorted list condition, TS (M = 5,119 ms) is also significantly faster ($t(15) = -2.428, p < 0.05$) than RB (M = 5,913 ms). However, no significant difference could be found for TS (M = 10,085 ms) vs. RB (M = 11,473 ms) in the unsorted condition. To be able to compare RB and DC, we consider the relative performance compared to the respective touch completion time as a baseline. Again, paired t-tests were used, but did not show a statistically significant difference in the relative task completion time for both list types.

	Sorted List	Unsorted List
$\text{Touch}_{\text{Samsung}}$	93.75	81.25
$\text{Touch}_{\text{Apple}}$	97.50	87.50
Rotatable bezel	88.75	83.75
Digital crown	90.00	85.00

Table 5. Median ratings of the System Usability Scale for the 16 participants in our third study.

Error rate

For both list tasks, Friedman tests did not reveal statistically significant differences in the error rate depending on the technique, which is expected due to the easy nature of the tasks.

Perceived usability/popularity

Regarding the scores of the SUS (see Table 5), no statistically significant differences could be found for the sorted task ($\chi^2(3) = 4.579, p = 0.205$) or for the unsorted one ($\chi^2(3) = 4.14, p = 0.247$). For the NASA TLX questions, a Friedman test revealed a significant difference in the unsorted list task for the perceived performance ($\chi^2(3) = 11.175, p < 0.05$). Post-hoc tests using the Bonferroni correction showed that people considered themselves significantly ($p < 0.05$) more successful in the touch condition using the Apple Watch (min = 5, max = 7, Mdn = 6) compared to touch (min = 3, max = 7, M = 6, $Z = -2.547$) or bezel (min = 2, max = = 7, Mdn = 6, $Z = -2.489$) interaction using the Samsung Gear S2. Also, interaction with Apple's digital crown (min = 4, max = 7, Mdn = 6) was considered significantly more successful than using touch on the Samsung Gear S2 (min = 3, max = 7, Mdn = 6, $Z = -2.228$). Considering the desired ranking (popularity), again no statistically significant difference could be found ($\chi^2(3) = 3.075, p = 0.38$).

According to our expectations, we see that participants were influenced by several factors that are not directly related to the interaction methods under consideration, e.g. P15 said "*The Apple Watch format (rectangular) provides more space for touch.*" or "*The touch functionality of the Samsung watch is very good. The touch of the Apple Watch reacts very hesitantly.*" (P12), but also the other way round (P8). Also, differences in the implementation of the mechanical input techniques influenced the results: P6 and P16 criticized the digital crown for giving no haptic feedback, while it was available on the rotatable bezel. In our own prototype, haptic feedback similar to that of Samsung's Gear S2 was implemented for both input controls to ensure a better comparison.

Also, the way people interacted with the off-the-shelf devices differed partially from the interaction with our prototype: Due to the small size of Apple's digital crown, only some of the participants grasped it with multiple fingers whereas most used it by moving their index finger or thumb on it. In line with this, several participants complained that the digital crown is too small or impractical (P2, P12, P15). Also for the rotatable bezel, a difference could be observed: When interacting with the bezel by moving it around without keeping the finger at a constant position, occlusions can occur (P6, P7, P10, P15, P16) and slipping off leads to accidental touches easily (P5). Participants reported that it takes a certain amount of time interacting with the bezel to find a suitable interaction style to avoid these problems. In contrast to this, our prototype provided a larger surface to interact at the side of the watch, which prevents occlusion and accidental touches. Using the off-the-shelf devices also required all selections to be made by touching (due to technical restrictions). Hence, participants P1, P2 and P8 mentioned the required modality switch for the selection as a negative aspect. Again, we excluded this potentially influencing aspect in our prototype study by enabling selection by pressing the digital crown.

To sum up, we see a number of influencing factors that came up in the last user study which are not necessarily connected to the interaction methods used, but mainly due to different implementations or technical restrictions. We therefore argue that our primary approach of having a single prototype excluding these factors as well as possible is sensible to assess the properties of the interaction techniques. However, it cannot be ruled out that a specific implementation always influences the results. As we not only compared the different interaction techniques, but also different technical realizations, we provide guidelines for both aspects in the next section.

DESIGN GUIDELINES

Based on the results of our user studies, especially the qualitative feedback in the third study, we derive the following design implications for creating a device providing one of the examined mechanical input controls:

- Moving the input control should always provide haptic feedback to enable an eyes-free estimate of the covered distance.
- A mechanical control such as the digital crown should be large enough to be easily graspable with multiple fingers.
- A rotatable bezel should be designed in such a way that it supports interaction on its side rather than its top.

Following our study results, we derive a set of guidelines that should be kept in mind when designing interaction for the respective tasks. The results are mainly based on the two studies conducted with our prototype device, as it provides the best basis for a comparison of the input techniques by keeping other influencing factors as constant as possible.

- For a one-dimensional vertical list selection task, the rotatable bezel is not a suitable input method. Consequently, digital crown or touch input should be utilized, with digital crown being the preferred method in our first user study.
- For navigation on a two-dimensional surface, touch should be favored over one of the mechanical interaction methods.
- For a complex, two-dimensional zoom/navigation task, the combination of mechanical and touch input is superior, where one of the mechanical interaction methods is used for zooming and touch should be used for navigation (in accordance with the preceding guideline).

It should be kept in mind that our findings are based on our smartwatch prototype and using current standard interface elements of Android Wear/watchOS/Tizen and hence, might not apply if the interface is adapted to the mechanical input. To leverage the full capabilities of these modalities, most likely an adaptation is needed. Samsung transferred the menu structure on the Gear S2 to a circular menu. It is not obvious if this has been done just to fit the design language of the rotatable bezel or to utilize its capabilities to a greater extent. Plaumann et al. showed that an adaption is meaningful for a sorted list selection task [30]. However, it is questionable whether such transformations also work for content other than a menu or a sorted list, such as e.g. a music playlist.

CONCLUSION & FUTURE WORK

In this paper, we presented results of three user studies comparing interaction techniques for state-of-the-art smartwatches. To be able to effectively compare the interaction techniques, we designed and built a 3D-printed smartwatch housing enabling mechanical input via rotatable bezel and digital crown based on two rotary encoders, a Raspberry Pi B+ and a Motorola Moto 360 as output device as well as for touch input, which we used for two of the user studies. To provide ecological validity, we conducted a third user study with two currently available commercial devices, each implementing one of the examined mechanical input techniques.

We focused on three typical tasks that are likely to occur in wearable applications: (1) selection in a one-dimensional, vertical list such as an address book (sorted), a music playlist (unsorted) or a menu (either sorted or unsorted), (2) navigation over a two-dimensional region and (3) zooming in addition to navigation over a two-dimensional region. While the latter tasks are most likely relevant for a digital map application, they might also be adopted to browsing a web page, for example.

While the results of our evaluation showed that the two mechanical input modalities present a valid alternative to touch input, they are not a universal solution for all needed input styles. Still, the digital crown and the rotatable bezel have the advantage that they afford a physical element that the user can grip and do not require precise pointing. This makes them particularly interesting for interaction while moving. Nevertheless, our investigation also showed that even for linear list search, touch is in general the faster input modality, although the results may differ when the user is physically moving.

For future work, we will investigate how the physical to digital movement ratio could be adapted to the actual user and the current task, instead of relying on a fixed ratio for all situations. Moreover, we want to examine how the overall user experience could be improved by further adapting the interface to the interaction method used. Additionally, we will investigate the effects of motion on the different interaction paradigms.

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