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Céline Coutrix, Camélia Prost. Impact of Fingernails Length on Mobile Tactile Interaction. CHI '24: CHI Conference on Human Factors in Computing Systems Proceedings, ACM, May 2024, Honolulu (Hawai'i), United States. 10.1145/3613904.3642037 . hal-04502132v1

HAL Id: hal-04502132

<https://hal.science/hal-04502132v1>

Submitted on 13 Mar 2024 (v1), last revised 19 Mar 2024 (v2)

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Impact of Fingernails Length on Mobile Tactile Interaction

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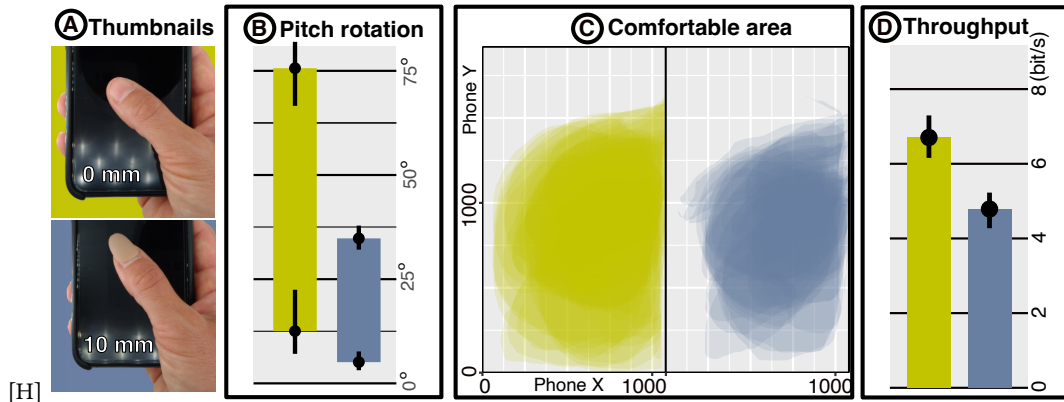


Fig. 1. (A) We study nails from 0 mm (top green) to 10 mm (bottom blue) length and show that 10 mm thumbnails decrease (B) by 35.39° (-52.92%) the range of pitch angle on the surface, (C) by 5.37 cm^2 (-36.46%) the comfortable area, and (D) by 1.91 bits/sec (-29%) the throughput when acquiring targets while holding and interacting with a single hand.

Mobile users have fingernails of different lengths. This paper measures the impact of fingernail length on the use of tactile mobile phones. We first conducted interviews with participants wearing long fingernails. They reported difficulties and non-satisfactory coping strategies to hold their phone securely and acquire targets accurately. We then conducted three experiments comparing different lengths of fingernails (0 mm, 5 mm, and 10 mm). Our results quantify the comfort and performance drop. We measured the range of incidental pitch angle on the surface, the comfortable and useful area of the thumb, and the target acquisition performance. 10 mm fingernails consistently decrease by 57% the range of the finger pitch angle, by 36% the comfortable area of the thumb, and by 24% the throughput when acquiring targets.

This paper contributes guidelines for future inclusive devices and techniques to also support users with long fingernails.

CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**.

Additional Key Words and Phrases: Fingernails, Length, Tactile interaction, Touchscreen, Mobile, Interviews, Fitts pointing study, Comfortable area of the thumb.

ACM Reference Format:

Céline Coutrix and Camélia Prost. 2024. Impact of Fingernails Length on Mobile Tactile Interaction. In *CHI '24: CHI Conference on Human Factors in Computing Systems Proceedings, May 11–16, 2024, Honolulu, Hawai'i, USA*. ACM, New York, NY, USA, 34 pages. <https://doi.org/10.1145/3613904.3642037>

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Manuscript submitted to ACM

1 INTRODUCTION

Current tactile interaction design and technology discriminate –possibly unknowingly– a large number of their users. Users with long fingernails struggle to use their UIs. They have to rely on ad-hoc solutions such as using the pads of the fingers rather than the fingertips, cutting the fingernails, using a stylus, or only a subpart of the screen. This paper explores how much current mobile phones impair the experience of users wearing long fingernails. Long fingernails raise specific problems: in addition to the “fat finger” problem due to interaction limited to the fingerpad, long fingernails decrease the reachability of the thumb on the mobile surface, not to mention the insecure grip. This paper equips the HCI community with data to also support users with long fingernails.

Unlike prior work in medicine [43], we are interested in the length of the nail beyond the junction of the nail and the skin at the fingertip (Figure 2). As of today, there is no data about the average length of fingernails and the number of users with long fingernails. While users have fingernails of varied length [24], and that long, especially artificial, fingernails are a threat to hygiene [58, 65], the popularity of very long nails has increased [24], including among young users. In addition, the mobile phone is the most widespread computing device. Yet, this problem has not been studied.

It is not acceptable to require users to cut their nails or to assume that users rate aesthetics higher than ergonomics. Long fingernails are an important aesthetic criterion [22, 43], a part of self-expression [70], and can even be an obligation (e.g., classical guitar player, beautician). It is the role of HCI to design interaction for users *as they are*, taking into account the social norms users have to comply with [25]. For these reasons, it is important and timely to address the lack of knowledge on the usability of mobile touchscreens with long fingernails.

HCI has not yet taken the length of nails into account, unlike other fields that studied the impact of nail practices (e.g., [9, 41]). In HCI, the gender of study participants tends to be either not reported or mostly men [11]. This increases the chances of having study participants with short fingernails, as wearing long fingernails is a bodily practice mostly culturally gendered as feminine in many cultures [53]. Therefore, designers currently lack formal data to take the length of nails into account in their design. Although they informally know that users with long fingernails struggle to use their UIs, quantifying the impact of fingernail length is difficult because we currently do not know which effects to study. This paper therefore addresses the following research questions (RQ):

RQ1 What are the effects of long nails on mobile tactile interaction?

RQ2 What is the magnitude of these effects?

To answer the first research question, we conduct a qualitative study investigating the difficulties encountered by users of mobile phones with long fingernails. Results reveal that users need to change the incidental pitch angle of their finger (effect #a, Figure 2). They also reported unstable handgrip resulting from limited reachability on the screen (effect #b) and reduced efficiency when tapping on targets (effect #c). We, therefore, detail our second research question into three RQ2a-c studying the size of these three effects #a-c.

With our (1) formative study and (2-4) three experiments, we learn:

- (1) Current users' usability issues and coping strategies when having long fingernails;
- (2) The 57% decrease of the range of the finger pitch angle on a mobile surface with a 10 mm fingernail;
- (3) The 36% decrease of the comfortable area on the mobile phone with a 10 mm thumbnail;
- (4) The 24% decrease in throughput when acquiring targets on a mobile phone with a 10 mm fingernail.

This paper provides knowledge for future inclusive design. With our results, we want to raise awareness of the *magnitude* of this problem in our scientific community and equip it to foster inclusive HCI.

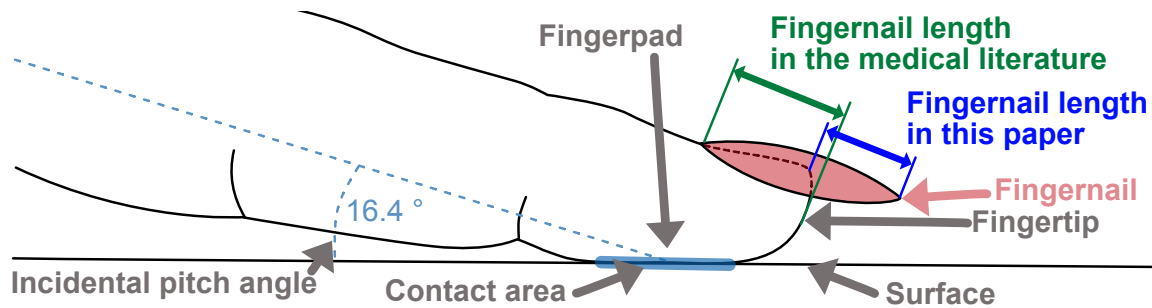


Fig. 2. Incidental pitch angle, finger anatomy, and the measure of the fingernail length.

2 RELATED WORK

Online communities informally report several problems when using a mobile touchscreen with long fingernails. These problems include dropping the mobile phone [73], struggling to type text [1, 17, 73], in particular typing slower and less accurately [1], and annoying noise when typing on the touchscreen [1, 59].

Online communities also share advice on how to interact with mobile touchscreens when wearing long fingernails. They propose several strategies, like changing the angle between the finger and the screen, in particular using the pads of the fingers rather than the tips [1–3] –which takes a long relearning time [2, 3]–, turning the finger to the side [3], using the tip of the nose instead of the fingertip [73], using the knuckle [2, 3], using specific areas of the screen –e.g., “the right side of the screen for vertical swipes and the bottom half for horizontal swipes to give your nail room” [3], and using a stylus [3].

This shows that users face many problems: not only a “fat finger” problem, but also, e.g., a lack of mobility of the finger on the screen and a lack of accessibility to particular areas of the screen. This paper aims at a better understanding the interaction with mobile phones in the light of fingernail length. For this, we now review the scientific literature that formally studies the intersection between nails and dexterity, accuracy, and HCI.

2.1 Nails, dexterity and accuracy

Only Shirato et al. observed an increasing dexterity with longer fingernails: 2 mm fingernails allow for more accuracy than 0 mm fingernails for a series of tasks such as grasping a pin [72]. Most prior work reports on decreasing accuracy with longer fingernails. Pinch and grip strength tends to decrease as fingernail length increases [41, 66]. Users with 20 mm fingernails type slower than those with shorter fingernails [41]. The active range of motion of the hand is smaller with such fingernail length [41]: when flexing the fingers into a fist, Jansen et al. show that long fingernails limit flexion of the finger joints, particularly in this task, the metacarpophalangeal (MCP) joints (Figure 10a).

No HCI work on accuracy on touch surfaces considers long fingernails or the length of fingernails as a variable. Previous work explored finger pitch and roll orientation on touch surfaces [28] and the angles of incidence between the finger and the touch surface [86]. Goguy and Ortega mention that long nails might lead to a significant difference in their evaluation of touch gestures. Mackamul et al. mention that long nails hindered the visibility of targets for one participant [54]. Wang et al. mention long fingernails and resulting low pitch angles as one of the opportunities to detect finger orientation [85]. Mayer et al. did not consider large incidental pitch angles because they are difficult to perform with long nails [57]. When Xiao et al. proposed to use the pitch incidental angle of the finger on the touchscreen to

augment the interaction [89], the authors found that the touchscreen did not detect the input at 90° (vertical finger) from participants with long fingernails. ScraTouch [38, 39] found that the capacitive touchscreen does not respond to a fingernail longer than 4 mm, which is much smaller than some of our observations in study #1. None of these formally evaluate the impact of nail length.

The generalized perceived input point model [33] shows that tapping a target with the finger pad (Figure 2) decreases users' accuracy. Further work found that the vertical center of the fingernail was found as the best model for vertical accuracy, rather than the contact area as currently used in capacitive surfaces [34]. While authors do not report on the length of their participants' fingernails, we infer that participants had short fingernails as they were able to touch to surface with a nearly vertical (65°) finger pitch angle (Figure 2). The largest error in direct touch pointing is on the finger axis [33, 34], i.e. in the direction of the fingernail extension. However, the authors did not study the impact of fingernail length on the touch efficiency for target selection.

