D-SWIME: A Design Space for Smartwatch Interaction Techniques Supporting Mobility and Encumbrance

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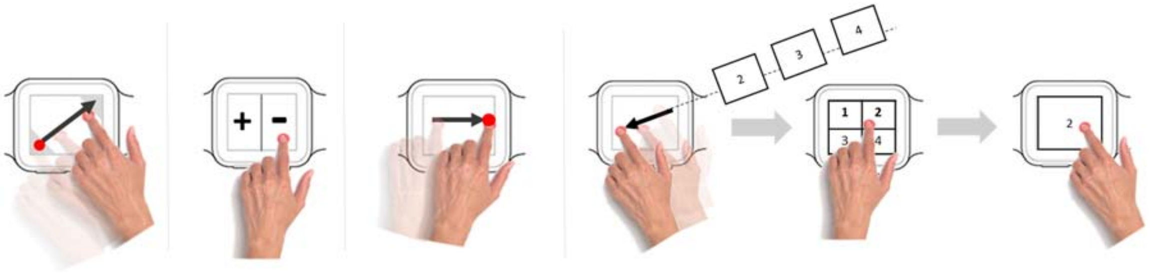

Swipe Zoom Tap Zoom PanPress FlickPan

Figure 1: Smartwatch zooming and panning techniques designed to support different mobility and encumbrance contexts.

ABSTRACT

Smartwatches enable rapid access to information anytime and anywhere. However, current smartwatch content navigation techniques, for panning and zooming, were directly adopted from those used on smartphones. These techniques are cumbersome when performed on small smartwatch screens and have not been evaluated for their support in mobility and encumbrance contexts (when the user's hands are busy). We studied the effect of mobility and encumbrance on common content navigation techniques and found a significant decrease in performance as the pace of mobility increases or when the user was encumbered with busy hands. Based on these initial findings, we proposed a design space which would improve efficiency when navigation techniques, such as panning and zooming, are employed in mobility contexts. Our results reveal that our design space can effectively be used to create novel interaction techniques that improve smartwatch content navigation in mobility and encumbrance contexts.

AUTHOR KEYWORDS

Navigation techniques; Design space evaluation; smartwatch input; mobility; encumbrance; zoom; pan; touch input.

ACM Classification Keywords

H.5.2 [User Interfaces]: Input devices and strategies, Interaction styles.

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INTRODUCTION

From portable health monitors to notification reminders and information portals, smartwatches have found a niche by giving users access to information on-the-go. Users can glance at and quickly interact with content without having to retrieve their smartphone. Despite the small screen size and varied usage scenarios on smartwatches, the same touch-based input techniques as those used on mobile handheld devices have been applied to this new form factor. Little concern if any has been given to issues of mobility and encumbrance [30] when designing content navigation techniques, such as panning and zooming, on smartwatches. This results in users having to suspend their core activity, whether it is walking or taking a jog, for smartwatch input [27]. Instead, consideration is needed to allow smartwatch interactions to take place in those contexts in which use of such a device is most appropriate.

Smartwatch navigation techniques should ideally be designed to account for common activity contexts. Such activity contexts can be viewed along at least two axes: (i) the degree of user mobility; and (ii) hand encumbrance. The degree of mobility can range from being inactive (standing or sitting), active (walking), or highly active (running) [5,23,24,34,35]. Hand encumbrance includes having both hands available for interaction, or having only one-hand or even no-hands available, such as when holding items using two hands [30]. Each of these activity contexts are known to have a negative impact on interaction performance for handheld devices [30]. However it is unclear how the diminished form factor, the use of a device on a wrist and all the associated input challenges, such as the exacerbated fat-finger problem [36], affect smartwatch interactions in cases of mobility and encumbrance.

In a first experiment, we studied the impact of mobility and encumbrance on common navigation techniques (flick, tap, pan and zoom) and found that: flick-based interaction techniques best support mobility and encumbrance; and, standard pan gestures (panning) and pinch gestures (zooming), which require either precise and/or dual-finger inputs, are not resistant to mobility or encumbrance. Based on these results, we next introduced a design space to propose two pairs of novel techniques namely, *SwipeZoom* and *TapZoom* for zooming, and *FlickPan* and *PanPress* for panning (Figure 1). We find that *SwipeZoom* and *TapZoom* lead to 27.59% and 48.45% improvement in completion times, respectively, over pinching gestures, whereas, *PanPress* and *FlickPan* respectively outperform traditional panning by 21.79% and 45% faster completion times.

The contributions of our paper are: (1) an investigation into the impact of two orthogonal activity contexts (mobility and encumbrance) on smartwatch interaction techniques; (2) a design space which can guide the development of new smartwatch navigation techniques; (3) two pairs of interaction techniques for panning and zooming on a smartwatch; and (4) a validation that our design space can effectively be used to improve performance.

RELATED WORK

We briefly present work on interaction techniques designed for on-the-go, results from studying hands-busy interaction techniques, and methods for panning and zooming, which are specifically relevant to our exploration.

Mobility: Interacting On-the-Go

Interacting with devices while in motion is challenging. Studies reveal the negative impact of mobility on target selection accuracy [34,35], reading time [35] and navigation time [24] for dragging or scrolling through content. To mitigate some of this impact, researchers have introduced adaptive user-interfaces such as the Walking User Interface (WUI) [17] or suggested new modalities to interact with mobile devices [38,39,41]. For instance, Goel et al. [12] used accelerometer data to improve mobile text-entry performance when the user is walking. Crossan et al. proposed wrist-rotation [10] and head-tilting [9] as complementary modalities to interact with portable devices under mobility contexts.

Lim and Feria [23] examined the influence on human perception under walking conditions. Results showed that an increase of mobility pace and targets in the inner area of the mobile screen have a negative impact on visual search. Lehtovirta et al. [6] found that performances remained stable when walking at 40-80% of participant's Preferred Walking Speed (PWS). Bragdon et al. [8] proposed various design-factors for touch-screen gestures to reduce attention load in mobile environments. Similarly, our work aims to first explore the impact of mobility on common content navigation techniques, and to further propose guidelines that can assist in designing novel techniques that are less impacted by mobility.

