NanoStylus: Enhancing Input on Ultra-Small Displays with a Finger-Mounted Stylus

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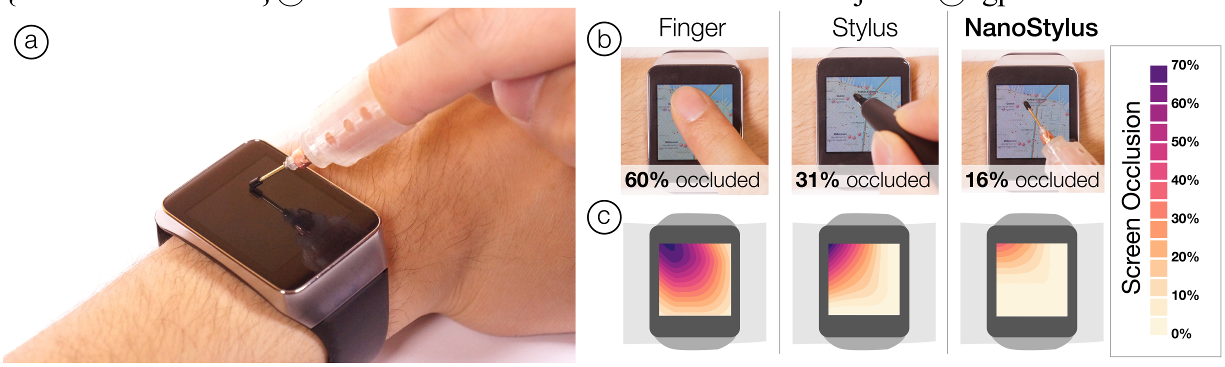

Figure 1. a) The NanoStylus is a finger-mounted stylus which improves touch precision on ultra-small devices. b) Compared to direct touch and a traditional stylus, the NanoStylus significantly reduces occlusion. c) The heat maps show the estimated percentage of the display that is occluded when pointing at each coordinate on the smartwatch surface.

ABSTRACT

Due to their limited input area, ultra-small devices, such as smartwatches, are even more prone to occlusion or the *fat finger problem*, than their larger counterparts, such as smart phones, tablets, and tabletop displays. We present NanoStylus – a finger-mounted fine-tip stylus that enables fast and accurate pointing on a smartwatch with almost no occlusion. The NanoStylus is built from the circuitry of an active capacitive stylus, and mounted within a custom 3D-printed thimble-shaped housing unit. A sensor strip is mounted on each side of the device to enable additional gestures. A user study shows that NanoStylus reduces error rate by 80%, compared to traditional touch interaction and by 45%, compared to a traditional stylus. This high precision pointing capability, coupled with the implemented gesture sensing, gives us the opportunity to explore a rich set of interactive applications on a smartwatch form factor.

INTRODUCTION

Smartwatches have become increasingly popular in recent years, bringing convenience to basic tasks, such as checking a calendar and setting an alarm. These devices typically rely on touch as their primary input modality. While the fat finger problem [37] occurs on any touch device, the problem is exacerbated by the ultra-small display size of a smart watch, where a single finger can easily occlude more than half of the display (Figure 1b, c).

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One approach to address this issue is to displace the interaction away from the watch face using hardware augmentations [29, 40]. Unfortunately, this negates the direct interaction paradigm that users have become accustomed to. Alternatively, designers can adapt the user interface for lower-precision input, such as supporting swipes [14], or multi-level taps [31]. However, such interactions limit the tasks and interfaces that can be presented.

With continued improvements to computation and battery technologies, complex tasks on small devices are now feasible. As such, we are motivated to seek out alternative input modalities that can enable rich graphical applications on smartwatches, such as image manipulation and email organization. While it is unlikely users would conduct such tasks for long periods on a smartwatch, short bursts of interaction can be foreseen, given their ease of access [6].

In this paper, we present the NanoStylus, a finger-mounted stylus. The device is built from the circuitry of an active capacitive stylus, mounted within a custom 3D-printed thimble-shaped housing unit (Figure 1a). An ultra-thin nib effectively eliminates occlusion and enables high-precision input on a smartwatch (Figure 1b, c). Additional touch sensors are used to turn the sides of the NanoStylus into 1D touchpads. Tapping, holding, and swiping are detected on both sides independently, yielding a rich set of gestures.

In the following sections, we detail our exploration of the possible form factors of a finger-mounted stylus, and then describe our implementation of the NanoStylus. A target acquisition study shows that the NanoStylus is 80% more accurate than touch, and 45% more accurate than traditional touch, while maintaining similar acquisition times. We then describe the set of gestures enabled by the NanoStylus and demonstrate sample interaction scenarios which they enable.

RELATED WORK

Our research draws from several areas of related work: interaction techniques developed for wrist-worn devices, finger-mounted wearables, stylus interaction, and small target acquisition.

Interaction Techniques for Wrist-worn Devices

Despite the ultra-small form factor of wrist-worn devices, touch is still the primary input modality on most commercial devices, exacerbating the *fat finger problem* [37]. One approach to addressing this problem is modifying the interface. For example, ZoomBoard [31] and Swipeboard [14] use iterative zooming and swiping on the touch screen to enable text entry on ultra-small devices.

Utilizing other available space on wrist-worn devices is another possible solution. EdgeTouch [29] enables a set of grasp gestures by bringing touch sensing to the edge of the device. Xiao *et al.* [40] propose using the watch face as a mechanical interface to support navigation on a smartwatch. Facet, consisting of multiple touch-sensitive displays, enables touch interaction to span across multiple segments [27]. NanoTouch [7] uses touch on the backside of the device to avoid finger occlusion.