2.2 Nails and Interaction techniques

Existing mobile tactile interaction techniques focusing on nails do not take long fingernails into account. HCI research has tried to augment fingernails of any length with computing and interactive capabilities [18, 36, 37, 44, 45, 52, 74, 78, 82, 83, 87]. For example, nail displays [74, 87] proposes to provide feedback on fingernails.

TapSense [32] studies nails tapping flat on a tabletop surface –palm up– as an opportunity for a novel interaction modality. However, the usability of such a gesture has not been assessed yet on mobile surfaces, and the gesture would not be possible to perform for one-handed mobile interaction with the thumb.

Conductive nail polish was proposed to enable conductive contact between the finger and the touchscreen through the nail without the need for an additional device [76]. However, the contact on the touchscreen through a nail leads to a very small contact area, which is not recognized as a contact point by today's systems –in an attempt to avoid false positives. To solve this issue, solutions were proposed but not yet adopted. TECH TIPS' stylus is a thimble allowing for conductive contact between the finger's last phalanx and the capacitive surface [79]. Researchers designed the comparable NanoStylus [88], allowing for precise input on very small capacitive surfaces. Elecktra nails [80] were conductive acrylic nails. Similarly, the artist Buttendorf proposes a DIY tutorial on how to make such a device with tinfoil and cotton [16]. These solutions try to solve the current problems with an additional device. The drawback of this approach is the need to carry the additional device around, which is not always practical. In this paper, we take another approach and deeply study users' issues, in order to adapt UIs to users rather than users to UIs, and guide the future design of novel *non-instrumented* interaction techniques.

In short, while little prior work mentions issues with long fingernails, most did not study the specific effects of long fingernails on mobile tactile interaction or unsuccessfully proposed an additional object to users to ease mobile interaction on touchscreen. This paper studies interaction on the mobile touchscreen to know the problems of users with long fingernails in order to support them better.

3 STUDY #1: CURRENT EXPERIENCES WITH LONG FINGERNAILS

To answer our RQ1 (“What are the effects of long nails on mobile tactile interaction?”) and identify potential effects of long nails on mobile tactile interaction, we conducted semi-structured interviews.

3.1 Participants and apparatus

We recruited 14 participants ($M=38$ years old, 18–60 y.o.), enough to reach data saturation [31]. Nine self-identified as women and five as men. All frequently had long fingernails and had different occupations (Table 1 in Annex A). Half came to our university, while we went to meet the others in their workplace or at home.

We recorded the audio of the whole interview, and took pictures and videos when participants were demonstrating their use of the mobile phone.

3.2 Procedure and analysis

After they signed a consent form, we asked for their demographic information, type of device and frequency of use. Then they talked about their experience with long fingernails on touch devices. Each interview lasted around 15 minutes.

We conducted thematic analysis [69] on the transcripts of the interviews.

Two coders separately coded the same seven interviews. Both coders then discussed the themes coded in the interviews and agreed on a coding scheme. Finally, a single coder coded all interviews with this coding scheme.

3.3 Results

3.3.1 Motivation for long nails. P2, P6, and P12 do not give them a special place or care to wear them relatively short for practical purposes. For others, nails are worn longer for the following reasons: habit (P2, P5, P12), aesthetics (P2, P4-8, P14), practicality in everyday life (P1, P3, P5, P9, P11, P13, P14), for artistic practices (P1, P3, P9-11) or quasi-professional obligation (P7, P9-10). Thus, for some people, their nails are a real focus of attention that they seek to preserve. Nails are part of everyone's bodily integrity, and long nails are a choice (P13).

3.3.2 Awareness of usability issues and expertise. Participants were divided about the problems caused by long nails on touchscreens. Six participants reported not being aware of any problems. This does not mean that there is no problem: e.g., prior work on touch latency showed that users were not aware of the negative impact of latency [61]. These participants reported being "like everyone else" (P4, P11). However, eight participants considered interaction with touch devices to be awkward and less convenient with long fingernails, e.g., "it is difficult" (P5). 12/14 participants had already thought about or noticed the impact of long fingernails with touch devices, either on themselves or someone else or when someone else commented their use.

We compared participants' (1) frequency of device use, (2) expertise with long nails, and (3) number of reported problems. We did not observe any correlation between the frequency of use and the expertise with long nails, and between the frequency of use and the number of reported problems. In addition, participants showing the most expertise with long nails did not report fewer issues: these 8 participants (57%) reported 25/41 issues (61%). As a consequence, expertise with long nails does not seem to counterbalance usability issues.

3.3.3 Handgrip issues. Seven participants felt their grip on the phone did not change with long nails compared to short nails, while two people reported negative points like "lower practicality" (P14) or higher risk of falling (P13). P14 uses a special ring at the back of their phone as a handle (Figure 3A) that "allows [her] to hold it better". Nevertheless, the ring at the back of the device cannot be a solution for everyone, e.g., "it wasn't quite what [P13] expected".

Participants mentioned that they need to stretch their fingers to tap on a target with the finger pad instead of the fingertip (Figure 3F). When interacting with the thumb of the same hand holding the phone, this results in a less secure

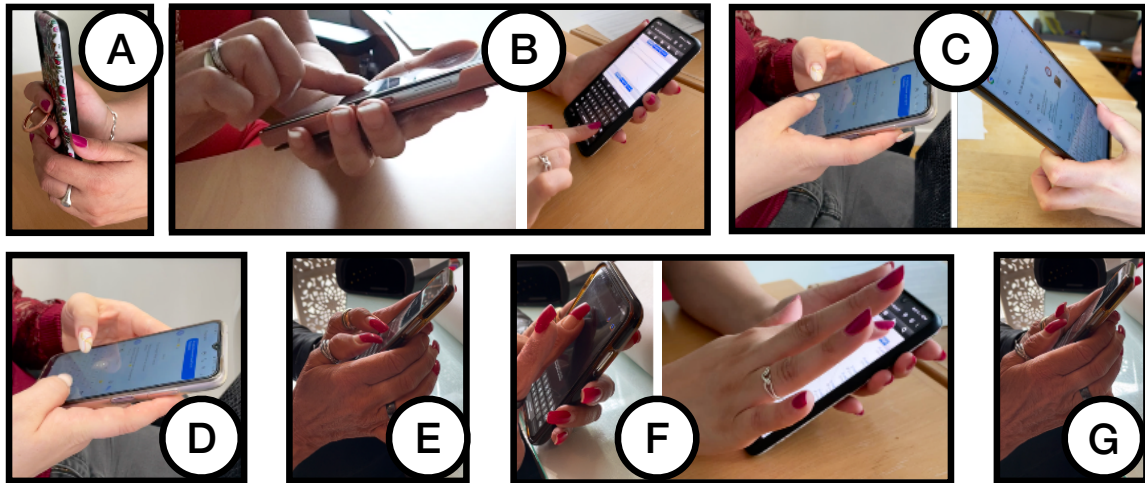


Fig. 3. Participants of our formative interviews demonstrate how they interact with the mobile phone with long nails. (A) P14 two-handed grip with accessory. (B) P2 and P14 tap with the pad of the finger (low pitch angle). (C) P8 and P4 stretch their thumbs to type with the finger pad. (D) P8 types with the side of the thumb. (E) P5 shows the impossibility of typing with the thumbs orthogonal to the screen (high pitch angle). (F) P5 and P14 stretch their hand. (G) P5 with their thumbs parallel to the screen.

grip. Slippery nails can also cause grip instability compared to sticky finger pads. E.g., “I’m more afraid of dropping it when I have long nails [...] because it doesn’t hold the same” (P13).

3.3.4 Touchscreen issues and resulting touch adaptation. While swiping and scrolling does not cause discomfort – “it’s just like scrolling so it’s fine” (P13)– our participants highlighted three main problems.

When trying to place the finger orthogonal to the screen (pitch angle $\sim 90^\circ$, Figure 3E), participants lose contact with the touch screen: “it is first the nail that taps” (P7). Their attempts are ineffective: “Sometimes it’s just that you press [the touchscreen], and it doesn’t do anything. It doesn’t touch” (P3).

Because they cannot vertically touch the screen, most participants ($n=10$, 77%) reported stretching their fingers to touch with the finger pad (Figure 3B and 3C). This also avoids the noise of the fingernails tapping the screen (P3, P13). However, P14 mentioned that this strategy prevents them from using more than one finger at a time, and P1, P9, and P14 reported a loss in accuracy: “we don’t control well where exactly the fat of the finger touches [...] it’s around 1cm accurate” (P1). For 5 participants (35%), long nails are a source of inaccuracy on touch devices. Participants spontaneously change their interacting finger to another nail-less finger, e.g., the little finger (P10). P10 even interacts with their short-nailed non-dominant hand.

Long nails make typing, tapping or dragging on-screen objects difficult: “When it comes to selecting or highlighting text, copying, and pasting, it’s always very complicated to be precise” (P9). When holding their phone in one hand, typing text with the index finger of the other hand – e.g., messaging, emailing, writing notes– was frequently mentioned as difficult (6/14 participants). Yet, 10/14 participants reported that typing text was the task they do most frequently on their mobile phone. To cope with this, they changed the angle between the phone and the finger, as mentioned above. Another strategy used by two participants, was to use swipe gesture input on the keyboard [91]. Typing with both thumbs tips (Figure 3E) is impossible: “I can’t” (P1), “I can’t type properly” (P5). To write a long text, seven participants

use both thumbs and type with the thumbs pads by stretching their thumbs (Figure 3G) and/or tapping with the side of the thumbs (Figure 3D). P3 and P9 mentioned that all these changes in behavior can lead to fatigue or joint pains.

3.3.5 Every nail is different. Participants compared short and long nails: “The longer [the nail] is, the more difficult it is [to interact]” (P11), “if [nails] are really long, it’s a bit more awkward” (P7). Participants also compared different types of nails: “When I wear artificial nails, [...] I find that there are fewer sensations, and so for writing [...] you make more mistakes, you must erase, you have to come back [and correct], and pay more attention” (P14).

3.3.6 Changing interaction modality. Cutting their nails was the radical alternative: “It’s sad, but [I have] to cut them off” (P13). To avoid this, participants mentioned using other interaction modalities instead of direct touch.

Using a stylus is an alternative seldom adopted: only P6 used it and P11 considered it for drawing. The reasons for its lack of adoption are that users need to get used to it (P6) and that the stylus is an additional element that users must carry around (P1).

Another alternative is to switch to a laptop. However, switching to a physical keyboard is not a solution. Consistently with prior work [41], four participants (29%) reported that typing with a physical keyboard is difficult with long fingernails.

Another alternative is to use voice interaction: “I use less and less the tactile [modality], but rather the voice [modality]” (P6). However, voice is not always reliable: “you have to read it again. Because sometimes [voice recognition] doesn’t understand anything” (P5).