Encumbrance: Interacting with Busy Hands

Ng et al. [28] examined the performance of a target acquisition task on a mobile touchscreen while carrying bags and boxes in the dominant and non-dominant hands while walking and sitting. The results demonstrated a negative impact of encumbrance on mobile device input leading to a decrease in selection accuracy. Ng et al. [29] also investigated the effect of mobility and encumbrance on one-handed and two-handed mobile interactions and found a significant negative effect of encumbrance irrespective of the input method. In another study, Ng et al. [30] examined the effects of encumbrance on four main touch-based gestures with handheld devices: tapping, dragging, pinching and rotating and found that all were affected with the exception of rotation. Results further suggested that two-finger gestures afford improved accuracy over single finger-gestures at the expense of longer task performance time. This earlier work was carried out on smartphones and not representative of smartwatch input where the device is wrist-worn and offers a comparatively smaller screen than that of a phone.

Zooming and Panning Interaction Methods

Zooming and panning are currently the two most common content navigation techniques. We only present a high level overview from the significant body of work on novel techniques which researchers have proposed for content navigation [1,4,11,25,26,32]. Aside from pinch gestures, another common zooming technique is double-tap. Double-tap, however, is less efficient for single-handed interactions or situations when precise zooming is required [22].

Researchers have proposed multi-level techniques for zooming [6,18,33]. However, these techniques share the limitation of only changing the scale by a fixed amount. Researchers have also focused on reducing clutching while navigating content on a touch interface. These techniques use 'to-and-fro' or oscillatory motion of the finger to reduce the need for clutching, such as Rub and Tapping techniques [32] or Cyclo Star techniques [25]. Avery et al. [2] also attempted to reduce the need for clutching by enhancing the classic pinch gesture for zooming.

Certain navigation techniques are dedicated to single-handed interactions [7,15,22,26]. For instance, Hinckley et al. [15] explored hybrid 'touch + motion' gestures to perform single-handed zoom: users hold the thumb tip on the screen and tilt the device to perform zooming-in and zooming-out tasks. Boring et al. [7] explored single-handed panning and zooming using the 'Fat Thumb'. Lai et al. [22] introduced ContextZoom as a one-handed temporary zoom mode.

To summarize, prior work focused on different form factors: particularly on larger screens than those commonly available on smartwatch [25,32]. Some techniques impose the use of extra-hardware [7,21,40] or use embedded sensors as input [9,10,13,15] which are not reliable in our investigated mobile and encumbered contexts. In contrast, our investigation focuses on the design of smartwatch touch-only navigation techniques that can be performed in different mobility and encumbrance contexts.

EXPERIMENT 1

We examine the effects of mobility and encumbrance on four main smartwatch interactions i.e. selection, flicking, panning, and zooming under 12 different activity levels. These 12 activity levels consisted of a combination of three mobility conditions (i.e. *standing, walking and running*) and four encumbrance conditions (i.e. *both hands available, dominant hand busy, non-dominant hand busy and both hands busy*). Researchers have proposed two methods, *Treadmill* and the *Ground Walking* to evaluate interactions during mobility [3,19,31]. A treadmill is better for controlling the walking speed, whereas Ground Walking is useful regarding the actual user experience [3]. We chose to use a treadmill to fully control the mobility factor. Similar to Ng et al.'s study [31], participants carried bags to simulate different encumbrance conditions. Encumbered hands are different than unavailable hands: bags still allow participants to interact (minimally) with a smartwatch.

Participants, Equipment and Physical Setup

We recruited 12 participants (mean age 24.75, SD 2.6, 7 males, 5 females). We gave $20 gift cards to participants and the experiment took around 1.5 hours. All participants had prior experience with touch gestures using a smartwatch or smartphone. We used a Precor 835 treadmill with safety hand rails (Figure 2) and an IMacWear M7 smartwatch running on Android 5.1 OS. The smartwatch weighed 118g, measured 28.36×4.65×1.38cms, had a glass capacitive multi-touch screen (39mm diagonal, 240×240px), 512MB RAM and a 1GHz Dual Core processor. We disabled all the built-in touch gestures to prevent disruption during the experiment. We used the common size 31.8×27.9×17cm grocery bags to simulate encumbrance. Similar to previous work [29], each bag weighed 1.6kg to replicate a realistic experience. Participants were permitted to take 10 min breaks between activity conditions to prevent fatigue. After the experiment, participants completed NASA TLX questionnaires [14] for qualitative data.

Figure 2 : Participant interacting with a smartwatch while walking with a bag in his non-dominant hand.

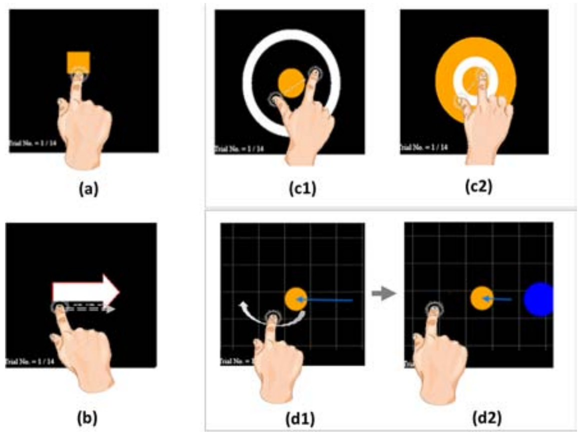

Figure 3: Experimental tasks. (a) Selection; (b) Flicking; (c1) pinching for zooming-out; (c2) zooming-in; and, (d1) Panning – initial screen - (d2) Panning – object close to the target.

Tasks

We designed four experimental tasks commonly used with smartwatches: selection, flicking, zooming, and panning.

Selection Task

Participants were asked to select a square target displayed on the screen (Figure 3, a). Based on Apple [42], Android [43], and Sony [44] guidelines, we used two different target sizes: 42px and 60px. In each trial, a single square target was displayed on the screen at a random position for participants to tap on. Any touch event missing the target was considered an error.