Using space around the watch for input has also been explored. Skin buttons [26] are icons projected onto the skin around the watch. Abracadabra [18] enables finger tacking and gesturing above the watch with a finger-worn magnet. Similarly, Gesture Watch [24] senses hand gesture made over the device by instrumenting an array of infrared proximity sensors to a watch.

The above review shows promising input techniques for wrist-worn devices. However, many require the watch to be augmented with additional hardware and sensing technologies, and most act as indirect control to the graphical interface on the screen. Our work attempts to enable high precision and direct input, by enhancing the finger, and not the watch.

Finger-Mounted Wearables

Prior work has explored different input and output capabilities of finger-mounted devices. The use of a ring form-factor has been a common approach of many of these works. The Nenya ring [5], made from a strong permanent magnet, can be tracked by a magnetometer worn on the wrist. iRing [30] uses infrared reflection sensor to sense the physical force on it. LigthRing [23] senses the fine-grained fingertip movements on a 2D surface.

Sensing devices have also been instrumented on other positions of hand. uTrack [13] converts the user's thumb and finger into a 3D input system with magnetic field sensing. FingerPad [11] uses a similar technique to turn the tip of the index finger into a touchpad. The Magic Finger [41], worn on the tip of the index finger, enables always-available touch input on physical surfaces and supports contextual actions by sensing the surface's texture.

These finger-mounted wearables enable mid-air input, or input on objects in the physical environment. Closer to our work, the NailDisplay [36] explores precise pointing on a smartwatch by simulating a transparent finger using a display worn on the fingernail. While participants found the technique useful, the vertical separation between the display and touch surface was reported as being problematic. Our work also augments the finger to support precise touch, but still supports direct interaction with the display.

Stylus Interaction

Since Fitts' early work on human motor control [16] the performance of stylus input has been widely examined [15, 28, 33], and shown to be an accurate alternative to touch input [15]. Research in pen-based computing has also demonstrated how additional input channels can be used to enable novel interactions, such as pressure [32], orientation [38], roll [9], and hover [17]. Other works [20, 35] explore the interaction possibilities enabled by sensing hand grips and touch gestures on the barrel of a stylus.

While such techniques provide inspiration for our work, their implications to smart watch interaction have not been explored. We build upon these techniques and adapt them to an interactive finger-worn form factor, to enable interaction with ultra-small devices.

Small Target Acquisition

Small target acquisition is a well-explored problem in the research literature [12]. A number of works have explored the limit of the human motor system with different input techniques [15, 28]. The stylus has been shown to be more accurate for selection, especially for target sizes close to 5mm, where touch becomes unreliable [10, 15]. Holz *et al.* showed how specialized hardware could be used to improve touch accuracy by sensing fingerprints [22].

Numerous software techniques have also been proposed to support ultra-small target acquisition [3, 8, 39, 42]. Although promising, most software techniques require additional input or display space, which is rarely available on an ultra-small device. NanoStylus is a straightforward approach for acquiring small targets that does not require software enhancements or additional screen real-estate.

Commercial Finger Styluses

It is important to acknowledge that a variety of passive finger-based styluses have been developed commercially[1][2], for use of tablets and smartphones. However, these passive devices need to be almost as large as the finger itself to be sensed properly on a smart watch. Furthermore, there is no academic literature discussing their implementation or reporting their performance. Our work investigates an active finger-based stylus with a smaller tip, specifically designed for high precision, which also enables interactive gestures through side-mounted touch pads.

[1] http://www.txtrng.com/
[2] http://www.usetechtips.com/

FORM FACTOR CONSIDERATIONS

Before arriving at our implementation of the NanoStylus, we first explored the possible form factors of a finger based stylus. To aid our explorations, we conducted a series of informal pilot observation sessions. We 3D printed a series of designs varying in shapes and sizes (Figure 2). For each design, a case was worn on the end of the index finger, and a small pipe extruded out which could house a standard pencil refill. We gathered feedback on these design variations from internal participants, who were asked to point and write with the stylus on physical paper.

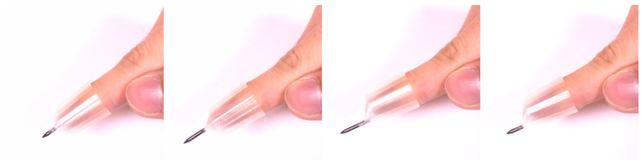

Figure 2. A series of design variations were 3D printed to gain initial insights on the possible form factors. Shown above are two of the variations in nib position and nib length.

Nib Size

Stylus Nib size has been hypothesized to influence pointing accuracy for hand-held styluses. Ren *et al.* [33] suggested that a nib size of 0.5mm was the best choice for pen interaction on a PDA with a *resistive* touch screen. On the contrary, Annett *et al.* found that participants were not receptive to nibs finer than 1.6mm [4]. We adopt a 2mm nib size, which is the finest nib that can function properly on today's *capacitive* touch screens.

Nib Position

The placement of the nib determines the contact point relative to the finger location. One option is to place the nib directly under the finger pad. However, this design would not aid in the occlusion problem. Instead, we explored various options for extruding the nib away from the finger. Extruding the nib directly from the center was preferred by participants, as they felt it provided the best control. Users commented: "*the nib is along the projection of my index finger*" and "*I feel my finger is prolonged and sharpened*".