3.3.7 Marginalization. Participants believed that there is a correct, inaccessible use of touch screens: “I imagine that I should have my finger vertical for the tip of my finger to touch. I can’t” (P1). Eight participants mentioned that they felt apart from the others wearing short nails.

To conclude, our study shows that asking users to cut their nails is not acceptable, as nails are important and can even be a professional obligation (professional guitar player, beautician). Expertise with long nails or mobile phone do not solve usability issues. To answer RQ1 (“What are the effects of long nails on mobile tactile interaction?”), the issues the most reported were (a) the need to change the incidental pitch angle of the finger on the surface (10/14), (b) the difficulty in reaching far areas (3/14), resulting in an instability of the grip, and (c) the lack of efficiency when tapping on targets (5/14). All alternatives have limitations. In particular, our participants did not follow tips and recommendations from online communities (section 2), nor solutions proposed in prior work (section 2.2). This shows the importance of better knowing these issues to recenter the design on these users.

Having identified the effects (RQ1) in study #1, we further detail our RQ2 into the following RQs:

RQ2a To what extent do long nails impact the pitch angle (effect #a) when interacting with mobile tactile interfaces?

RQ2b To what extent do long nails impact the reachable area (effect #b) when interacting with mobile tactile interfaces?

RQ2c To what extent do long nails impact the target acquisition performance (effect #c) when interacting with mobile tactile interfaces?

We now present three experiments respectively addressing RQ2a-c.

4 STUDY #2: IMPACT OF FINGERNAILS LENGTH ON THE RANGE OF INCIDENTAL PITCH ANGLE

To address RQ2a, this first experiment measures the effect of fingernail length on the pitch rotation of the finger on a mobile surface and on the data captured by the surface. Participants of study #1 mentioned their will to touch the screen with vertical fingers –in order to easily use multiple fingers and accurately tap on targets– and complained of

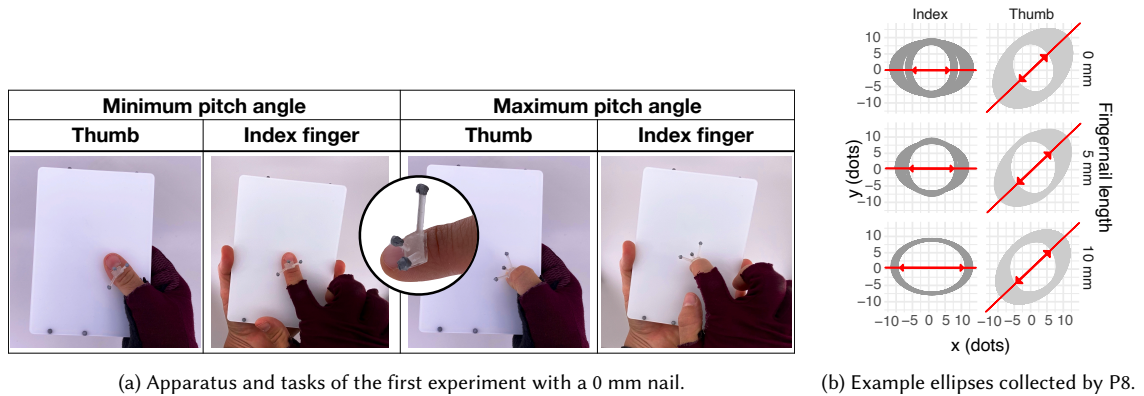


Fig. 4. First experiment: apparatus and example ellipses captured by the surface during the first experiment for P8.

their inability to do so. This first experiment brings new knowledge on how far users with long nails are from the pitch angle amplitude of users with short nails. To reduce unintentional false positive inflation of results [27], our study was registered before collecting the data¹[5].

4.1 Participants

We recruited 12 participants ($M=27.42$ years old, 18–39 y.o.) at the local university. We noted that users are accustomed to having the length of the nails change. This can happen slowly, like when the nail grows: in this case, users get used progressively to the length. This can also happen suddenly like when they break or cut their nails or when they get artificial nails: in this case, users need to adapt to the new length rapidly. Our previous study also suggests that expertise is not decisive in noticing and reporting usability issues. Our participants had 0 mm fingernails on their thumb and index finger. None of them usually wear long fingernails. Six self-identified as women, and six as men. We verified that our participants' thumb and index finger sizes, measured from crotch to tip, are representative [4] (Thumb $M=57.13$ mm, 44.97–66.25 mm and Index finger $M=73.64$ mm, 60.67–82.95 mm). All participants were right-handed. Participants daily used smartphones with touchscreens.

4.2 Apparatus

To control the length of the nail, participants wore an artificial fingernail of prepared length (Figure 1 bottom left). To prevent accidental touches from the palm of the hand, participants wore a fingerless glove (Figure 4a and as in [46]).

We used a 130×110 mm² Apple Magic Trackpad 2 as a hardware device. The weight and form factor of the trackpad (231 g, D 0.49–1.09 cm \times H 16.0 cm \times W 11.49 cm) is similar to current smartphones. Using the trackpad instead of the mobile phone allowed us to build on top of previous work [14] to collect low-level information from the surface.

To measure the incidental pitch angle of the finger on the surface, we positioned a light (0.45g) rigid body composed of 3 markers on the participant's finger (contact area 10.52×6.57 mm², Figure 4a). We ensured in a pilot study that the rigid body did not hinder finger mobility. An Optitrack system [63] tracked the reflective markers attached to the finger and the mobile surface (Figure 4a). We verified the precision and accuracy of this pitch angle tracking system. We tracked for 1min the pitch angle of a static marker placed at controlled incidental pitch angles of 0° , 45° , and 90° on

¹https://osf.io/fjt2w/?view_only=1633350abb8e4ed687e4b5345a92bdf2

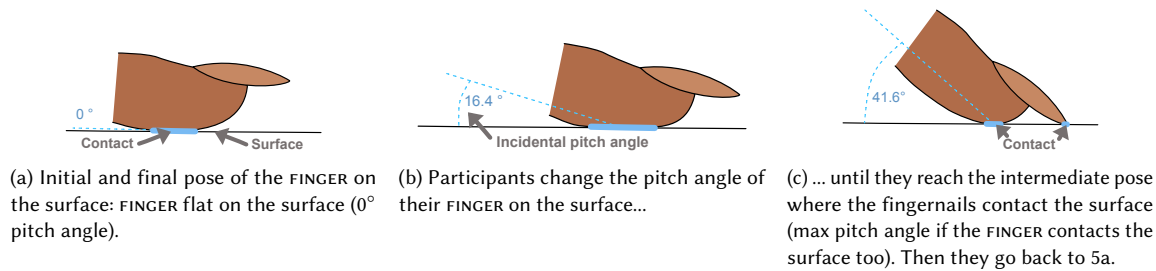


Fig. 5. Experimental task of the first experiment: a trial consists of a participant changing the pitch angle of the FINGER on the surface from flat (5a) to the maximum pitch angle (5c), and back to flat (5a).

the mobile surface resting on a table (around 4700 samples for each angle). We measured the accuracy as the distance between the mean measured angle and the controlled angle: 5.261° for 0° , 0.737° for 45° , and -2.349° for 90° . We measured the precision as four times the standard deviation: 0.112° for 0° , 0.115° for 45° , and 0.060° for 90° .

4.3 Experimental design

We used a within-subject design with LENGTH of fingernail and FINGER as independent variables:

LENGTH of fingernail: 0 mm, 5 mm and 10 mm, measured as in Figure 2.

FINGER: Thumb or index finger.

We study the two most widespread ways to hold and interact with the surface [35] while varying fingers (Figure 4a): First, holding the phone in the dominant hand while interacting with the *thumb* of the dominant hand. Second, holding the phone in the non-dominant hand while interacting with the *index finger* of the dominant hand.

The order of presentation of LENGTH and FINGER was fully counterbalanced. We collected the pitch angle of the finger on the surface and the length of the major axis of the ellipse derived from the touch area captured through Apple's MultitouchSupport private framework. We could not reverse engineer the units of the length of the major axis (the framework is not public) and call it *dot*. This measure informs on how current touch devices could detect the incidental pitch angle and potentially infer users' nail length: A high (resp. low) pitch angle is supposed to decrease (resp. increase) the contact area (Figure 2) [28, 33], and therefore the length of the major axis. For both measures, we collected 3 LENGTHS of thumbnails \times 2 FINGERS \times 3 repetitions \times 12 participants = 216 values.

4.4 Experimental task

The experimental task consisted of performing a pitch rotation of the finger while keeping the finger in contact with the surface (Figure 5). Participants first placed their finger pad (distal phalanx) horizontally on the surface (Figure 5a). Participants then changed the pitch angle of the finger (Figure 5b) until the fingernail touched the surface (Figure 5c). Participants then went back to the initial horizontal position (Figure 5a). The roll and yaw angles of the FINGER remain constant. Participants repeated this task three times for each fingernail LENGTH and each FINGER.

4.5 Procedure

Participants first signed an informed consent form, put the glove and the nail on, and sat at a table. The experimenter explained the task to the participant. Participants trained until they felt comfortable doing the task. Participants then performed 3 repetitions of the task for each combination of variables. The experiment lasted around 30 minutes.

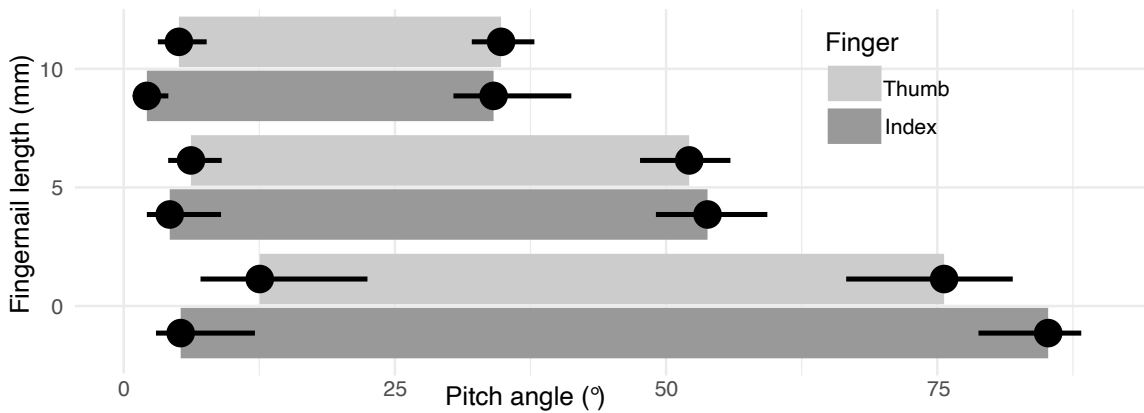


Fig. 6. Range of pitch angle measured during our first experiment. Error bars show 95% confidence intervals on the minimum and maximum of the range of pitch angle.

4.6 Analysis

We use estimation techniques based on geometric means and 95% bootstrapped confidence intervals (CI), and pairwise differences to show effect sizes. These methods are recommended [26] by the APA [8] and largely adopted, e.g., [21, 23, 42, 46, 48, 60]. Rather than the dichotomous inference supported by p-values, we opted for this more nuanced analysis of the direction and magnitude of the effect. A p-value-approach reading of the results presented in this paper can be done by comparing the CIs spacing with common p-value spacing, as shown in Figure 3 in [47]. A pairwise difference is an intra-subject measurement that expresses the effect size and is computed between each of the geometric means. We used existing scripts to generate these statistics [13]. The same method is used in the remainder of this paper.

