Comparing Mid-air Finger Motion with Touch for Small Target Acquisition on Wearable Devices

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Abstract
Mid-air finger motion takes advantage of the vast free 3D space around a device for input. Although previous research has compared mid-air finger motion with touch for mobile and large interactive surfaces, little is known about their performance for small target acquisition on ultra-small screen devices. In this paper, we empirically study the performance of mid-air finger motion and touch as input techniques for small target acquisition on smartwatches with 16 participants. Results show that mid-air finger motion can be as fast as touch but has significantly fewer errors. No statistically significant difference has been found in either mental or physical demand while using two techniques, but mid-air finger motion technique is perceived to have better performance with less frustration compared with touch.

Author Keywords
Mid-air finger motion; ultra-small screen devices;

ACM Classification Keywords
H.5.2. Information Interfaces and presentation (e.g., HCI): User Interfaces - evaluation/methodology.

Introduction
Ultra-small screen wearable devices (*e.g.,* smartwatches and bands) have become increasingly

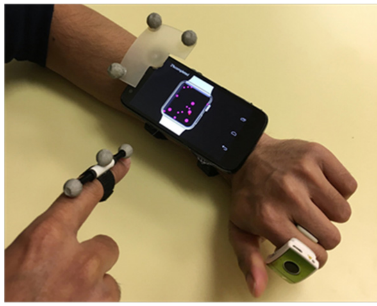

Figure 1. Mid-air finger motion for smartwatch interaction. The smartwatch is rendered at the center of a smartphone. Reflective makers on the index finger and the phone are used by VICON motion tracking system to detect their fine-grained 3D positions in real time. Button activated by the thumb is for confirming target selection. Note that the cursor rendered on the smartwatch is controlled by the relative motion of the finger and thus the user does not have to point their finger to the target as if using a laser point, and is free to move their finger in their comfortable way.

popular. They typically equip with touch screens that enable direct touch input. However, due to the extremely small screen size, UI elements have to be miniaturized to cater the limited real-estate, which intensifies the issues of touch input, such as fat-finger [19] and occlusion.

Previous research has explored different techniques to address the issues, such as augmenting touch input by introducing novel UI elements [1,10,16,18,20], reducing the touch point size [24], or moving interactions away from the touch screen [8,13–15]. For example, previous research has explored sides of devices [14], projected UIs [15], touch-sensitive wristband [5], mechanical motions [12][25], and mid-air finger motion around the device [4,11] as input methods for target selection, text entry or interactions.

In this paper, we focus on one of these techniques, mid-air finger motion, and study its use for ultra-small screen wearable devices. Although the performance of mid-air finger motion for large interactive surfaces [2,3] and mobile phones [23] have been empirically studied, little is known about its relative performance to touch on recently emerged ultra-small screen wearable devices. These devices have even smaller screen real estate than mobile devices and are also used in a different way from mobile devices and large surfaces. Understanding its performance compared to touch on ultra-small screen devices can potentially provide insights for interaction design that leverages mid-air finger motion as input technique.

In this work, we present an empirical study that evaluates the performance of the mid-air finger motion input technique (**see Figure 1**) for small target acquisition on an ultra-small screen wearable device and compares it to that of the direct touch input. With the input technique as one independent variable, we also choose the target size as the second independent variable. We measure two dependent variables: the task completion time and the miss-hits rate (error rate). We also measure participants' perceived task loads of the two input techniques. Experimental results show that the mid-air finger motion technique with a convenient selection confirmation mechanism can be as fast as the direct touch input technique, and also is significantly more accurate (with lower miss-hit rate) for target selection. Subjective assessment shows that there is no statistically significant difference in mental or physical demand for two input techniques. However, the mid-air finger motion input technique is perceived to have significantly better performance and less frustration than touch input.

Related Work

We present the touch-enhanced target selection and mid-air input techniques that motivate this work.

Touch-enhanced Techniques for Target Selection

Previous research has explored different approaches to addressing small targets selection on touchscreens. Early research typically focused on designing novel interaction techniques [1,18,20], which utilized an additional step in the interaction or extra space on screen. However, these techniques are not specifically designed for ultra-small screen devices.

Mid-air finger motion Interaction Techniques

Recently, mid-air interaction has been spotlighted in various areas such as desktop [17], large-display [2,3], and mobile phone [3,8,11,13].