Flicking Task

Participants were asked to perform a sequence of several flick gestures per trial (Figure 3, b). An arrow was displayed to represent the current flick direction. Participants had to accurately flick in the direction of the arrow. Arrows could have four possible directions, i.e. left, right, up and down. In the case of an incorrect flick, an additional flick was added to the trial.

Zooming Task

Participants were asked to scale a circle to the size of a ring target [37] (Figure 3, c1 & c2). Participants performed a pinch gesture to scale the circle (radius of 20px or 100px) to fit inside a white ring (radius of 100px or 40px, width of 5px). When the circle enters the white ring, the ring turns green and when dwelled upon for 100ms, the trial is ended successfully.

Panning Task

Participants were asked to perform consecutive pans to move a circle to the center of a circular target (Figure 3, d1 & d2). An orange circle at the center of the screen represented the target destination. An arrow displayed the pan direction (from the object to the target location). The length of the arrow represented the distance of the circle from the target. For each trial, the panning distance (240px for one screen or 480px for two screens) and the target direction were selected randomly.

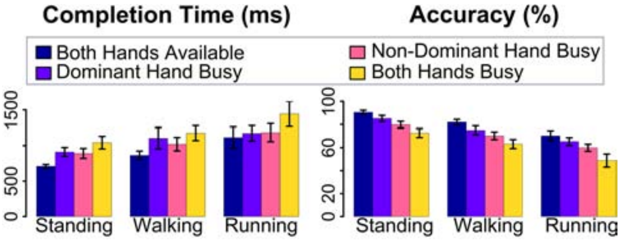

Figure 4: Average completion time (ms) and accuracy (%) during the selection task. Error bars represent 95% CI.

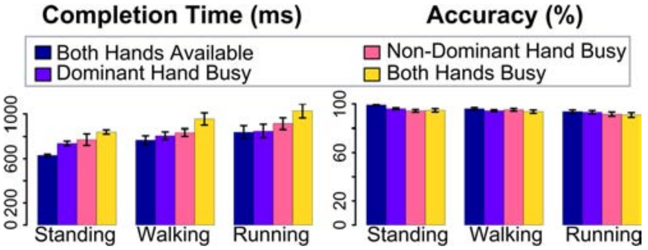

Figure 6: Average completion time (ms) and accuracy (%) during the flicking task. Error bars represent 95% CI.

Results

We applied a repeated measures two-way ANOVA with two independent factors, mobility *MOB* and encumbrance *ENC*, on completion time and accuracy data. We verified for normality and homogeneity of variances with the Shapiro-Wilk and Bartlett tests, respectively.

Selection Task

The ANOVA shows a significant main effect of *ENC* ($F_{3,121}$ =10.297, p<0.001) and *MOB* ($F_{2,121}$=20.020, p<0.001) on completion time (Figure 4-left). There was no significant *ENC×MOB* interaction (p=0.919) on completion time. We also found a significant main effect of *MOB* ($F_{2,121}$=45.536, p<0.001) and *ENC* ($F_{3,121}$=12.998, p < 0.001) on accuracy (Figure 4-right). We observe a sharp decrease in selection accuracy with an increase in mobility and encumbrance (48.81% for running with both hands).

Flicking Task

We found a significant main effect of *ENC* ($F_{3,121}$=13.140, p<0.001) and *MOB* ($F_{2,121}$=13.330, p<0.001) on completion time (Figure 6-left). There was no significant *MOB×ENC* interaction (p=0.607). We also found a significant main effect of *ENC* ($F_{3,121}$=7.960, p<0.001) and *MOB* ($F_{2,121}$ = 10.437, p<0.001) on accuracy (Figure 6s-right). There is no significant *MOB×ENC* interaction (p=0.306). Interestingly, flicking accuracy was not affected by encumbrance levels (p>0.05).

Zooming Task

We observed a main effect of *ENC* ($F_{3,121}$=29.082, p<0.001) and *MOB* ($F_{2,\ 121}$=24.642, p<0.001) on completion time (Figure 5-left). A significant main difference is observed between all mobility levels. All encumbrance conditions are significantely different from each other, except between *Dominant Hand Busy* and *Non-Dominant Hand Busy* conditions (p=0.244). Across all tasks, mobility and encumbrance have the strongest negative effect on pinch gestures. Participants were 3.05 times slower when they were running with bags in both the hands than when standing still without bags. With pinch gestures participants performed multiple clutches for completing a single zooming task. On average, participants performed 2.7 clutches while standing, 3.4 while walking, and 4.4 while running. In addition, participants overshot the target more often with an increase in mobility and encumbrance level, partly leading to the additional clutches as reported above. On average, participants overshot the target 0.7 times while standing, 1.3 times while walking, and 1.7 times while running.

Panning Task

We found a significant main effect of *ENC* ($F_{3,121}$=25.26, p<0.001) and *MOB* ($F_{2,121}$=29.52, p<0.001) (Figure 5-right) on completion time. There is no significant *MOB×ENC* interaction (p= 0.874). Post hoc pairwise comparisons with Holm p-value adjustments show that there is a significant effect between all mobility conditions (i.e. as mobility 'increases' from standing to walking to running, panning performance declines significantly). All encumbrance conditions are also significantely different from each other, except between *Dominant Hand Busy* and *Non-Dominant Hand Busy* conditions (p=0.195).

Discussion

We discuss the main findings of our first study.

Which task was least affected by mobility and encumbrance? Among the four commonly used gestures, tap, flick, pan, and pinch, flick was least affected by mobility and encumbrance. Flicking accuracy remained well above 90% under all activity conditions. The uniformly high accuracy observed with flicking across all mobility conditions, an effect that was not observed with any of the other evaluated techniques, suggests that flicking is a robust interaction when the user is mobile and encumbered. This can be due to the fact that flick requires only one finger, is a single action event, is discrete, and requires small on-screen duration.