4.7 Results and implications

4.7.1 Pitch angle. Figure 6 shows the measured average range of pitch angle. The longer the nail, the smaller the range of incidental pitch angle. For the thumb, a 0 mm thumbnail leads to a range of 63.09° (CI [50.58, 73.05]). A 5 mm thumbnail leads to a 27.19% smaller range of 45.93° (CI [41.00, 49.90]). A 10 mm thumbnail leads to a 52.92% smaller range of 29.70° (CI [25.27, 32.40]). For the index finger, a 0 mm fingernail leads to a range of 79.98° (CI [72.00, 84.50]). A 5 mm fingernail leads to a 38.01% smaller range of 49.58° (CI [44.41, 55.49]). A 10 mm fingernail leads to a 60.03% smaller range of 31.96° (CI [28.00, 39.35]). Table 2 in appendix B show the detailed figures.

RQ2a questioned the extent to which long nails impact the pitch angle (effect #a) when interacting with mobile tactile interfaces. Overall, we found that a 10 mm fingernail leads to a 57% decrease of the range of the finger pitch angle on a mobile surface, compared to a 0 mm fingernail. The magnitude of the effect of the fingernail length is important – a mean loss of 41.30° in finger pitch rotation between 10 mm and 0 mm fingernails.

Surprisingly, we can see in Figure 6 that participants adapted their minimum pitch angle –without being asked to– by putting their finger flatter on the surface with longer fingernails. This maximizes their range of pitch angle with long fingernails, although touching with the finger pad is known to be less accurate [33].

The first implication of these results is methodological: prior HCI studies [57] chose not to investigate pitch angle greater than 77.5° to account for long fingernails. Our results refine this assumption: the fingernails ≥ 5 mm cannot

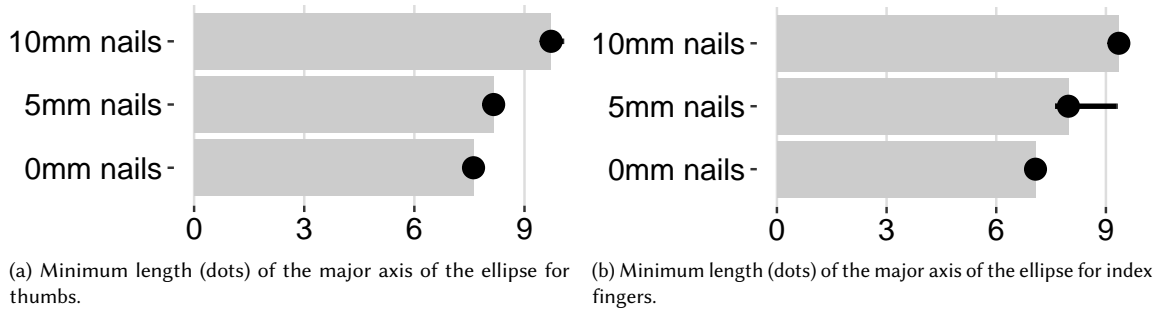


Fig. 7. Minimum length (dots) of the major axis of the ellipse for the index fingers and thumbs. Error Bars indicate Bootstrap 95% CIs.

reach pitch angles $>53.82^\circ$ (corresponding to the index finger with 5 mm fingernails). To include users wearing 10 mm long fingernails, interaction technique should work with pitch angles $<34.10^\circ$.

We explored if we could model the pitch angle based on the data collected. For interaction designers to support further fingernail lengths, e.g., like some of our participants in the qualitative study, we build a model of the max pitch angle (A_{max}) depending on the length of the fingernail (L_{nail}). From Figure 5c, we derive the following geometric formula: $A_{max} \approx \arctan\left(\frac{T_{finger}}{L_{nail}+L_{nailbed}}\right)$. We found in prior work the average nail bed measurements ($L_{nailbed}$) [43], and average finger thickness (T_{finger}) [4]. When using the average value for the thumb, we find $A_{max} \approx \arctan\left(\frac{18.5}{L_{nail}+14.65}\right)$. When performing least squared regression of $a * \arctan\left(\frac{18.5}{b * L_{nail}+14.65}\right)$, we converged to $A_{max} = 1.6906 * \arctan\left(\frac{18.5}{3.1138 * L_{nail}+14.65}\right)$ ($CI_a = [1.62, 1.76]$ and $CI_b = [2.72, 3.55]$). Using this model, designers can make sure future techniques leverage a usable range of pitch angles for any thumbnail length.

TODO provide R2 and a figure?

4.7.2 Ellipses captured by the surface. Current mobile applications cannot directly capture the pitch angle of the incidental finger but rather use the captured ellipse provided by the mobile operating system from the capacitive touchscreen. We were therefore interested to see if mobile applications could infer the users' nail length from the touch ellipse in order to adapt interaction to users with long nails. Figures 7a and 7b show the average of the minimum length of the major axis of the touch ellipse for all participants. Figures 7a and 7b show that the longer the fingernail, the larger the smallest size of the major axis of the ellipse captured by the mobile surface. Figure 4b illustrates with P8's example that the minimum length of the major axis of the ellipse increases as the fingernail gets longer. Table 2 in appendix B show the detailed figures.

We explored if we could find a model of the nail length depending on the minimum length of the major axis. We found individual variations between participants. Figure 8 shows such individual models. Through individual calibration with pitch angle rotation, the system could measure the minimum length of the major axis of the touch ellipse to infer the length of the nail and adapt the system, e.g., by fostering techniques improving precision and reach [19, 20, 71, 77, 84] or offsetting the touch location [33]. Using deep learning [49] to offset the touch location [33] correctly could further benefit users with long nails.

TODO provide R2 and a figure?

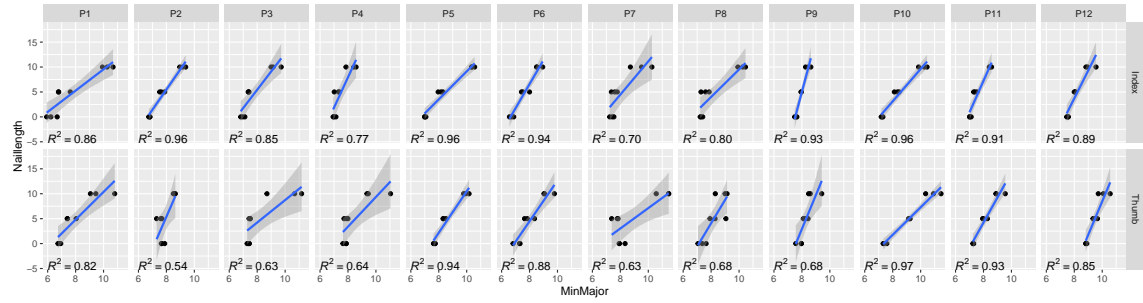


Fig. 8. Individual linear modeling of the nail length according to the minimum length of the major axis of the touch ellipse.

5 STUDY #3: IMPACT OF THUMBNAIL LENGTH ON THE REACHABLE AREA OF THE THUMB

To address RQ2b (“To which extent do long nails impact the reachable area (effect #b) when interacting with mobile tactile interfaces?”), this study aims at measuring the impact of long thumbnails on the comfortable and useful area with the widespread one-handed grip on a smartphone [35]. We explore two types of reachable areas: comfortable and useful areas [46]. The comfortable area involves moving only the joints of the thumb, whereas the useful area involves moving the whole hand. We used a similar study procedure as in prior work [46, 51]. In addition to prior work, we explore 3 different lengths of thumbnails: 0 mm, 5 mm, and 10 mm. To reduce unintentional false positive inflation of results [27], our study was registered before collecting the data²[6].

5.1 Participants

We recruited 12 participants ($M=28.92$ y.o., 23–39 y.o.) at the local university. They had 0 mm nails on their thumb. Nine of them participated in the first study. Six self-identified as women and six as men. Participants’ thumb sizes, measured from crotch to tip, are representative [4] ($M=55.92$ mm, 44.97–66.25 mm). All participants were right-handed. Participants daily used their smartphones with touchscreens. None of them usually wear long fingernails.

5.2 Apparatus

We ran the study on an Android Asus ZenFone 3 Max (ZC553KL) phone of size $151.4 \times 76.2 \times 8.3$ mm, and with a 5.5” screen (Figure 9a). The phone ran a custom application logging the touched points on the screen. We used the same artificial nails, gloves, and Optitrack tracking system as in the previous experiment.

5.3 Experimental design

We used a within-subject design with type of AREA and LENGTH of thumbnail as independent variables:

Type of AREA: *comfortable* or *useful* area. The comfortable area involves moving only the joints of the thumb (Figure 10a), whereas the useful area involves moving the whole hand (Figure 10b).

LENGTH of thumbnail: 0 mm, 5 mm and 10 mm, defined as in the previous experiment and in Figure 2.

The order of presentation of AREA and LENGTH was fully counterbalanced. We collected the touched points, and the finger pitch angle as in the previous experiment. For these measures, we collected 2 types of AREA \times 3 LENGTHS of thumbnails \times 3 repetitions \times 12 participants = 216 values.

²https://osf.io/7hfsa/?view_only=9d21b49e6a65443c9bf87ca952a80bfc

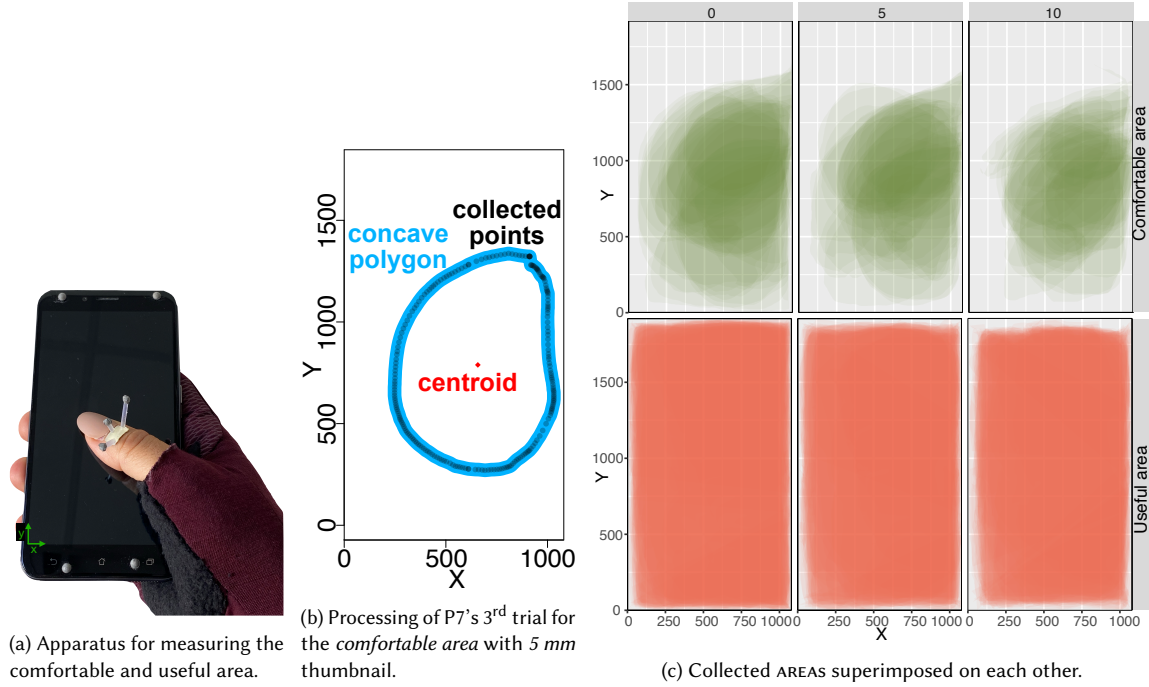


Fig. 9. Apparatus, pre-processing, and resulting areas collected.