Jones et al. [11] studied the target acquisition task on a mobile phone by using freehand gesture in its surrounding 3D space. Their study confirmed mid-air space around the device provide natural user experience and alleviate screen occlusion issue. Our work extends this work by examining the performance of mid-air finger motion being used in a different form factor, ultra-small screen devices.

Abracadabra shows the promise of mid-air finger motion for interacting with small devices.[8]. The magnetically driven sensing technique was used to control a 1D polar cursor for 1D wedge shaped buttons selection. Our work builds upon this idea and explores higher precision & resolution mid-air finger motion for 2D small target selection on ultra-small display devices. Our findings contribute to the understanding of the differences between mid-air finger motion and touch for 2D small target selection on ultra-small display devices.

Previous research also tries to enrich smartwatch interaction by using mechnical motion of the watch [25], tilt of the device [7], or the smartwatch band [5]. We choose to focus on exploring the performance of mid-air finger motion for the scope of this study and leave comparasion with these techniques for future work.

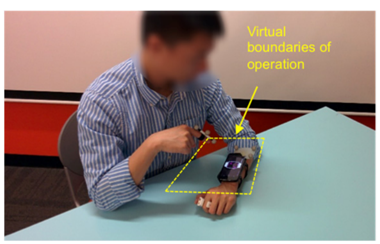

Figure 3. The user can position his finger in a comfortable position, and then move from that position.

Experiment

Apparatus & Participants

Two android applications, one for measuring touch input (APP1) and one for measuring mid-air finger motion (APP2), were implemented on a mobile phone running Android 4.2 (Moto G) by creating a squared interactive area of size 3.5cm x 3.5cm to simulate a smart watch (see **Figure 2**). APP2 renders a cursor, and responds to user input by moving as the pointing

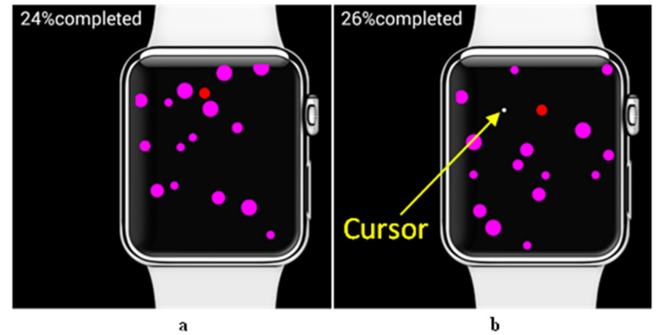

Figure 2. The target acquisition task: (a) APP1 for touch. (b) APP2 for the mid-air finger motion. Red circle is the target.

finger moves. Our system tracks the positions of the smartwatch and the user's index finger using VICON motion capture system [26]. We use VICON to simulate future high-precision non-obstructive finger tracking technique because we are interested in studying how mid-air finger motion will change wearable interactions compared to touch. Reflective markers attached to the smartphone are used to compute the pose of the device while markers on the index finger are used to compute the finger's position (see **Figure 1**). Our system computes the fingertip's position with respect to the simulated smartwatch, calculates the relative motion of the fingertip in two adjacent frames and maps it to the movement of the cursor with a constant scaling ratio α in real time. α is chosen for optimal moving speed based on the results of the pilot study with five participants and is kept constant for all participants in the experiment. Such mapping design allows users to move their finger in a finite area (see **Figure 3)**. The cursor is initially rendered at the center of the screen when the experiment starts. To confirm a target selection, participants click the button on a Genius wearable controller [27] worn on the index finger of the arm that wears the simulated smartwatch. Participants are free to adjust their index finger with tracking markers to a comfortable position before pressing the button on the Genius wearable controller to start the experiment. In our study, we did not observe any noticeable hand shaking due to clicking the thumb controller that could affect the target selection. The cursor will stop at the smartwatch boundary even if they keep moving their fingertip in the same direction. The cursor will move back immediately when they move back their fingertip.

We recruited 16 participants (graduate students-5 females). All were right-handed and aged between 22 and 31 (μ=24.6, δ=2.7). All participants were familiar with touch-based devices, however participants had little experience with smartwatches (median experience score is 1 with 0 for no experience at all and 5 for the highest experience). All participants were compensated with candy when they completed the experiment.