Nib Length

We also explored the effect of different nib lengths, by varying the length and position of the pencil refill. Since the human finger has a natural tremor, the longer tip felt less accurate to participants, making it more difficult to control the position of the endpoint. However, participants reported that with the longer nib, less effort was needed to move the nib from one position to another, as they could leverage angular movements of the finger. Additionally, the longer nib reduced the extent of occlusion over the writing surface. Given these potential trade-offs between speed, accuracy, and occlusion, we defer our recommendation of nib length, and will later present a study that we used to better understand the optimal nib length.

Additional Observations

In general, pointing and writing with the finger stylus seemed to work well. A number of participants commented that the finger stylus felt like an extension of their own finger. One important observation we made was that participants tended to hold their thumb on their index finger, for stabilization. Without this stabilization, it was difficult to accurately control to stylus nib. As such, the designed form factor should allow for comfortable placement of the thumb on the side of the finger.

NANOSTYLUS IMPLEMENTATION

Guided by our exploration of the possible form factors, our goal is to develop a finger-based stylus that is capable of high-precision input, minimizes occlusion, and works with today's off-the-shelf smartwatches. Our prototype is built from a disassembled active capacitive stylus, housed in a custom 3D-printed case that fits on the index finger (Figure 3). A circuit board and power source are mounted on an arm band, but we envision a future implementation where any circuitry is encased within the finger-mounted case.

Figure 3. The NanoStylus consists of a disassembled active capacitive stylus, housed in a custom 3D printed case that fits on the index finger. A circuit board and power source are mounted on an arm band.

Stylus Sensing Technologies

The majority of today's touch sensitive devices are implemented using capacitive touch screens. These touch sensors contain drive lines, which emit signals, and sense lines, which receive signals (Figure 4a). If a finger is present, part of the signal is drawn by the finger, causing a voltage drop on the sense lines. This triggers a touch event.

There are two types of styluses that can be used to activate the touch sensor: passive and active. Passive styluses are made of conductive material but have no electronic parts. However, they typically need a large deformable nib (i.e., 5.6mm) to draw enough signal from the drive lines to trigger a touch event (Figure 4b). Instead we leverage an active stylus, which sends electric signals to the touch sensor, allowing the use of a smaller nib (i.e. 2mm) (Figure 4c).

Because of its smaller tip size, an active stylus needs to send a strong negative charge to the sense lines to create the required voltage drop. To do so, an active stylus requires: i) a conductive nib to receive the signal from the drive lines; ii) a circuit to amplify the signal; iii) a battery to provide power to the amplifying circuit; and iv) a conductive stylus cover to send charge to the human body (Figure 4c).

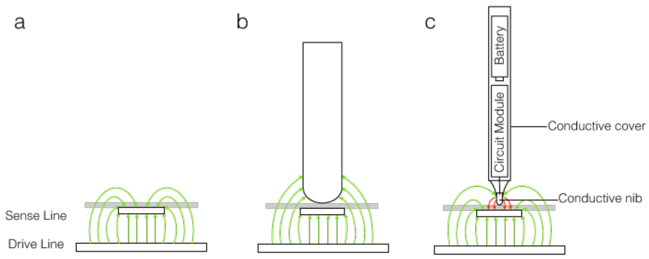

Figure 4. a) Schematic of a capacitive touch screen. b) A passive stylus requires a large tip to trigger a touch event. c) An active stylus can achieve a smaller tip size by actively sending a negative charge to the sense lines.

Active Stylus Hardware

Our prototype is built using the hardware from a Songtak Active SENSE stylus [2] which has a 2mm nib. To achieve a finger-worn form factor, we disassembled the stylus and removed the circuitry from its body (Figure 5a), and separated the nib from the circuit board. To preserve the signal picked up by the tip and to avoid oscillations, a low-resistance shielded wire was necessary to connect the nib and circuit board (Figure 5c).

The stylus circuitry includes an outer metal pipe (Figure 5b) to form a connection between the circuit board and the metal body of the stylus. This is required to charge the human body with the amplified signal. To preserve this connection to the human body, we affixed a sheet of conductive copper tape to the metal pipe (Figure 5c), and placed the sheet as a band around the users forearm. A Velcro strap was used to secure the conductive sheet, battery, and circuit board, onto the users forearm (Figure 3).

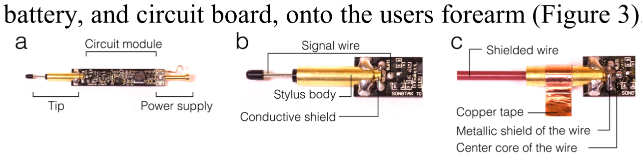

Figure 5. a) Circuit of the active stylus removed from its body. b) Zoomed view of the tip. c) For the NanoStylus, shielded wire is used to separate the tip from the board; Copper tape forms the connection between the circuitry and human body.

Housing Unit

The housing unit which is worn on the index finger consists of two parts, a case and a head. The case is worn on the finger and does not contain any of the device hardware. We 3D printed several plastic cases with different inner radii to fit fingers of different sizes. Small ventilation holes were placed throughout the cases to prevent the accumulation of sweat (Figure 6c).