5.4 Experimental task

Participants draw the contour of the comfortable or the useful AREA (Figure 10) [46]. For the comfortable area, participants drew the contour of the area reachable by moving only the joints of the thumb (IP, MCP, CMC in Figure 10a), while the rest of the hand was fixed [46, 51]. For the useful area, participants drew the contour of the largest possible area reachable by the thumb (Figure 10b). We allowed participants to change their grip freely when drawing the useful area. Participants could draw the useful area in multiple strokes if necessary. Participants repeated the task three times for each combination of fingernails LENGTH \times AREA.

5.5 Procedure

Participants first signed an informed consent form. Then they put a fingerless glove on and sat at a table. We placed a marker on the thumb, attached the artificial fingernail and asked the participants to find a comfortable position to hold the phone. We explained and demonstrated the task to the participant. We then asked them to perform the task for each type of AREA as training. Participants performed 3 repetitions of the task for each combination of variables. We conducted a semi-structured interview of the participants at the end of the experiment to collect their subjective feedback. The experiment lasted around 30 minutes.

5.6 Pre-processing and analysis

Figure 9b illustrates the pre-processing performed on the data in the example of a trial. From the collected sparse 2D coordinates of the touched points, we compute their concave hull [30]. Unlike prior work [46], we did not use the

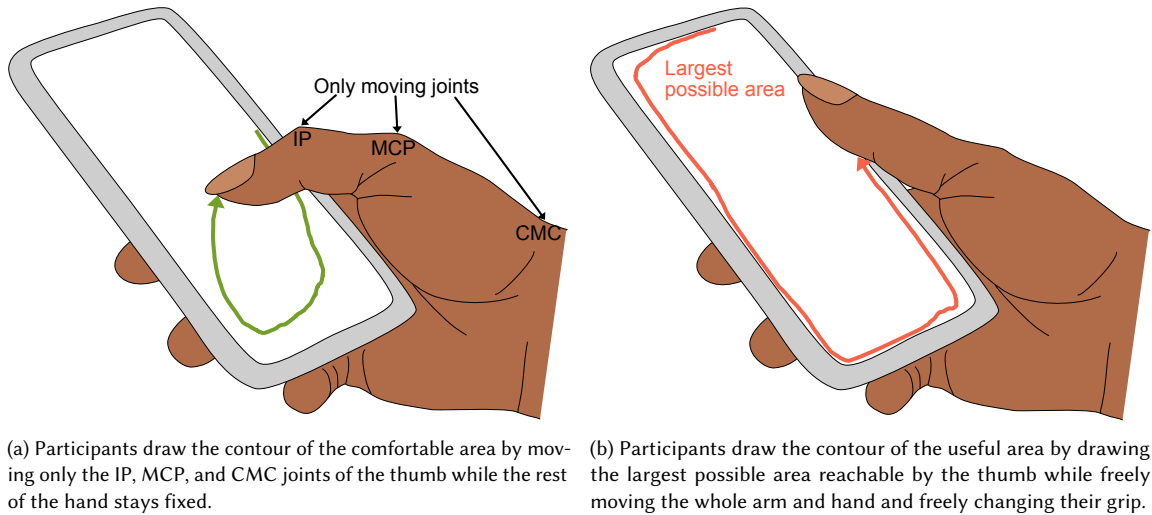


Fig. 10. Experimental task for the second experiment.

convex hull algorithm to obtain the contour because the shape of the collected areas can be slightly concave due to long fingernails. We then compute the size of the area and the centroid 2D location of the resulting polygon for each trial. We used the same analysis methods as the previous study. The details of these computations are in the analysis scripts available as supplementary material.

5.7 Results

5.7.1 Areas. Figure 9c shows the comfortable and useful areas for thumbnail lengths of 0 mm, 5 mm, and 10 mm. Figure 11 shows the size of the comfortable and useful areas according to thumbnail length. The longer the thumbnail, the smaller the comfortable area (Figure 11a and 11b) and the useful area (Figure 11c and 11d). The size of the comfortable area is 14.72 cm^2 (CI [17.24, 12.39]) with a 0 mm thumbnail, 11.88 cm^2 (CI [13.52, 10.00]) with a 5 mm thumbnail, and 9.35 cm^2 (CI [11.08, 7.76]) with a 10 mm thumbnail. The size of the useful area is 50.36 cm^2 (CI [51.50, 48.79]) with a 0 mm thumbnail, 47.08 cm^2 (CI [48.71, 44.82]) with a 5 mm thumbnail, and 45.89 cm^2 (CI [47.05, 44.39]) with a 10 mm thumbnail. We further quantify the difference in the size of areas with a within-subject analysis based on pairwise differences. As the 0 mm thumbnail shows the largest comfortable and useful areas, we compute the pairwise differences of the sizes of areas to 0 mm (Figure 11b and 11d). Since the LENGTH is a within-subject variable, we compute the difference for every participant individually. The pairwise differences confirm a clear difference between 5 mm and 10 mm thumbnails with 0 mm thumbnails, for both types of areas, because none of the confidence intervals for these differences overlap with 0. Having a 0 mm thumbnail leads to having 2.84 cm^2 more comfortable area (CI [4.434, 1.54], +19.30%), and 3.28 cm^2 more useful area (CI [4.37, 2.61], +6.51%), than 5 mm thumbnail. Having a 0 mm thumbnail leads to having 5.37 cm^2 more comfortable area (CI [8.22, 3.55], +36.46%), 4.47 cm^2 more useful area (CI [5.27, 3.70], +8.88%), than 10 mm thumbnail.

5.7.2 Subjective difficulty. 16/24 comments on the difficulty were about 10 mm thumbnails. E.g., (P4) “more difficult”, (P11) “really disabling” and (P2) “prevents me from moving my fingers”. All the negative feelings (10 occurrences)

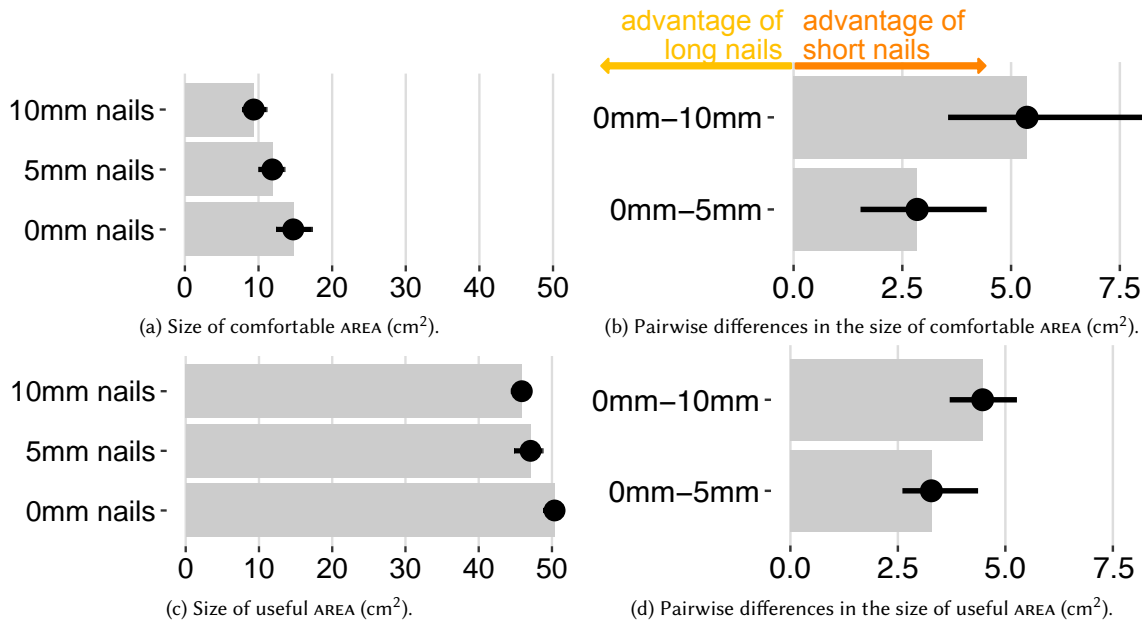


Fig. 11. (Left) Size of reachable AREAS according to thumbnail LENGTH, and (right) pairwise differences in the size of reachable AREAS compared to a 0 mm nail: (top) comfortable and (bottom) useful areas.

participants expressed during the interviews were with long thumbnails, 8 of them with 10 mm thumbnails, e.g., (P3) “unbearable”. Comments on the difficulty with 5 mm fingernails were mixed. E.g., (P1) “5 mm is not that bad”, (P3 about the comfortable area) “It’s much better [than 10 mm], but it’s still going to keep me from doing stuff” and (P10) “The nail touched a little, but it does not bother particularly”. Interestingly, P3 and P10 commented their accuracy: (P3 with 10 mm thumbnails) “I have the feeling to be less precise” and (P10 with 0 mm thumbnails) “I [...] use [...] the tip, and therefore I’m more precise”.

5.7.3 Subjective areas. Participants found the bottom part of the screen difficult to reach. In particular (P9) “It’s a problem at the bottom right because I can’t have my thumb upright” and (P4) “At the bottom right I can’t reach it anymore because I can’t bend my thumb”. The bottom left corner was also pointed out as a very difficult part to reach by P2, P5-6, P9 and P11. Participants also found the right side of the screen more difficult to reach. E.g., (P4) “If the position is too close [to the palm], I can’t reach it anymore”.