Figure 5: Zooming task (left): average completion time (ms), average number of zoom gestures, and average number of overshoot events. Panning task (right): average completion time (ms) and average number of pan gestures.

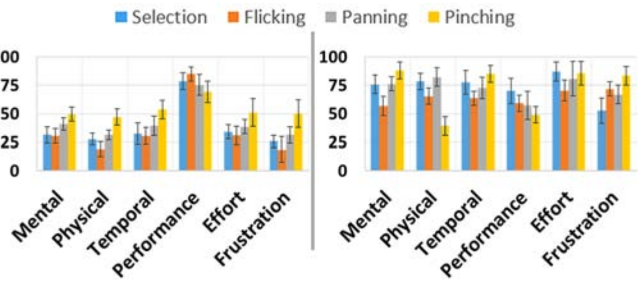

Figure 7: NASA TLX results. Participants standing still without bags (left), and running with bags in both hands (right).

Which task or gesture was most affected by mobility and encumbrance? We observed the greatest impact of mobility and encumbrance on the pinch gestures. Participants overshot the target ring several times due to the complexity of the gesture, leading to more clutches. For the panning gesture, mobility and encumbrance increased the number of pans, which in turn increased the task completion time.

What was the response of participants and how did they feel while performing the interaction tasks? Most of the participants found the pinch gesture frustrating and physically demanding, particulary when in motion and while encumbered (Figure 7). When asked, 'which gesture they would most like to have replaced?', eleven out of twelve participants stated the desire for modified pinch gestures.

Comparing our results with previous studies? Although our conditions (mobilty + encumbrance) and materials (smartwatch vs. smartphone) differ from that of Ng et al. [30], we can still make a few broad comparisons. Ng et al. [30] reported that two-finger gestures can be performed more accurately than single-finger gestures at the expense of a slight payoff in execution time. However, this was not the case on smartwatches due to the limited screen. On smartwatches, we propose that two-finger gestures should be avoided. Ng et al. [31] found a significant difference between carrying a bag in the dominant or the non-dominant hand for target selection. However, in our case, there was no such significant difference. In our study, we found that the flick gesture remained the least affected by mobility and encumbrance as compared to the target selection. This falls in line with results from Bragdon et al. [8]. It is evident that mark-based or flicking gestures can lead to performance gain for discrete events such as navigation [20].

DESIGN FACTORS FOR SMARTWATCH USE

From our first experiment and prior work, we propose the following guidelines. Smartwatch touch interactions should:

1. avoid double-finger gestures;
2. avoid precise positioning of finger(s);
3. avoid situations with potential fat-finger and occlusion issues [16];
4. promote eyes-free interaction [20];
5. reduce the number of clutches or repetitions;
6. if clutches are required, reduce the interval time between clutches;
7. reduce screen motion during input.

Considering the above guidelines, we introduced the concept of *touch efforts*. While interacting with a touch screen, the finger(s) can either be in contact with the screen (*on-touch*) or off the screen to prepare for the next touch event (*pre-touch*). For example, while performing pinching or panning gestures on a small screen, the finger sequentially switches between *pre-touch* and *on-touch* states.

On-Touch Efforts

On-touch efforts involve actions performed while the finger is in contact with the touch screen. We consider the number of fingers, and the degree of contact involved during the *on-touch* state:

Number of Fingers: Two-finger interactions are not desirable for smartwatch input. The *on-touch* efforts can be reduced by having few fingers or ideally just one finger in contact with the screen.

Degree of Contact: The degree of contact is defined in terms of duration and motion of the touch:

- *Touch Duration:* To reduce the *on-touch* efforts, interaction techniques should aim at reducing the time during which the finger is in contact with the screen.
- *Touch Motion:* To reduce the *on-touch* efforts, interaction techniques should aim at reducing the number of pixels traversed by the finger while in contact with the screen.

Pre-Touch Efforts

Due to the limited screen size of a smartwatch, users often cannot complete the task in a single touch event. This then requires users to lift their finger(s) from the screen to perform a clutch action. We focus on the moment preceding the next contact, i.e. when users prepare their finger movement for the next touch event. *Pre-touch* efforts involve the motor (physical movements) and cognitive (visual aiming) loads required to reposition the finger(s) on the screen.

Number of Repetitions: Gestures should reduce the number of clutches (or repetitions) to complete the interaction task. After each *on-touch* state, users have to physically prepare the on-screen repositioning of their finger(s). By reducing the number of repetitions, an interaction technique reduces the overhead time required for this extra physical action.

Visual Attention: Before going in the *on-touch* state, the input gesture might require visual attention to determine a precise positioning of the finger(s). By reducing the visual attention needed for repositioning the finger, an interaction technique reduces the overhead time required for aiming and the number of potential errors.

Based upon the concept of *touch efforts*, we put forward the structure of our design-space (Figure 8). We articulate the notion of *on-touch* and *pre-touch* efforts according to two design dimensions. This allows us to visually characterize existing techniques from the literature according to their touch efforts level. Surprisingly, there is an empty space in the bottom-right corner (Figure 8, area C), i.e. the area