The head was also 3D printed as a separate piece (Figure 6a). A metallic cylinder extrudes directly from the center of the head. A metallic tube is placed within this cylinder, which houses the stylus nib. The nib from the active stylus was mounted on a small conductive brass rod (diameter = 1mm). The brass rod can easily slide in and out of the cylinder, so that its size can be easily interchanged. The shielded wire is soldered to the base of the metallic cylinder, and connects to the arm-mounted circuit board. A strip of copper tape is wrapped around the base of the head to shield the finger from the nib. Figure 6b illustrates the connection between the nib and the circuit board.

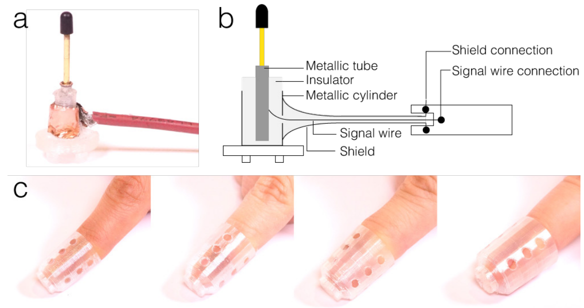

Figure 6. a) The head was designed to hold the stylus nib. b) Connection between the head and the circuit board c) A series of case sizes were 3D printed, which were worn on the index fingers. Holes in the case improve finger ventilation.

At the bottom of the head is a physical socket connection which is used to connect the head to the case. The socket connection snaps securely together but was detachable. This allows users to choose a case size that fits properly. Once the unit is powered on, the nib will trigger touch events on any traditional capacitive touch screen. In our tests, the device successfully provided input on all smart phones (iPhone 5/6, Samsung GALAXY S4) and smartwatches (Moto 360, Samsung Gear Live, and LG G Watch R).

STUDY #1: NIB LENGTH

In our pilot study, we observed possible effects of nib length on performance. This study was used to better understand the impact of nib length and to choose an optimal length for the NanoStylus.

Participants

We recruited 12 right-handed participants, 6 female, aged 20-37, from the local community. All participants were smartphone users, with two of them owning smartwatches. Participants received a $25 Amazon giftcard.

Apparatus

A target selection task was implemented on a Samsung Galaxy S4 smartphone. The smartphone was used for the study as its touch sensor is more accurate than existing smartwatches. A region of 29.3mm by 29.3mm (1.63inch diagonal), was used on the smartphone screen to simulate the smartwatch surface area. Touch events outside this region were ignored. Participants wore the NanoStylus on the index finger of their dominant hand. The smartphone was affixed to the non-dominant wrist with a Velcro strap.

Design

A repeated measures within-participant design was used. The independent variables were: *Width*, the diameter of the target (1.5, 2.0, 2.5, and 3.0mm); *Distance*, the distance between targets (3.0, 6.0, 9.0, and 12.0mm); and *Length*, the length of the nib, measured from the base of the head to the tip of the nib (15, 20, 25, and 30mm) (Figure 7).

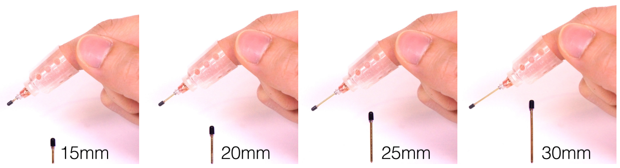

Figure 7. The four nib lengths tested in the study.

To reduce potential learning effects, the study consisted of 3 blocks, with participants completing trials for all four tip lengths in each block. The order of *Length* in each block was counterbalanced across participants using a Latin Square design. For each *Length*, participants were presented with the 16 *Width-Distance* target conditions in randomized order. Within each of these conditions, there were 5 repetitions, with the target position randomized for each trial. In total, there were: 3 blocks x 4 lengths x 16 conditions x 5 repetitions = 960 trials per participant.

Procedure and Task

Participants were first given instructions on how to use the apparatus, followed by a 10 minutes training session with different nibs. Participants were instructed to acquire the targets as accurately and quickly as possible. Given our prior observations, we specifically asked the participants to put their thumb on the side of the NanoStylus for stability.

At the beginning of each target condition, the screen displayed a green target (diameter = 2.3mm) in the center of the screen. Participants were instructed to acquire the green target to begin the trials. Immediately after the touch point hit the inside of the target, a new target would be displayed, until all 5 targets for a condition were acquired. If the participants failed five times in a row, the next target would be displayed automatically. Participants took a 5-mintute break between blocks.

Measure and Analysis Methodology

Movement time was measured from the take-off event of the previous target to the land-on event of the current target. Trials, in which the participants failed to acquire the target on the first tap, were marked as errors and not counted towards our calculation of movement times. Trials that took more than 4 seconds were marked as outliers and removed from the recorded data (0.2%).

Results

Error rate

A repeated measures analysis of variance found significant effect of *Length* on error rate ($F_{3,33} = 16.12$, $p < 0.01$). The mean of error rates were 9.1%, 12.0%, 14.6%, and 21.4% in order of increasing nib lengths. Post-hoc pairwise comparison with Bonferroni correction revealed significant difference in *Length* between 15mm and 25mm, ($p < 0.05$), 15mm and 30mm ($p < 0.01$), and 25mm and 30mm ($p < 0.01$) (Figure 8a). These results indicate that nib length does indeed influence accuracy: the shorter the nib, the more accurate.