5.7.4 Relocation of the hand, effort and rapidity. Although Figure 9c shows that the useful areas are close for all thumbnail lengths, the interviews reveal that extra effort is required when having long nails. About the useful area with a 10 mm thumbnail: (P3) “I feel like I make more effort”, (P4) “you have to keep your thumb extended”, and (P9) “it hurts my hand”. P4 made a connection between the length of the nails and the number of times they had to clutch, i.e. to take their thumb off the screen and relocate their hand by moving their fingers at the back of the device. They said that they drew the useful area with a 10 mm thumbnail “in 4 strokes”, whereas they drew the same area with a 5 mm thumbnail “in 2 strokes like with 0 mm”. Participants commented on the need to move their fingers at the back of the device as an extra effort, e.g., P11 about the useful area with 5 mm thumbnail “I need to move the phone less to reach

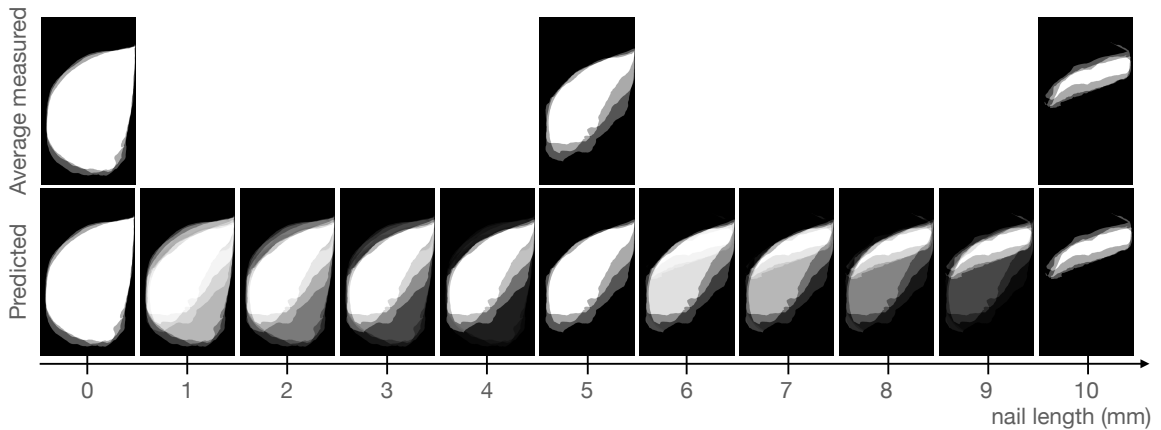


Fig. 12. (Top) Average images of the comfortable areas measured for P9 and (bottom) images predicted by the polynomial model of degree two for the comfortable area for P9.

[the area]”. P9 commented on the need to move their fingers at the back of the device as a risk of dropping the device: about drawing the useful area with 0 mm thumbnail, “I was able to leave my little finger at the bottom [of the phone]. Without my little finger underneath, I feel my phone is not safe.”

RQ2b questioned the extent to which long nails impact the reachable area (effect #b) when interacting with mobile tactile interfaces. Overall, we found a 36% decrease in the comfortable area on the mobile phone with a 10 mm thumbnail. In addition, participants’ qualitative comments show that reaching further in the useful area costs extra effort compared to short nails.

The first implication of these results for design is that users with long fingernails are currently exposed to hazardous movement of the mobile phone, with a risk of dropping and breaking it. Inclusive design for comfortably reachable items on the phone should not take previous large areas [12, 51] for granted, and importantly reduce to 14.72 cm² the area that is meant to be easily reachable for everyone. In particular, the current placement of important input widgets such as the bottom app bar in Android is too low for users with long fingernails.

For further precise placement of widgets, we explored if we could model the comfortable area but could not find a satisfactory consensus for all participants because the shape of the comfortable area varies between participants (Figure 9c). This can be explained by different hand sizes, for instance [12]. However, we were able to compute intra-participant models of the comfortable area. Figure 12 (bottom) illustrates the results of the prediction of a polynomial model of degree two for each pixel to be inside P9’s comfortable area, depending on their thumbnail length. Figure 18 in Annex C shows the predictions and the R^2 scores of each participant’s model. For instance, for P9, the median of the R^2 scores of all models (one for each pixel) is 1, and the 95% CI of R^2 scores is [0.25, 1.0], depending on the location on the screen. Typically the borders of the comfortable areas have lower R^2 scores, and far inside (resp. outside) these borders, we are sure that P9 will (resp. not) be able to reach these pixels. Through individual calibration, such individual models could inform on the probable comfortable area for a user’s current nail length and enable fine-tuning techniques. E.g. this allows TiltReduction [19] to adapt the reduction of the screen to the current comfortable area, and ForceRay [20] to adapt the control-display gain to enable the largest amplitude while staying within the comfortable area.

TODO provide all R2 and figures in the appendixes?

6 STUDY #4: IMPACT OF FINGERNAILS LENGTH ON TARGET ACQUISITION

To address our RQ2c (“To which extent do long nails impact the target acquisition performance (effect #c) when interacting with mobile tactile interfaces?”), the following experiment aims to measure the impact of nail length on the throughput of Fitts’ target acquisition tasks. To reduce unintentional false positive inflation of results [27], our study was registered before collecting the data³[7].

6.1 Participants and apparatus

We recruited 12 participants ($M=26.83$ y.o., 18–39 y.o.) at the local university. They had 0 mm fingernails on their thumb and index finger. Six participants self-identified as women and six as men. Eleven of them also participated in the first experiment and eight in the second experiment. Our participants’ thumb and index finger sizes, measured from crotch to tip, are representative [4] (Thumb $M=57.05$ mm, 44.97–66.25 mm, and Index finger $M=73.59$ mm, 60.67–82.95 mm). All but one participant were right-handed. Participants daily used smartphones with touchscreens. One of them frequently had 5 mm long fingernails. We used the same apparatus as the previous study, except that the phone ran the GoFitts software for Android [55].

6.2 Experimental design

We used a within-subject design with **FINGER**, **LENGTH** of thumbnail, **WIDTH** and **DISTANCE** as independent variables:

FINGER acquiring the targets: *Thumb* or *index* finger as in the first experiment (Figure 4a).

LENGTH of nails: 0 mm, 5 mm and 10 mm. We measured the length of the fingernail as in Figure 2.

WIDTH of target: 110px and 183px, i.e. ≈ 0.70 cm and 1.17cm.

DISTANCE to target (also called amplitude): 220px, 439px and 878px, i.e., ≈ 1.40 cm, 2.80cm, and 5.60cm.

The order of presentation of the 6 blocks of **FINGER** \times **LENGTH** was fully counterbalanced. The order of presentation of the 6 series of **WIDTH** \times **DISTANCE** was randomized within each block.

We collected the starting position, the position of the target, the position when the finger touched the screen, the position when the finger was released from the screen (selection position), how long it stayed in contact with the screen, the distance between the selection point and the target center, if it was missed, and the total movement time it took to select the target (*MT*). As in the previous experiment, we collected the pitch angle of the finger on the surface and conducted semi-structured interviews. For these measures, we collected 2 **FINGERS** \times 3 **LENGTHS** of nails \times 2 **WIDTHS** of target \times 3 **DISTANCES** to target \times 20 repetitions \times 12 participants = 8 640 values.

6.3 Experimental task

Participants performed a standard 2D target acquisition task [40] (Figure 13) in each series. Participants acquired in sequence 20 opposite targets around a circle. The current target was highlighted in pink. Once selected, the next target, opposite to the current one in the circle, became the current target. If a target was missed, a beep sound informed the participants. We started to collect the data after the first tap and stopped collecting it after all 20 targets were selected. Participants were asked to acquire the targets as fast and accurately as possible.

³https://osf.io/48xsm/?view_only=1eebdac312f44c729dc5009790314e1f

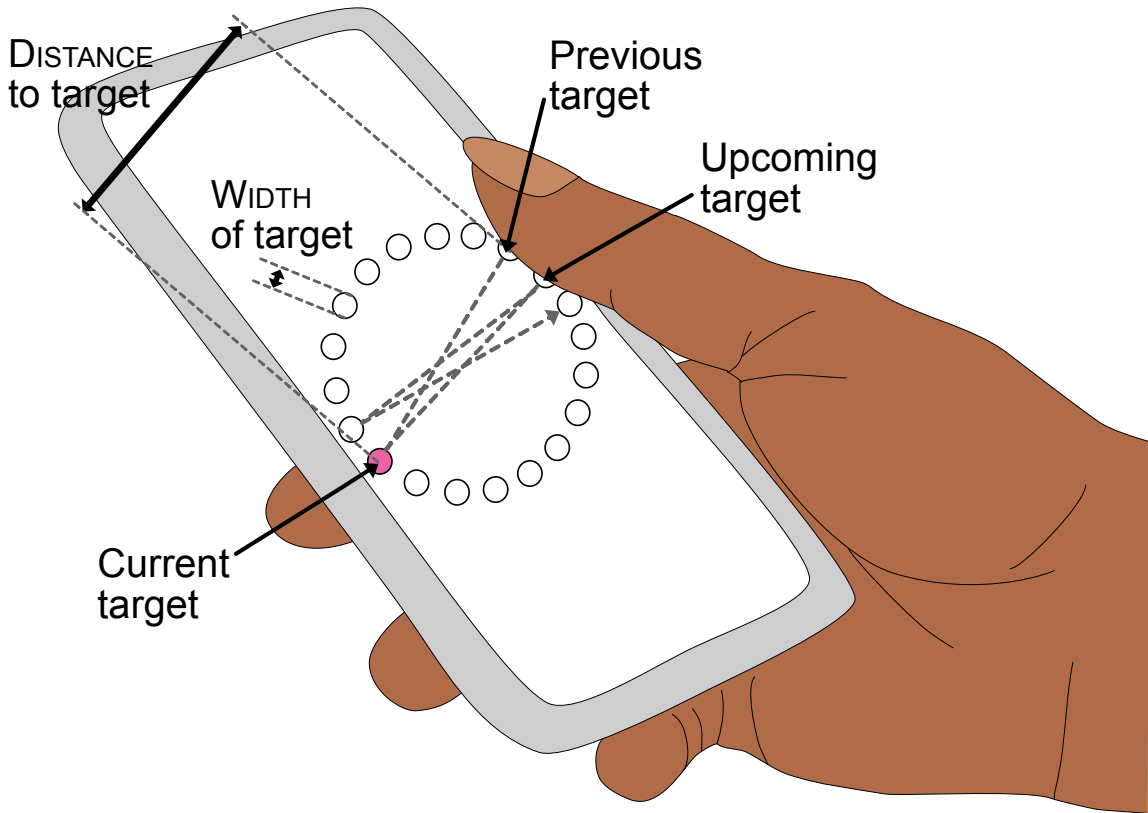


Fig. 13. Target acquisition task.

6.4 Procedure

After signing the informed consent form, participants put the glove on and sat at a table. We placed a marker on the finger currently tested, secured the artificial nail on their finger, and then explained to the participant the target acquisition task. Participants trained by performing the 6 series with the current fingernail length, before performing the recorded series. Within a block, participants could rest between series. The experiment lasted around 30min per participant.

6.5 Pre-processing and analysis

As we aim at comparing the normalized efficiency of each fingernail length, we compute the throughput (TP) of each fingernail length based on the effective index of difficulty (ID_e) and the recorded movement time (MT): $TP = ID_e / MT$. The effective index of difficulty is computed as $ID_e = \log_2(A_e / W_e + 1)$. The effective width W_e is computed as $4.133 \times SD$. SD is the standard deviation of the selection coordinates. A_e is the mean of the actual movement amplitudes. We mirrored the data of the left-handed participant. We then use the same analysis methods as in previous experiments.