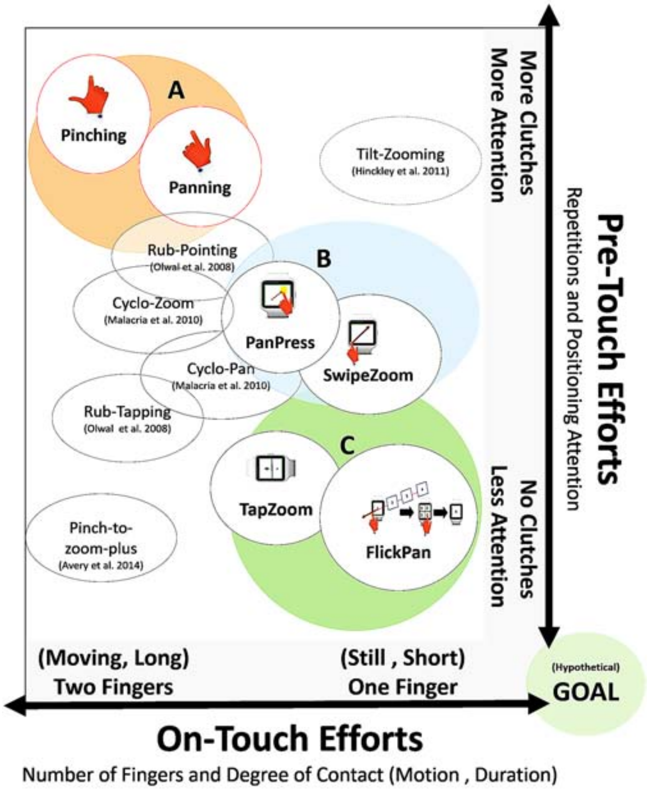

Figure 8 Design space for smartwatch interactions organized according to on-touch and pre-touch efforts dimensions. The design space reveals the area occupied by current standard techniques (A), and unexplored areas (B and C).

theoretically ideal, minimizing both on-touch and pre-touch efforts. This directs our study to explore new techniques for smartwatch interactions (theoretically) ideal under mobile and encumbered contexts.

DESIGN SPACE EXPLORATION

We hypothesize that the empty space revealed by our design space can lead to interaction techniques efficient under different levels of mobility and encumbrance. To verify our hypothesis, we propose two approaches: the *creation* and the *adaptation*. The *creation* approach leads to novel interaction techniques in unexplored areas, creating large gaps of touch effort levels between techniques. The *adaptation* approach deals with pre-existing techniques, exploring the surrounding area of their touch-effort levels.

Creation Approach

We introduce two new zooming and two new panning techniques: *SwipeZoom*, *TapZoom*, *PanPress* and *FlickPan*. The design of these techniques is based on two rationales to explore the center area and the bottom-right area of our design space. During the design process, we created the interaction techniques with two requirements:

1. Unambiguous**:** the techniques must not conflict with any known smartwatch interactions.
2. Self-Contained: the techniques must not use any external hardware, only embedded smartwatch sensors.

Figure 9: (a) SwipeZoom. (b1) initial screen. (b2) User presses in the bottom-left corner. (b3) User performs a diagonal swipe for continuously zooming in.

Exploration of the Center Area

For the design of *SwipeZoom* and *PanPress*, we decided to explore interaction techniques (1) using a single finger; (2) using as little clutch action as possible; and (3) minimizing the on-screen motions (Figure 8, area B).

SwipeZoom (Figure 9) is triggered after a 150ms touch-dwell gesture in a corner of the screen (bottom-left or top-right). Once the mode is triggered, the system displays a translucent diagonal line. Users can then continuously zoom-in (from bottom-left to top-right) or zoom-out (from top-right to bottom-left) by moving their finger along the diagonal. We chose the diagonal as it is the longest distance traversed on a rectangular screen (*pre-touch* – number of repetitions). Note that this would have no impact with a circular screen. *SwipeZoom* uses only one finger (*on-touch* – number of fingers).

PanPress (Figure 10) is triggered after a first panning gesture. The panning motion continues while the user holds the contact between the screen and the finger. The first pan gesture determines the speed of the panning (i.e. the longer distance, the faster), while the direction remains the same as the first panning direction. However, the user can adjust the direction with subtle finger motions. Users stop the panning motion by lifting up the finger. In addition to the standard panning, PanPress uses a single finger (*on-touch* – number of fingers), and aims to reduce both the need for clutching (*pre-touch* – number of repetitions) and the amount of motion of the finger on the screen (*on-touch* – touch motion).

Exploration of the Bottom-Right Area (Theoretical Ideal)

For the design of *TapZoom* and *FlickPan*, we decided to explore interaction techniques (1) using a single finger; (2) minimizing touch motions and visual attention; and (3) using discrete tap and flick gestures.

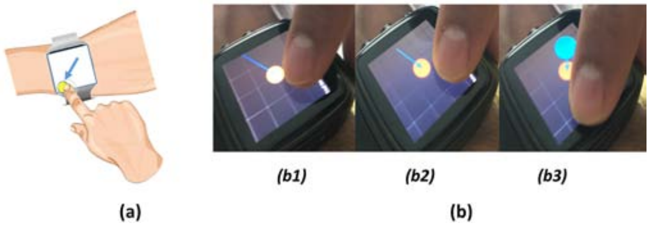

Figure 10: (a) PanPress. (b1) Initial screen. User performs a first pan. (b2) User holds contact for continuously panning. (b3) User adjusts the panning direction with subtle finger motion.

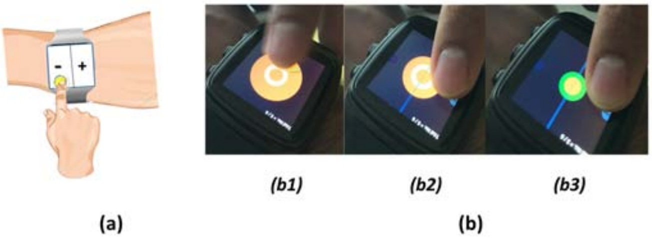

Figure 11: (a) TapZoom. (b1) Initial screen. (b2) User double-taps on the left side of the screen. (b3) User holds contact for continuously zooming out.

Indeed, although our first experiment revealed an impact of mobility and encumbrance on these gestures, we capitalize on the fact that this impact is less critical with flick, than with pan and pinch gestures (Figure 8, area C).

TapZoom (Figure 11) is triggered with a double tap and exits when kept untouched for more than one second. The screen is divided into two equal areas: left for zooming-in, and right for zooming-out. Users can then (i) tap in one area to discretely zoom in or out by 0.3, or (ii) touch-and-hold one area to continuously zoom in or out by 0.05 every millisecond. This integration of tap and touch-and-hold avails the benefits of both the discrete and continuous zooming for fast and approximate control followed by a short precise final control (*pre-touch* – clutches). Unlike *SwipeZoom*, it removes the need for moving the finger on the screen (*on-touch* – motion). This lowers the attention requirement by providing two large areas on the screen dedicated to each zooming functionality (*pre-touch* – visual attention).