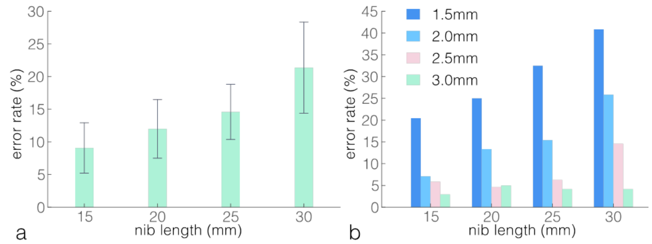

Figure 8. a) Accuracy for each nib length. b) Accuracy by target width.

This effect is reinforced when the accuracy levels are separated by target sizes. There is a significant effect of *Width* on error rate ($F_{3,33} = 130.23$, $p < 0.001$) and significant interaction effect between *Length* and *Width* ($F_{9,99} = 3.33$, $p < 0.01$). As shown in Figure 8b, the difference between nib sizes is more pronounced for the smaller target sizes. However, even for the smallest nib size, the error rate for *Width* 1.5mm is 20.4%. Therefore, targets for the NanoStylus will need to be at least 2.0mm, where the error rate is 7.1%. There was no significant effect of distance on error rates.

Movement Time

The mean of movement time by *Length* is shown in Figure 9. There was a significant effect of nib length on movement time ($F_{3,33} = 3.87$, $p < 0.05$). Post-hoc pairwise comparison with Bonferroni correction revealed significant difference in *Length* between 15mm and 20mm ($p < 0.001$), and 15mm and 30mm ($p < 0.001$). However, these differences were not as pronounced as the differences in error rates. There was also a main effect of target size ($F_{3,33} = 40.14$, $p < 0.001$) and target distance ($F_{3,33} = 80.73$, $p < 0.001$) on movement time, but neither had a significant interaction effect with the nib size.

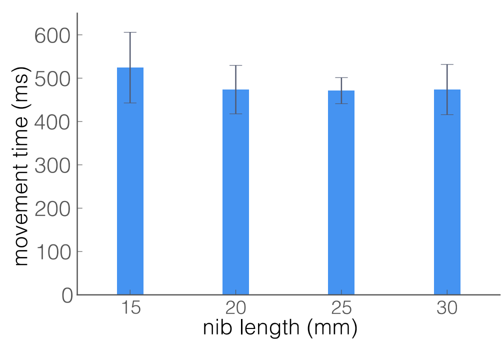

Figure 9. Movement time for each nib length.

Summary

Among all nibs the 15mm and 20mm lengths are most promising. The 15mm nib was the most accurate (9.1% vs 12.0%, ns), while 20mm was slightly faster (514ms and 466ms, $p < .001$). This may be a classic speed accuracy tradeoff; however, our analysis does confirm that error rates will increase with nib length. Because the 20mm nib will also reduce occlusion compared to the 15mm nib, we use a length of 20mm in our implementation of the NanoStylus.

STUDY #2: COMPARISON EVALUATION

Having identified a suitable nib length for the NanoStylus, we now compare the performance of the NanoStylus with more traditional techniques for pointing on touch devices.

We compare the finger stylus to a handheld stylus (*Stylus*) and to standard touch input (*Touch*). As shown in Figure 10, the NanoStylus not only differs from a traditional stylus by how it's held, but it also has a longer nib length. To isolate which, if either, of these factors might cause a performance difference, we also include a handheld stylus that uses the exact same nib as the NanoStylus (*StylusNib*) (Figure 10c). We custom built this stylus in a similar manner to the NanoStylus, and controlled its weight to be equal to that of the traditional handheld stylus (27 grams).

In addition, we wanted to further investigate the effect of using the thumb to stabilize the positioning of the NanoStylus. As such, we included two conditions for the NanoStylus, one in which the thumb was used for stabilization (*NanoStylusThumb*), and one in which it wasn't allowed (*NanoStylus*). To summarize, five conditions are compared in our evaluation study: *NanoStylus, NanoStylusThumb, StylusNib, Stylus, and Touch* (Figure 10).

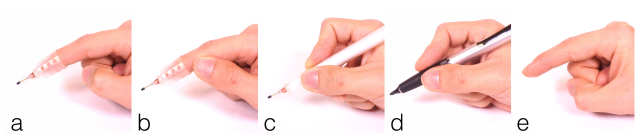

Figure 10. The five techniques used in the comparison evaluation: a) *NanoStylus,* b) *NanoStylusThumb,* c) *StylusNib,* d) *Stylus,* and e) *Touch*.

Participants

We recruited 10 new right-handed participants (4 female) from the local community, aged 21-35, all with exposure to touch screen devices. Participants received a $25 Amazon gift card for a one-hour session.

Experiment Design and Procedure

The task, procedure, and design were identical to the first study, with the exception of the 5 new input techniques replacing the 4 nib sizes in the study design. In addition to the 5 techniques, the independent variables were *Width* (1.5, 2.0, 2.5, and 3.0mm), and *Distance* (3.0, 6.0, 9.0, and 12.0mm). The ordering of *Technique* within each block was counterbalanced using a Latin Square design. A short questionnaire was administered after the study.

Results

Error rate

A repeated measures analysis of variance found significant effect of *Technique* on error rate among different devices ($F_{4,36}$ = 46.50, $p < 0.001$). The overall error rates were 19.5% for *NanoStylus*, 11.8% for *NanoStylusThumb*, 17.4% for *StylusNib*, 21.5% for *Stylus*, and 54.0% for *Touch*. Post-hoc pairwise comparison with Bonferroni correction showed that *NanoStylusThumb* was significantly more accurate than *NanoStylus* ($p < 0.05$) and *Stylus* ($p < 0.01$), and that *Touch* was significantly less accurate than all the other devices ($p < 0.001$) (Figure 11a). *Width* had a significant effect on error rate ($F_{3,27}$ = 79.86, $p < 0.001$), with smaller targets having higher error rates (Figure 11b), but there was no interaction effect with *Technique. Distance* did not have a significant effect on error rate.