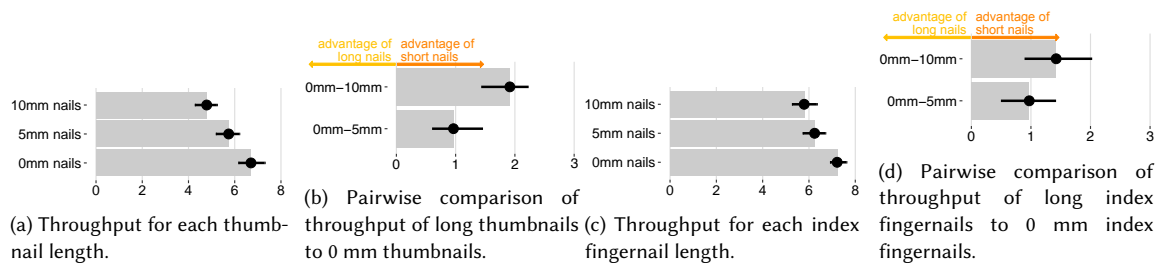


Fig. 14. Analysis of the throughput (bits/sec).

6.6 Results

6.6.1 Throughput. Figure 14a shows the throughput for the thumb: 0 mm thumbnails lead to a mean throughput of 6.70 bits/sec (CI [7.30, 6.16]). 5 mm thumbnails lead to a mean throughput of 5.74 bits/sec (CI [6.20, 5.18]). 10 mm thumbnails lead to a mean throughput of 4.79 bits/sec (CI [5.23, 4.27]). Figure 14c shows the throughput for the index finger: 0 mm index fingernails lead to a mean throughput of 7.22 bits/sec (CI [7.62, 6.91]). 5 mm index fingernails lead to a mean throughput of 6.25 bits/sec (CI [6.71, 5.73]). 10 mm index fingernails lead to a mean throughput of 5.79 bits/sec (CI [6.34, 5.26]).

As 0 mm nails shows the highest throughput for both FINGERS, we compare the pairwise differences of the throughput to 0 mm (Figure 14b and 14d). Since the LENGTH of the nail is a within-subject variable, we compute the difference for every participant individually. The pairwise differences confirm that there is a clear difference between fingernails of 5 mm and 10 mm with 0 mm thumbnails, because none of the confidence intervals overlap with 0. Having 10 mm long thumbnails results in a mean drop of 1.92 bit/sec (CI [2.23, 1.43], -29%). Having 5 mm long thumbnails results in a mean drop of 0.96 bit/sec (CI [1.46, 0.60], -14%). Having 10 mm long index fingernails results in a mean drop of 1.42 bit/sec (CI [2.03, 0.89], -20%). Having 5 mm long index fingernails results in a mean drop of 0.97 bit/sec (CI [1.42, 0.50], -13%).

6.6.2 Subjective feelings. 34/45 of the negative feelings participants expressed during our interviews were when having the 10 mm fingernails. For instance, “it is unusable” (P7), “unbearable” (P9), “horrible” (P1, P12), “impossible” (P6), and “abject” (P3). In contrast, our participants did not comment so strongly with 5 mm fingernail: “Clearly the nails get in the way, even the [5 mm] nail” (P7), “the nail gets much less in the way, the position is more natural” (P11). Participants complain about the 5 mm nail only when the targets are more difficult to reach, such as small and/or far targets (P3, P4, P11), or when targets are in the lower part of the screen (P7). Seven participants found the 5 mm nails closer to the 0 mm nails than to the 10 mm nails. However, P4 has “the feeling that it is more difficult anyway than with no nails”.

6.6.3 Subjective usability issues. When commenting on their experience with 5 mm and 10 mm fingernails, the most reported usability issue is **accuracy** (29 comments from P1-9 and P11): E.g., P8 “I felt like I was typing on a target, but I was just typing next to it”. P7 and P11 made a direct association between accuracy and the length of the nail, e.g., “I find it much more difficult to aim with the long nail” (P7).

The second most commented usability issue is the **visual occlusion** caused by the fingernail (23 comments from P1-5, P7-10 and P12): E.g., P4 “it’s more complicated because you can’t see the surface because of the nail. I don’t know where my fingertip is” or P10 “the discomfort was visual: I could not see under the nail”.

The third most commented issue was the effort they needed to produce in order to complete the task with long nails (15 comments from P1-3, P6-10, and P12). This extra effort was either a **cognitive effort**, e.g., P2 “When I had long

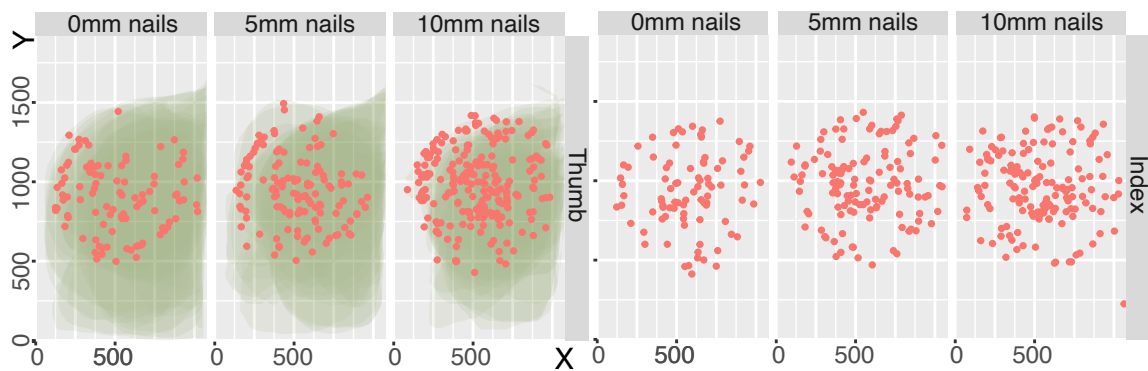


Fig. 15. Selection position of the missed targets (in red), with comfortable areas collected in the second experiment superimposed in green for the thumb.

nails, I felt like I had to visualize more in my head where I was going to put my finger” or P8 “I had to be more focused”, or a **physical effort**, e.g., P1 “the fingernail is so long that to see the [targets], I have to place my body like this [bends down to look under their finger] to see the targets”. Accordingly, the **fatigue** was also commented by P1, P5-6 and P10 as an issue: E.g., P1 “it’s more tiring because [...] you have to extend a lot the index” and P5 “I feel it on my wrist”.

6.6.4 Exploratory analysis of the accuracy and reachable area. Figure 15 shows the selection position of the missed targets. For the thumb (Figure 15 left), the missed positions are denser at the top left edge of the comfortable area, showing that the lack of comfort decreases the accuracy of users with long fingernails. However, for both the thumb and index finger (Figure 15), targets are missed in all locations, also within the comfortable area.

Based on this analysis, we hypothesize that the decreasing accuracy might also be due to the fact that users have a hard time to predict the location of the touch point. Both fingers suffer from this inaccuracy due to visual occlusion and a low pitch angle. However, the thumb additionally has to balance between numerous relocations of the hand on the phone, or the limited ability to adapt the incidental pitch angle and reachability at the top left.

RQ2c questioned the extent to which long nails impact the target acquisition performance (effect #c) when interacting with mobile tactile interfaces. Overall, we found a 24% decrease in throughput when acquiring targets on a mobile phone with a 10 mm fingernail. Qualitative comments highlight the lack of accuracy, the visual occlusion and the extra effort needed when acquiring targets with long fingernails.

7 LIMITATIONS

Is the experience with all long nails comparable? Studies #2-4 mostly involve participants with minimal prior experience with long fingernails. Our results, therefore, directly apply to this large set of users that occasionally wear long artificial nails.

Users wearing long fingernails on a daily basis, as the ones we interviewed in study #1, might develop specific expertise when interacting with their mobile phones. We are not sure whether our results generalize to users wearing long nails on a daily basis. In addition, our experiments involved artificial nails, which might not lead to the same experience as natural nails (P14 in study #1). We are not sure whether our results generalize to users wearing long natural nails.

We made the experimental choice of using artificial nails of controlled length, in order to control this independent variable, and establish causal relationships [56] between the length of nails and the measured pitch angle, reachable areas and target acquisition performance. Alternatives would be to leave enough time between each experimental condition (0, 5, and 10 mm) for participants to grow/cut their nails, and additional time to develop the expertise to interact with their mobile phones with the new length. This would require participants to cut or grow their nails for the experiment, which takes around 100 days to grow from 0 mm to 10 mm⁴ –in the best-case scenario where the nail does not break. In addition, we could not recruit any participant willing to do so, and we were not comfortable interfering with their bodily practice.

To assess whether the expertise or the nature of the nail (natural vs. artificial) might have an effect on our results, we conducted pilot studies. We recruited participants wearing long natural nails on their dominant hand. We measured the length of their nails, but did not ask them to cut or grow their nails specifically. We therefore do not control this variable and only measure a correlation between natural nail length and comfortable area and target acquisition performance.

We recruited 12 participants (M=41 y.o., 23–56 y.o.) at the local university. The length of their thumbnail was between 2.22–6.75 mm (M=3.73 mm). The length of their index fingernail was between 2.09–4.64 mm (M=3.03 mm). We could not find participants with natural nails longer than these, as natural nails tend to break when they grow too long. All participants had from 1.5 to 36 years of expertise in wearing long natural fingernails. Ten participants self-identified as women and two as men. Three of them participated in study #1.

We reproduced the exact same procedures and designs as studies #3 and #4, except that (1) the LENGTH of the nail was not an independent variable, and (2) we did not measure the finger incidental pitch angle, in order for the experiment to be transportable and thus reach more easily participants. For each measure of the partial replication of study #3, we collected 2 types of AREA \times 3 repetitions \times 12 participants = 72 values. For each measure of the partial replication of study #4, we collected 2 FINGERS \times 2 WIDTHS of target \times 3 DISTANCES to target \times 20 repetitions \times 11.5 participants⁵ = 2760 values.

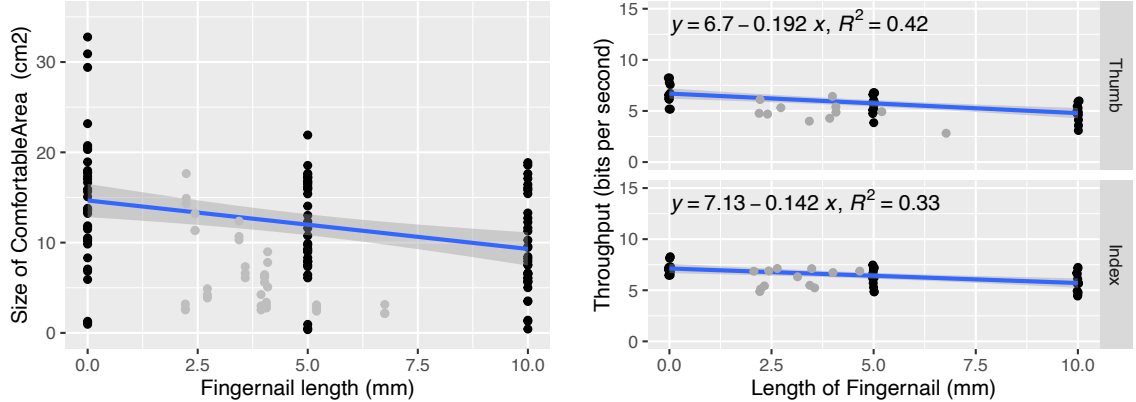
When superimposing both data sets in Figure 16, we notice that the data collected from users experts with natural long nails lie within the range of the data collected in study #3 (Figure 16a) and #4 (Figure 16b). The effect seems even larger for the comfortable area (Figure 16a). One hypothesis is that participants in the pilot study did not take any risks and avoided damaging their natural nails, compared to participants in study #3 that did not take special care of the experimental apparatus. Based on the results of these studies, we are confident that the results of studies #3 and #4 generalize to expert users with long natural nails.