FlickPan (Figure 12) is triggered with a flick gesture. Thumbnails representing the next three screens in the flick direction are displayed. The user can then return to the initial screen by pressing 'RETURN' or navigate to any other screen by tapping the corresponding thumbnail. After tapping the thumbnail, the selected screen is displayed and users can perform a standard panning gesture or trigger *FlickPan* again.

FlickPan allows for navigation of long distances with a single flick-and-tap action, allowing users to quickly skip the in-between locations between the original and the desired end-point positions (*pre-touch* – clutches). *FlickPan* reduces the motion and duration of the finger on the screen (*on-touch* – motion and duration).

Figure 12: (a) FlickPan. (b1) Initial screen. User flicks. (b2) Thumbnails of next screens (in the flick direction) appear. (b3) Selected thumbnail is now the current screen.

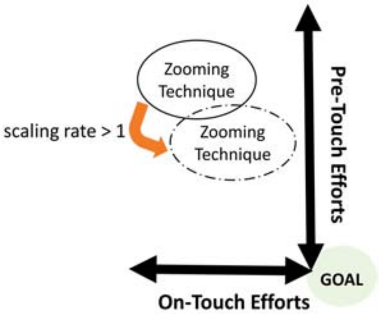

Figure 13. Illustration of the intra-technique adaptive behavior. An adaptive scaling rate can modify the *on-touch* and *pre-touch* efforts depending on the context.

Adaptation Approach

We propose two approaches based on an adaptive behavior: *intra-technique* and *inter-technique*. The *intra-technique* adaptive behavior allows designers to modify the behavior of a given interaction technique according to users' activity conditions. The *inter-technique* adaptive behavior allows designers to explore transitions between existing techniques.

Intra-Technique Adaptive Behavior

We propose an adaptive version of a given technique based on the user's activity. We define the core idea of this adaptive behavior in the context of an example. Let's consider a pinch gesture for the zooming task. When the user is standing still without bags, the content could zoom by a larger proportion than the change in distance between the two fingers (scaling rate > 1). This hence reduces *on-touch* efforts (touch motion and touch duration) as well as *pre-touch* efforts (number of repetitions) (Figure 13). The hypothesis is that users can overcome overshoot problems in comfortable settings (standing still without being encumbered). However, when running with bags, content could zoom in a smaller proportion than the change in distance between the two fingers (scaling rate < 1). This may lead to a slight increase in *pre-touch* efforts (number of repetitions) and *on-touch* efforts (duration and motion), but reduces the potential number of overshoots revealed by our first experiment. The hypothesis in this scenario is that reducing overshoot problems will decrease *on-touch* efforts (duration and motion) to a greater extent than the increase originally induced by a small scaling rate.

Inter-Technique Adaptive Behavior

The system could propose different interaction techniques depending on the activity context. For instance, a two-finger pinch gesture while standing still, and *TapZoom* when the user starts walking. However, this adaptive behavior at the system-level is theoretical at this point. We first need to evaluate each interaction technique to be able to propose relevant inter-technique transitions in the appropriate activity contexts. We hence do not consider this *inter-technique* adaptive behavior in the following experiment.

EXPERIMENT 2

All non-adaptive techniques use a panning or scaling rate of 1 in all conditions. For the adaptive versions, based on informal pilots, we chose to decrease panning (respectively scaling) rates by 0.1 (respectively 0.071) at each encumbrance level grouped by mobility level, starting from 1.3 (respectively 1.207) when standing still without being encumbered (Table 1).

Experimental Setup and Participants

Similar to our first experiment, we used 1.6kg grocery bags to simulate encumbrance conditions, the treadmill to provide different mobility levels, and the Imacwear M7 smartwatch.

We recruited 24 participants (mean age 24.042, SD 7.17, 19 males, 5 females) who received $15 gift cards for compensation. 12 participants used the zooming techniques, and 12 participants used the panning techniques.

Procedure and Experimental Design

The study lasted 1.5h per participants after which they completed NASA TLX questionnaires for qualitative data. Each task was the same as in the first experiment.

In both conditions (zooming and panning), we used a repeated-measures within-participants experimental design. The independent variables were the interaction techniques TECH (zoom condition: *Standard*, *SwipeZoom*, *TapZoom*, and their adaptive version *Standard++*, *SwipeZoom++*, *TapZoom++*; pan condition: *Standard*, *Standard++*, *PanPress*, *PanPress++*, *FlickPan*, *FlickPan++*), the mobility MOB (*Standing*, *Walking*, *Running*), and the encumbrance ENC (*Both Hands Available*, *Dominant Hand Busy*, *Both Hands Busy*). Note that since we did not find any significant difference between *Dominant* and *Non-Dominant Hand Busy* in the first experiment, we removed the *Non-Dominant Hand Busy* condition. Participants used six different interaction techniques for either the zooming or panning task. We counterbalanced interaction techniques between participants using a Latin square design. Participants could practice with the current technique as long as they wanted (~15mins based on our observations). After practice, participants performed 10 trials under each activity conditions before using the next technique. The sequence of activity conditions was randomized, and participants could rest between techniques. We collected 12 participants × 3 mobility × 3 encumbrances × 6 techniques × 10 trials = 6480 trials per condition, for a total of 12960 trials.

		Panning rate	Scaling rate
Standing	Both hands available	1.3	1.207
	Dominant hand busy	1.2	1.136
	Both hands busy	1.1	1.065
Walking	Both hands available	1.1	1.065
	Dominant hand busy	1.0	0.994
	Both hands busy	0.9	0.923
Running	Both hands available	0.9	0.923
	Dominant hand busy	0.8	0.852
	Both hands busy	0.7	0.781

Table 1: Panning and scaling rates of the adaptive behaviors.

Results

We report both techniques' names and their area in the design space to help making the connection between the results and the design space.