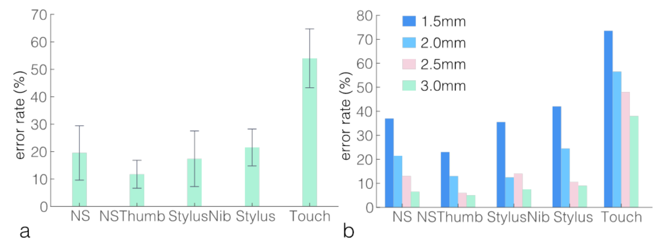

Figure 11. a) Error rates by *Technique*. b) Error rates for each individual *Width*.

Movement Time

Technique also had a significant main effect on movement time ($F_{4,\ 36}$ = 4.19, $p < 0.01$) (Figure 12). *NanoStylus* (without thumb stabilization) was found to be significantly slower than the other four conditions ($p < 0.001$); no significant difference was found within the other four conditions. As expected, *Width* ($F_{3,\ 27}$ = 17.45, $p < 0.001$) and *Distance* ($F_{3,\ 27}$ = 132.29, $p < 0.001$) also had a significant effect on movement time, but neither of these factors had an interaction effect with *Technique*.

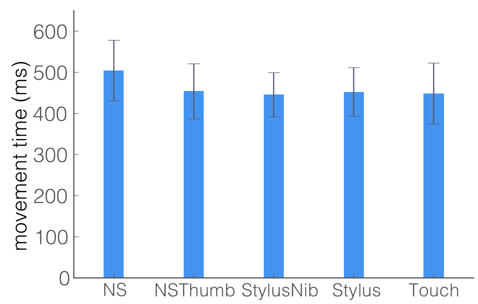

Figure 12. Movement times for each *Technique*.

Summary and Interpretation of Quantitative Results

The *NanoStylusThumb* produced a virtually equivalent movement time to *Stylus* (453ms and 452ms), but features a 45% lower error rate (11.8% and 21.5%). Overall, this result is promising, and justifies the development of specialized stylus form factor for ultra-small devices.

There are two possible explanations for the reduced error rate. First, the finger stylus reduces occlusion alleviating the fat finger problem. Second, the NanoStylus is controlled by smaller muscle groups, which may also improve precision [25]. Based on the progressively decreasing accuracies between *NanoStylusThumb, StylusNib,* and *Stylus,* it would seem that both of these factors play a role in the performance difference.

While not a new result, the study data also provide clear indication of the limitations of touch interaction on small devices. Even at the largest tested target size (3mm), the error rate for *Touch* was over 35%, while for *NanoStylusThumb* error rate was 5.0%. Finally, the significant difference in accuracy between *NanoStylusThumb* and *NanoStylus* validate our earlier observations that thumb stabilization is needed to improve performance with a finger-mounted stylus.

Participant Feedback

During debriefing, we asked the participants to rank the five conditions based on their ease of use. *NanoStylus* was ranked highest by 7 of 10 participants. We summarize our key observations below.

First, participants like the ease of control with the NanoStylus. For example, P5 felt controlling the NanoStylus "*is like using my finger, but more accurate*". P4 liked the "*lightweight control*" and P10 commented that "*NanoStylus required less effort, while the pen took over my entire hand*". P8 felt the normal stylus was "*bulky*".

Participants also report the occlusion problem of a normal stylus: "*It felt like using a normal pen was obstructing my field of view. But with the long nib stylus and NanoStylus, I had a much better view of the screen*" (P7).

On the other hand, participants did express some concerns with the NanoStylus. Most notably, participants would like the NanoStylus to be designed in a compact form factor. P1 considered "*extruding the long nib only when I need to use it with my smartwatch*". P2 expressed the preference of an adjustable nib: "*users should be able to adjust the tip length as they want*". Two participants ranked the normal stylus as their best choice, as it felt "*more familiar*".

ADDITIONAL INTERACTIONS

The results of our comparative evaluation show promise for the use of the NanoStylus for smartwatch interaction. In this section, we explore additional interactions and gestures that could further enhance the NanoStylus. The interactions were implemented on a Samsung Gear Live smartwatch.

NanoStylus + Touch

While the NanoStylus is efficient for precise actions, direct touch may still be preferred for less-constrained manipulations. The pad of the index finger is covered by NanoStylus, but the middle finger can be used when physical touch is desired. Guidelines on how to efficiently combine pen and touch, presented by Hinckley *et al.* [21], could thus be adapted to the NanoStylus.

We found that the capacitive signals generated by these two input modalities were too similar to be used for discrimination. As a proof-of-concept, we instead used the smartwatches' embedded accelerometer. The forces of the two devices, in the direction perpendicular to the screen, were different enough to perform the disambiguation. Alternative implementations, such as classifying sounds [19], could also be explored.

Gestures on the NanoStylus

Inspired by the observed benefit of thumb stabilization, we explore the idea of embedding gesture sensing on the sides of the NanoStylus. Doing so could increase the input vocabulary of the device, similar in nature to augmenting the barrel of a handheld stylus with multitouch sensors [35].