Experimental Design

The experiment follows a 2 x 5 within-subjects design. The independent variables are the input technique (2 levels: touch and mid-air finger motion) and the target size (5 levels: 3.42, 2.96, 2.50, 2.02 and 1.56 in mm). The biggest size is the same as the size of a number key in QWERTY keyboard when it is displayed on the simulated smartwatch. Other sizes are chosen to examine the performance of smaller target selection Dependent variables are task completion time, error-rate, and task workload [9]. We randomized the sequence of target sizes and their positions in which they appeared during each trial. To reduce the learning effect, we counterbalanced the input techniques administered to participants: 8 started with mid-air finger motion while the other 8 started with the touch. There were 32 trials (16 x 2) with 3200 data points (100 targets per trial).

Tasks and Procedures

We started by collecting participants informed consent and basic demographic information. We then introduced the study objective and each technique. For the touch based target acquisition task, participants were asked to locate and tap on the red circle (see **Figure 2** (a)) among other circles. In mid-air finger motion based task, the participants were asked to move the cursor to the red circle by moving their finger and confirm the selection by pressing the button on the thumb controller. Before each trial, a short training session was provided to allow participants to practice and get familiar to each technique. Each trial consisted of selecting 100 targets. The participants were given 5 minutes break between the trials. At the end of each trial, participants were asked to fill in a task load assessment questionnaire.

Measures and Data Collection

We measure *task completion time*, *error rate*, and *perceived task workload*. Completion time is the time taken to select a target. The counting starts as soon as the target appears on the screen and stops when the participants hits the target. Considering that participants might not be able to select a target and thus cannot proceed to the next task, we set a timeout time (15 seconds) to let participants continue to the next target. Data from time out trials is not used for the statistical analysis of the completion time but will be considered for error rate computing.

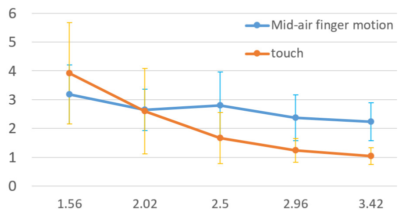

Figure 4. Mean and standard deviation (STD) of the completion time (vertical axis: seconds) for 5 target sizes (horizontal axis: mm).

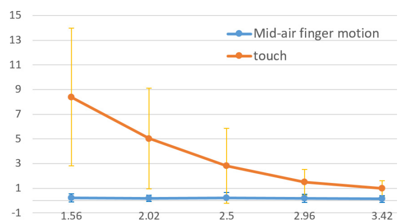

Figure 5. Mean and STD of miss-hits for 5 target sizes (vertical axis: number of miss-hits; horizontal axis: mm).

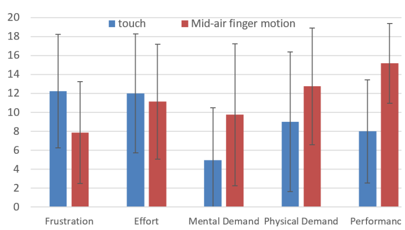

Figure 6. Mean and STD of subjective ratings of task load (vertical axis: ratings, 10 is neutral).

Error rate is defined as the total number of miss-hits for all target selection trials before the participant successfully acquired the target or the time is out divided by the total number of targets in the task. Task workload measures the participant's subjective assessment of mental demand, physical demand, effort, frustration, and performance [9].

Results

Completion Time

The average target completion time for each input technique and the target size is shown in Figure 4. The average completion time for mid-air (μ = 2.648s, δ = .930) is longer than that of touch (μ = 2.093s, δ = 1.529). However, two-way repeated measure ANOVA results show that the difference of the completion time between two input techniques is not statistically significant ($F_{1,15}$ = 4.048, *ns*). Results show that the difference of the completion time among different target sizes is statistically significant ($F_{4,60}$ = 39.712, $p < .001$). Results also show the interaction term (input technique * target size) has a significant effect on the completion time ($F_{4,60}$ = 8.683, $p < .001$). It suggests that Mid-air finger motion might be faster than touch for smaller target sizes (e.g., 1.56mm and 2.02mm).