Comparison Between Zooming Techniques

There is a significant main effect of techniques on completion time ($F_{5,583}$=34.324, p<0.001) (Figure 14). Pairwise post hoc tests with Holm p-value corrections reveal a significant difference between all techniques (p<0.01), except between *TapZoom* and its adaptive version *TapZoom++* (p=0.47). This suggests that the effect of the adaptive behavior decreases as we go toward the bottom-right corner of the design space. Compared to the *Standard* baseline, users are 27.59% and 48.45% faster with *SwipeZoom* (center area in the design space) and *TapZoom* (bottom-right area of the design space) respectively. This validates our hypothesis of an ideal area in the bottom-right corner of our design space. To explain these results, we analyze the number of clutches and the number of overshoots (Figure 14) performed with each technique. As expected, novel techniques lead to less clutches than the baseline. However, due to its continuous nature, the SwipeZoom family (center area) leads to less clutches than the TapZoom family (bottom-right area). On the other hand, the TapZoom family leads to less overshoots than the SwipeZoom family, which explains the faster time performance.

Comparison Between Panning Techniques

Results of the panning task follow the same trends as those of the zooming task. There is a significant main effect of TECH on completion time (F5,583=21.836, p<0.001) (Figure 14). Pairwise post hoc tests with Holm p-value corrections reveal a significant difference between all

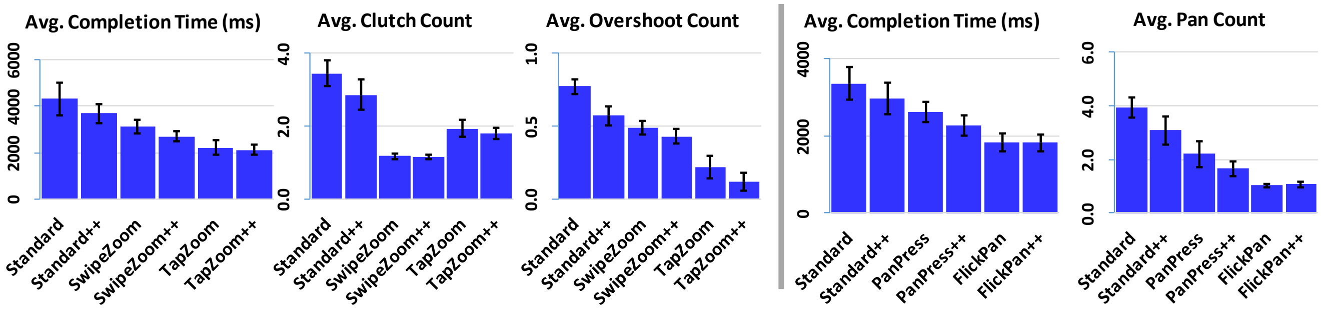

Figure 14: Zooming techniques (left): average completion time (ms), average number of zoom gestures, and average number of overshoot events. Panning techniques (right): average completion time (ms) and average number of pan gestures. Error bars represent 95% CI.

Figure 15: Effect of mobility on the average completion time for zooming (left) and panning (right) techniques (with 95% CI).

techniques (p<0.01), except for the results between *FlickPan* (bottom-right area) and its adaptive version *FlickPan++* (p=0.78). Compared to the *Standard* baseline, users are 21.79% and 45% faster with *PanPress* (center area) and *FlickPan* (bottom-right area) respectively. This validates results found for the zooming techniques.

These results can be explained by analyzing the number of pan actions (Figure 14). The closest a novel technique is to the bottom-right corner of the design space, the fewest number of pan events occur during the panning task, hence reducing the overall completion time.

Effect of Mobility on Zooming and Panning Techniques

For the zooming task, MOB has a significant main effect on completion time ($F_{2,583}$=22.05, p<0.001), leading to a longer completion time at each increase of mobility level (p<0.01) (Figure 15, left). We also found a significant MOB × TECH interaction effect on completion time ($F_{10,583}$=5.819, p<0.001). Interestingly, the closer a technique is to the bottom-right corner of the design space, the less impact mobility has on the completion time. Pairwise post hoc tests with Holm p-value corrections revealed a significant difference between all mobility conditions for *Standard* and *Standard++* (p<0.05). However, these differences between mobility levels become less present with the novel techniques and their adaptive versions the significance of the differences between *Standing* and *Walking* disappears with *SwipeZoom* (center area) (p=0.47), between *Walking* and *Running* with *SwipeZoom++* (p=0.125), and the largest gap between *Standing* and *Running* disappears with *TapZoom* (bottom-right area) (p=1.00).

For the panning task, MOB also has a significant main effect on completion time ($F_{10,583}$=2.203, p<0.001) (Figure 15, right). The MOB × TECH interaction follows the same trends as for the zooming task: all mobility levels are different with *Standard* (p<0.001), the difference between *Standing* and *Walking* (p=0.13) and *Walking* and *Running* (p=0.40) disappears with *PanPress++*, and *FlickPan* does not present any difference between mobility levels at all (p=1.00).

Effect of Encumbrance on Zooming and Panning Techniques

For the zooming task, there is a significant main effect of ENC on completion time ($F_{2,583}$=66.63, p<0.0001), leading to longer completion times at each increase of encumbrance level (p<0.0001). We also found an ENC × TECH interaction effect (F10,583=4.90, p<0.0001) (Figure 16, left). This effect is less progressive than the one we found with the mobility levels: the significant difference between *Both Hands Available* and *One Hand Busy* disappears with *SwipeZoom++* (center area) (p=0.08), and all other differences between encumbrance conditions disappear with *TapZoom* (bottom-right area) (p>0.77).

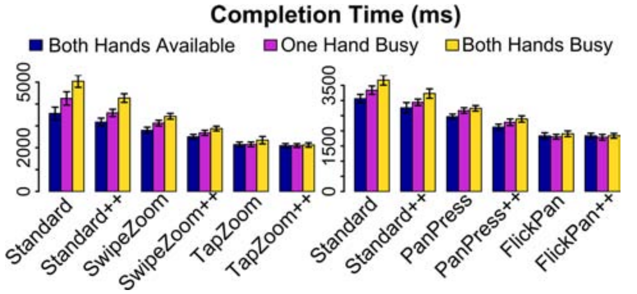

Figure 16: Effect of encumbrance on the average completion time for zooming (left) and panning (right) techniques (with 95% CI).