To explore this concept, we enhanced both sides of the NanoStylus with touchpads. The touchpads are implemented using a Freescale MPR121QR2 capacitive touch sensor, which can detect touch on 12 individual electrodes. We separated them into 2 groups and attached them to the left and right side of the NanoStylus (Figure 13). An Arduino board with an ATmega168 microprocessor bridges the touch controller and the smartwatch through a Bluetooth module, all mounted on the armband.

With this implementation, we can detect 1-dimensional gestures on each side independently, performed by either the thumb or middle finger. The gestures which we implemented include: tap, hold, swipe up, and swipe down (Figure 14). These gestures can be performed when NanoStylus is in the hover state or in contact with the display, further increasing the possible vocabulary of actions.

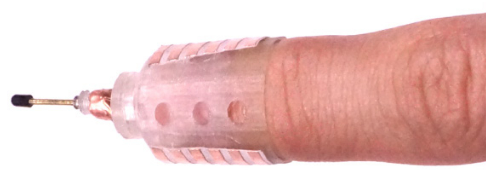

Figure 13. A Capacitive touch sensor senses 1D gestures on each side of the NanoStylus.

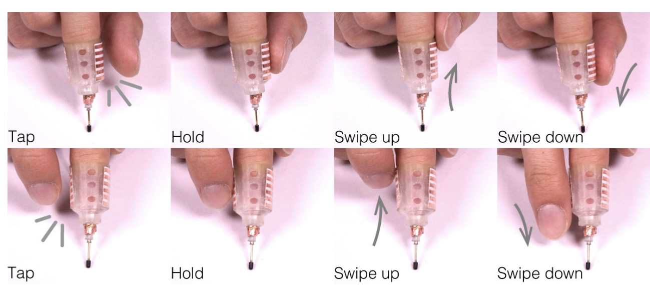

Figure 14. The gestures supported by the NanoStylus. First row: Gestures of the thumb. Second row: Gestures of the middle finger.

USAGE SCENARIOS

To demonstrate the potential of the NanoStylus and its additional interactions, we now discuss a set of sample usage scenarios. We developed a set of prototype apps that would typically require precise interaction and could thus benefit from the use of the NanoStylus. The applications were all implemented on a Samsung Gear Live smartwatch.

Email

The Email application explores techniques used to organize email lists and perform actions on individual email items. These concepts could be adapted to other list management applications. Typically a touch-based device the size of a smart watch would have 4 items or icons that a user can tap on. By using the NanoStylus, more selectable email items can be placed on a single screen (Figure 15).

Tapping an email with the NanoStylus opens it, while Swiping with the middle finger scrolls the list. Alternatively, to reduce occlusion, the user can swipe on the NanoStylus in the hover state to scroll. Holding the thumb on the left touchpad and tapping an email selects it, to allow for actions on multiple items (Figure 15a).

Gestures on the NanoStylus touchpad, when the NanoStylus is in contact with an individual email item, are mapped to actions applied to that item. Swiping the thumb down while touching an email archives it (Figure 15b) and swiping up with the thumb replies to it. Swiping middle finger up forwards it and swiping down deletes it.

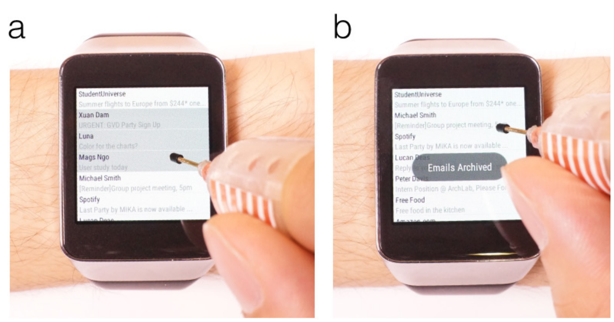

Figure 15. The email app displays a list of emails. a) Tapping on an email selects it. b) Gestures while an item is being tapped perform actions on that item.

Text Editing

Text entry on a Smart Watch is particularly challenging, as the target size required to display a full QWERTY keyboard is too small to access with traditional touch. However, with the NanoStylus, a full-scale QWERTY keyboard can be used, leveraging the high-precision pointing capability which it provides. This avoids the need for users to learn new gestures or interactions [14, 31]. In addition to basic text entry, the NanoStylus can also be used for more functional text editing interactions. The functions described here could be utilized in any text-based application, such as email, twitter, and instant messaging.

Text Entry

The QWERTY keyboard measures 29.24 mm by 10.23mm, with an individual key size of 2.92mm by 3.29mm (Figure 16a). A tap on the key inputs a character. A swipe to the left deletes a character, while a swipe to the right enters a space. A tap on the left touchpad starts a new line and a tap on the right touchpad switches to a special character keyboard (Figure 16c). Holding the thumb on the left touchpad while tapping on the keys enters capital letters (Figure 16b).

Figure 16. The Text Editing Application. a) A QWERTY keyboard displayed at the bottom of the app. b) Holding the thumb on the left touchpad while typing enters capital letters. c) A middle finger tap accesses a special character keyboard.

In our own use of this text entry application, we were able to achieve text entry rates of approximately 22WPM. While future studies are warranted, these observations are promising when compared to other smartwatch text entry rates in the literature [14, 31].