Error Rate

The means and standard deviations of miss-hits of all target sizes using two input techniques are shown in Figure 5. It shows that: 1) the number of miss-hits for mid-air finger motion is much smaller than that of touch for all target sizes; 2) the number of miss-hits while using touch input decreases as the target size increases. In contrast, the numbers of miss-hits while using mid-air finger motion for all target sizes are always extremely small. Two-way repeated measure ANOVA results show that the input technique ($F_{1,15}$ = 31.207, $p < .001$), the target size ($F_{4,60}$ = 22.886, $p < .001$) and the interaction term ($F_{4,60}$ = 22.282, $p < .001$) all have significant effects on the miss-hits. Results suggest that mid-air finger motion is more accurate than touch for all tested target selection.

Subjective Measurements

The post-questionnaire results are shown in **Figure 6**. The answers were ordinal data and lacked normality, we thus applied Wilcoxon Signed-Rank test on them. Results show that participants felt that mid-air finger motion: 1) was not more physically demanding than touch (z = -1.636, *ns*); 2) was not more mentally demanding than touch (z = -1.891, *ns*); 3) did not require significantly more effort than touch (z = -0.456, *ns*); but 4) was perceived to have higher performance than touch (z = -2.901, $p < .05$); 5) was significantly less frustrating than touch (z = -2.010, $p < .05$);

DISCUSSION & FUTURE WORK

Experimental results show that the completion time of mid-air finger motion is not statistically different from that of touch. It contradicts with the intuition because mid-air finger motion seems to require participants to put more effort in controlling their finger than touch does. One possible explanation is that participants used the thumb controller to confirm the selection, which allowed target selection to happen as soon as the cursor landed on targets. It implies that mid-air finger motion with a convenient and accurate selection confirmation strategy can be as fast as direct touch. Recognizing the gesture of the thumb tapping on the index finger [22] may be a promising substitution of the thumb controller we used in our experiment.

The results also show that the extremely small targets (*e.g.,* 1.56mm) can be significantly more difficult to select for both input techniques. As a result, 1.56mm and even smaller sizes should be avoided even for mid-air finger motion, that has little or no occlusion or fat finger effect. In contrast, there is no statistical significant difference among relatively bigger sized target selection using mid-air finger motion. It suggests that the size of UI components can be reduced if needed while using mid-air finger motion.

Mid-air finger motion yields significantly fewer errors and better performance than touch. This might be due to the alleviated fat finger and occlusion issues, because the finger controlling the cursor moves outside of the screen area, which provides the user with unblocked continuous real time visual feedback.

Our experimental results have a reasonable level of external validity. Participants were not forced to rest their arms on the desk surface. Instead, they were informed to position their arm in a natural posture comfortable for performing mid-air finger motion. This decision of allowing participants to freely use a posture they were pleased of was based upon the assumption that interaction sessions with wearable devices tend to be short [6] and the fatigue caused in resting and not resting arms in real world will likely not be significantly different. Previous research has also found no significant performance difference between the seated and standing position while using mid-air finger motion in short study sessions [8]. We thus believe that the findings of our study can be used as a reasonable reference for similar conditions as well (such as sitting without supporting surface for short period of time and standing still for short period of time). However, in the walking condition, the motion of arms will change the user's behaviour in target selection, which deserves further validation.

We focused on exploring the performance of the mid-finger motion for target acquisition on ultra-small screen devices and thus used an external high-precision tracking system, which limits the practicality of using the approach in the wild. Recent advances in unobtrusive and high-precision finger tracking (*e.g.*, Project SOLI [21]) make mid-air finger motion closer to be infrastructure independent. Thus, it is also worth exploring how it performs in the wild with such infrastructure independent techniques.

Conclusion
In this paper, we empirically studied the performance of mid-air finger motion as input technique for small target acquisition on ultra-small touch-screen devices in the sitting condition, and also compared it with the touch input. Results show that mid-air finger motion can be as fast as touch yet cause fewer errors. No statistically significant difference is found in mental or physical demanding while using two techniques. Mid-air finger motion has a higher perceived performance and less perceived frustration than touch. In the future, it is worth exploring the mid-air finger motion for target selection on ultra-small screen devices in the walking condition with infrastructure-independent finger motion detection technique and non-instrumented target selection confirmation mechanism.

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