For the panning task, ENC also has a significant main effect on completion time ($F_{2,583}$=21.02, p<0.0001) (Figure 16, right). The ENC × TECH interaction follows the exact same trends as for the zooming task, except that the difference between *One Hand Busy* and *Both Hand Busy* disappears with *PanPress* (center area) (p=0.17) (Figure 16, right).

Qualitative Results

Interestingly, qualitative results follow the same order as defined by the position of the techniques in our design space: top-left, adaptive top-left, center, adaptive center, bottom-right, adaptive bottom-right (Figure 17). This indicates that users were able to perceive (1) the reduction in touch-efforts we considered for the design of our novel techniques, and (2) the effect of each adaptive behavior.

Discussion

We examine two aspects raised by the current work: (1) the introduction, implementation, and evaluation of four new smartwatch navigation techniques, and (2) the establishment of a new design space.

Interaction Techniques: We introduced four novel navigation techniques for smartwatches: two zooming techniques, and two panning techniques.

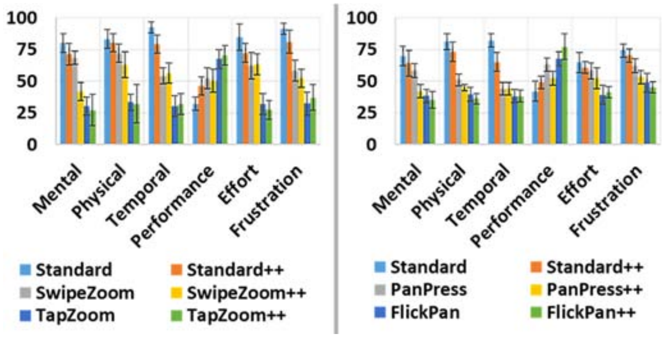

Figure 17: NASA TLX results. Participants running with bags while zooming (left), and panning (right).

SwipeZoom and *TapZoom* showed a 27.59% and 48.45% decrease in completion time compared to standard pinching gestures. *PanPress* and *FlickPan* outperformed the standard panning technique by 21.79% and 45% respectively. These techniques do not conflict with other current smartwatch interaction techniques, and do not use extra-hardware.

Design Space: We proposed a new design space for supporting mobility and encumbrance. This design space is based on the notions of *on-touch* efforts (number of fingers, degree of contact) and *pre-touch* efforts (number of repetitions, visual attention). With this design space:

- We used its *descriptive power* to organize existing techniques according to the required level of touch-efforts.
- We then used its *generative power* to identify unexplored areas and to design novel interaction techniques.
- We empirically assessed its *evaluative power*, showing that we can compare design options and their relative performance based on their position within the design space.

These two components of the present work, i.e. theoretical (design space) and practical (interaction techniques) allow us to draw three major conclusions. First, as expected, reducing *touch efforts* leads to faster completion time – for both zooming and panning techniques (Figure 18, left). Second, reducing *touch efforts* also reduces or cancel the potential negative impact of mobility and encumbrance (Figure 18, middle). Lastly, the adaptive behaviors tested in our study have less impact as the technique requires less *touch effort* (Figure 18, right).

DESIGN GUIDELINES AND KEY FINDINGS

We summarize the key findings and design recommendations from our studies:

1. To the contrary of smartphone usage, smartwatch interaction techniques should avoid two-finger gestures (experiment 1).
2. Flick-based and tap-based interactions are more resistant to mobility and encumbrance conditions than pan-based and pinch-based gestures (experiment 1).
3. Reducing theoretical touch efforts required by interaction techniques also reduces the impact of mobility and encumbrance (experiment 2).
4. We validated two methods to reduce touch efforts: the creation of novel techniques and the modification of existing techniques with an adaptive behavior (experiment 2).

CONCLUSIONS AND FUTURE WORK

Smartwatches enable access to information on-the-go, anytime and anywhere. This can lead to scenarios in which users are mobile and/or encumbered. However, current navigation techniques for zooming and panning have been directly transposed from smartphone environments to smartwatch environments. Our work investigates the impact of mobility and encumbrance on smartwatch interaction techniques.

Figure 18: The relationship between the concepts of touch efforts and completion time (left), mobility and encumbrance effect (middle), and adaptive behavior effect (right).

The first experiment revealed that standard interaction techniques are not resistant to different mobility contexts (standing, walking, and running) nor different encumbrance contexts (both hands available, non- dominant hand busy, and both hands busy). We hence proposed a design space dedicated to the design of smartwatch interaction techniques supporting mobility and encumbrance. Our design space defines a structure based on the concept of *on-touch* efforts (while the fingers are in contact with the touch screen), and *pre-touch* efforts (while the fingers are preparing the next touch event). For the second experiment, we designed and evaluated two novel zooming techniques and two novel panning techniques in unexplored and theoretically promising areas revealed by our design space. We also proposed an adaptive version of each technique. Results showed that: (i) our new techniques outperformed standard ones in all mobility and encumbrance contexts; and, (ii) reducing touch-efforts can reduce or cancel the negative impact of mobility and encumbrance. Qualitative results also showed a clear preference for navigation techniques reducing touch-efforts.

In this work, we evaluated one version of adaptive behavior for each technique. We based the scaling and panning rates on informal pilots. We plan to further study the effect of varying zooming and panning scales on each technique to better understand their influence on touch efforts. Another extension of this work can be the exploration of the relationship between touch efforts, learning efforts (motor), and memory efforts (cognitive). Such exploration could extend our 2-axes design space into a four dimensional one. Due to the precision required for navigation tasks, eye-free interaction remains an open challenge. Our work is a step toward the goal of optimal smartwatch interaction techniques by first reducing the motor requirements. Future work can consider other factors, such as feedback, to improve eye-free input.

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