Text Editing

In addition to text entry, the application supports text editing. A single tap in the text area moves the cursor focus to the tapped location. Users can select text by holding the thumb on the left side of the NanoStylus while dragging. When a section of text is selected, a single swipe up with thumb copies it, as if it is being withdrawn (Figure 17a). Users can then move the focus to another location. A single swipe down with thumb pastes the text to the current location, as if it is being pushed into the canvas (Figure 17b). Swiping with the middle finger scrolls the document.

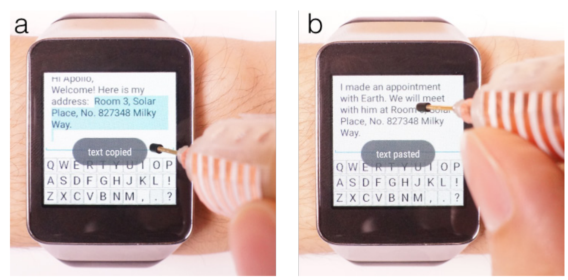

Figure 17. Swiping up copies text. Swiping down pastes it.

Sketching

The Sketching app enables users to create drawings and illustrations on a smartwatch. While this may not immediately seem like an intuitive application for a smartwatch, we believe that this could generate a new class of creative art for small devices, similar to how the popularity of sketching on mobile devices has grown[3].

The drawing app consists of a canvas and a small tool palette (Figure 18a), with icons for the pen tool, eraser tool, and color picker. Users can sketch directly on the canvas using the NanoStylus. When the NanoStylus is in contact with the screen, swiping the left touchpad adjusts the stroke width. Tapping the color picker icon brings up a full color palette (Figure 18b). The eraser tool can be used to erase regions of the sketch.

[3] https://www.sketchbook.com/mobile

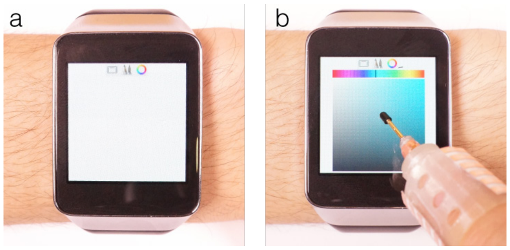

Figure 18. a) The sketching app allows users to sketch directly with the NanoStylus. b) A color picker allows users to select color.

To navigate, users can swipe with the middle finger on the canvas to pan the scene. Zooming is accomplished by swiping the left touchpad when the NanoStylus is hovering above the screen. Such navigation techniques could be similarly applied to other zoomable applications, such as map viewing or web browsing. Undo and redo are made easily accessible through the right side of the NanoStylus touchpad. An upwards middle finger swipe triggers an undo; a downwards swipe triggers redo. Figure 19 illustrates a set of drawings created by local artists using the NanoStylus on a smartwatch.

Figure 19. Sample drawings created using the NanoStylus.

DISCUSSION AND FUTURE WORK

In this section we discuss issues and opportunities arising from our work that could inform future investigations.

PicoStylus?

In both of our studies, participants reported that the 2mm nib of NanoStylus was still occluding the smallest target size (1.5mm) and expressed the desire for an even finer nib. We term this as *fat nib problem*. Existing studies on the limits of pen-based target acquisition may thus be influenced by the size of the nib being used [33, 34], as recently demonstrated by Annett *et al*. [4]. Our future work will examine whether a sub-millimeter nib size could increase accuracy even further.

Passive NanoStylus

We built the NanoStylus by modifying an active capacitive stylus. The current prototype requires a circuit board and a battery, which is cumbersome for daily use. However, progress of capacitive sensing technology has been made. Some manufacturers have claimed to be able to detect a 1mm passive stylus [1]. Therefore, a lightweight passive NanoStylus may be achievable in the near future.

Retractable NanoStylus

A current issue with the NanoStylus is that it needs to be carried when not in use, detracting from the experience of always-available wearable technologies. One possibility is to design a form factor that could be stored in the watchband when not in use. Alternatively, we would like to explore a form factor in which the stylus is embedded on the user's finger, and only protrudes from the finger when it enters the proximity of the smart watch. A spring-loaded or telescoping mechanism could potentially enable this form of interaction. In general, we imagine a future where the stylus is not thought of as an external device, but as an augmentation of one's own body, which can be used to enhance interactions with digital devices.

Multitouch NanoStylus

In our current prototype, we only detect one dimensional gestures on the NanoStylus body. In our future work, we hope to embed a full 2D multitouch sensor onto the NanoStylus. This could further expand the input vocabulary when interacting with smartwatches.

Mutli-NanoStylus Configurations

Our implementation focused on wearing a single NanoStylus on the index finger of the dominant hand. While less practical, there could be scenarios where wearing multiple NanoStyluses could be useful. For example, this could enable high precision multitouch interactions. Each stylus could potentially have different form factors or functionalities. This could be an interesting avenue for future exploration.

CONCLUSION

Advances in processing and battery technologies have allowed for more computation power to be embedded into ultra-small devices. As such, there is a new possibility for rich interactive applications to be implemented. However, for such applications, fast and precise input modalities may be required. We have presented the NanoStylus, a new device that works with off-the-shelf smartwatch devices, which enable fast and precise input, while minimizing finger occlusion during touch events. Our evaluation study demonstrates that NanoStylus can be as fast as a normal stylus, but 45% more accurate, and, 80% more accurate than traditional touch. Coupled with gesture sensing on its surface, NanoStylus can enable a broad range of tasks, such as text editing and sketching, on a smartwatch. We hope this work will inform and inspire future research and developments for smartwatch applications.

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