Measuring the pitch angle. A limitation of our experiments could be the precision and accuracy of our pitch angle tracking system. On the contrary to the $10.52 \times 6.57 \text{ mm}^2$ contact area of our rigid body (0.45 g) to measure the pitch angle, Goguey et al.'s attached a larger sensor ($12.7 \times 17.78 \text{ mm}^2$) and included cables [28]. Comparatively, Goguey et al. accuracy was -0.3° for 0° , -1.1° for 45° , and -0.2° for 90° . Their precision was 1.7° for 0° , 0.9° for 45° , and 1.6° for 90° . However, Goguey et al. measured their precision and accuracy over 50 samples, which does not take the drift of the sensor into account. On the contrary, we took around 4700 samples in 1 minute. We therefore think that the accuracy of our system is comparable or better to previous work.

Measuring the reachable area. We found no standard way to measure the comfortable area to allow the comparison of results. With 0 mm thumbnails, we found a mean comfortable area of 14.72 cm^2 . Le et al. report a larger comfortable

⁴Fingernails grow at a rate of 0.1 mm a day [64].

⁵P7 (3.58 mm thumbnail) kept tapping outside of targets and, therefore, was not able to complete the target acquisition tasks with the thumb.



(a) Size of comfortable area in study #3 (black points and blue linear model) and in our pilot study with participants with natural long nails (gray).

(b) Throughput in study #4 (black points and blue linear model) and in our pilot study with participants with natural long nails (gray).

Fig. 16. Data collected in studies #3 and #4 (black points), and in our pilot study with participants with natural long nails (gray points). Blue lines show the linear regression of the data sets collected in study #3 and #4.

area of 35.2 cm^2 on the phone closest to ours [51]. Yet for both experiments, the instructions given to the participants were the same, and participants' hands were within the representative range. We believe the reason for this difference is the computation of the size of the area. Le et al.'s goal was to locate the comfortable area, while our goal was to measure it. Le et al. computed the area by adding up the pixels reached by each participant and kept the ones that were reached by 25% of their participants. As a consequence, they do not report the mean area. On the contrary, we strive to also report the uncertainty about our measure of the comfortable area through the mean and the 95% CI. This difference in pre-processing of the data can explain the difference.

8 IMPLICATIONS

From the results of this paper, we draw concrete recommendations for methodology and design.

Methodological recommendation: include participants with long fingernails in the experiments on mobile tactile interaction. The first implication of this paper concerns the selection and recruitment of participants in the experiments conducted by the HCI community. For decades the HCI community has been constructing knowledge on mobile tactile interaction without taking users with long fingernails into account. This paper shows that long fingernails have an impact on two of the most researched problems, namely the target acquisition performance and the comfortable area of the thumb. Therefore users with long fingernails should be included in the experiments involving mobile tactile interaction. In doing so, the HCI community will study mobile tactile interaction in a way that is more inclusive and reliable.

Design recommendation #1: generalize techniques improving precision. Target acquisition performance decreases with long nails, both inside and outside of the comfortable area (study #4). To solve this, existing improved pointing techniques could be generalized to larger targets or screens. Techniques improving precision could be triggered when the system detects 5 mm thumbnails (study #4), thanks to calibration through touch ellipses (study #2). For instance, the Shift technique [84] currently triggers a magnifying glass when touching small targets and is already applied for the

precise positioning of the text cursor on mobile devices. Interaction techniques designed for ultra-small touchscreen, such as panning the content of the screen while the cursor stays fixed on the screen [71, 77] to avoid occlusion (study #4), or completely avoiding using touch and using different interaction modalities such as tilting and muscle contraction [50].

Design recommendation #2: generalize techniques improving reach. The size of the comfortable area decreases with long nails (study #3). To solve this, the system could gather data on the user's comfortable area at different nail lengths over time. The system could then use the resulting model (study #3) to trigger existing techniques that bring potential targets closer to the thumb's comfortable area through gestures performed from within the comfortable area (study #3) with a low pitch angle of the thumb (study #2). Examples of such techniques include TiltSlide [19], TiltReduction [19] and TiltCursor [19] that first require tilting the device to trigger a quasi-mode, and then respectively panning the content of the screen, scales it down, or enables relative pointing. Another example is ForceRay [20], which uses the force of the touch on the screen to reach for far target with movement of limited amplitude.

Design recommendation #3: avoid techniques that rely on pitch rotation or a large comfortable area. The limited ability to perform a pitch rotation of the fingers with long nails (study #2) impact the efficiency of interaction techniques such as Fat Thumb [15], vertical swipe gestures, and micro-gestures such as micro-rolls [68]. The decrease in the range of pitch angle that we report in study #2 causes the amplitude of the gestures to be smaller. The amplitude may then not be sufficient or lowers the users' accuracy in the control of the gesture. For the same reasons, some of the techniques designed to reach far targets might not be usable with long fingernails. For instance MagStick [67] and 2D-Dragger [75] require the use of the pitch angle, e.g., to control a stick acting as a cursor extension [67] or to jump from targets to targets [75]. For designers to also include users with long fingernails, alternative techniques should be proposed, such as the ones mentioned in the design recommendations #1 and #2 above.

Design recommendation #4: avoid techniques that rely on a large comfortable area. We found in study #3 that the size of the comfortable area decreases with long nails. Techniques such as BezelSpace might be difficult to use with long fingernails: BezelSpace [90] uses a distant cursor controlled from within the comfortable area to trigger the selection of a target when the users release their touch. The comfortable area can be so reduced with long nails that clutching is necessary, and cause unwanted selection. Other techniques like MovingScreen [81] should be improved as it requires an initial vertical swipe gesture on the right edge of the screen, which is not comfortable with 10 mm fingernails as shown in Figure 9c (top right). For designers to include users with long fingernails, alternative techniques should be proposed, such as the ones mentioned in the design recommendations #1 and #2 above.

9 FUTURE WORK

Study hardware. The lack of pitch angle amplitude was one of the most reported issues in study #1. Participants mentioned their will to touch the screen with vertical fingers –to use multiple fingers easily, and to tap on targets accurately. To enable this, the hardware could be improved, e.g., HCI could work on the sensing of the tip of long fingernails with self-capacitive touch screens such as the Samsung Galaxy S5.

Study additional factors and effects. Future interesting factors or effects to study include the curvature of the nail, the use of a mobile phone holder, and further interaction such as swipe, pinch, drag, and multitouch gestures. Future work refining this study should investigate the range of pitch angle in all areas of the mobile surface.

Study #2 measured the pitch angle as we focused on the primary effects of long nails, and this was the angle most reported in study #1. The change of roll angle, observed in study #1, is a secondary effect, compensating for the lack of

pitch angle (primary effect) by enabling users to touch more precisely. Future work should study to which extent users compensate for the drop in comfortable area and throughput through the roll angle, and more particularly focus on fatigue implications of using the roll angle.

Verify whether the perceived input point model holds for users with long fingernails, i.e. whether the vertical center of any fingernail is the best model for vertical accuracy. The generalized perceived input point model [33, 34] shows that the vertical center of ~0 mm fingernail is the best model for vertical accuracy [34] for users with short fingernails. In addition, the largest error in direct touch pointing is on the finger axis [33, 34], i.e. in the direction of the fingernail extension. As our paper shows that the target acquisition performance decreases with longer fingernails –in particular the error rate increases (Figure 15), this shows that the perceived input point is further away from the actual input point when wearing long nails. Therefore, future work should verify whether the perceived input point model holds for users with long fingernails, i.e. whether the vertical center of *any* fingernail is the best model for vertical accuracy.

Compensating the error caused by long fingernails. Study #2 shows that the minimum of the touch ellipse major axis is correlated to the length of the nail, and study #4 shows that the length of the nail has an impact on target acquisition efficiency. Based on these insights, the next step is not to gather ellipse and target acquisition efficiency data to study if we can build a model able to compensate for the error caused by long fingernails.

10 CONCLUSION

We investigate the impact of fingernail length on mobile interaction: our formative study identifies usability issues with mobile phones when having long nails. Most participants struggle with the incidental pitch angle, the reachable area, and tapping efficiency. Our three experiments measure the important difficulties experienced by users with long nails: 10 mm fingernails decrease by 57% the range of the pitch angle, by 36% the comfortable area of the thumb, and by 24% the efficacy of target acquisition.

The primary goal of this paper is to raise the awareness of the HCI community about the (unintended) consequences of current design of mobile tactile UIs on users with long nails. We were surprised that users with long fingernails were not included in the research earlier. When we compare to other problems addressed by the community, their problem is as important. E.g., assuming the number of users wearing long fingernails is as important as encumbered users [62], the effects are comparable (-23.48% in [62]).

This paper provides designers and researchers with new data and models. Our results open an exciting research area for inclusive design, also supporting users with long fingernails. Designers and researchers can readily use the measured ranges and models related to pitch angle and comfortable area and the baseline measure of target acquisition efficiency, and integrate them in a generative approach [10]. They can now better understand what interactions are possible with long fingernails, and carefully choose and design interaction techniques. The data and its analysis are available as supplementary material and will be on the Open Science Framework.

ACKNOWLEDGMENTS

We thank the participants, Renaud Blanch and François Bérard for making their code available, and our colleagues who reviewed the earlier version of this paper. This work was supported by Université Grenoble Alpes and by the French government funding managed by the National Research Agency under the Investments for the Future program (PIA) grant ANR-21-ESRE-0030 (CONTINUUM).

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ID	Age	Self-identified gender	Occupation	Current thumbnail size	Frequency of use
P1	55	men	Research director	3.4 mm	less than 1h
P2	47	women	Chief financial officer	3.33 mm	3h
P3	46	men	Researcher	0 mm	less than 1h
P4	18	women	Saleswoman	7 mm	5h
P5	55	women	Special needs assistant	10.8 mm	3-4h
P6	47	women	Nail prosthetist	2.16 mm	less than 1h
P7	26	women	Esthetician	0.95 mm	1-2h
P8	30	women	Cashier manager	8.42 mm	2-3h
P9	22	men	Music teacher	7.18 mm	all day
P10	60	men	Guitar teacher	5.15 mm	6h
P11	25	men	PhD researcher	5.25 mm	2-5h
P12	47	women	Lecturer-researcher	4.5 mm	1h
P13	23	women	Trainee/Student	1.88 mm	3-4h
P14	32	women	Student	4.4 mm	4h

Table 1. Description of the participants we interviewed. Their thumbnails (resp. index fingernails) were between 1.88 mm and 10.8 mm (resp. between 2.12 mm and 8.13 mm) –except for P3, who had 0 mm nails as they had just broken them. We interviewed 4 researchers, 2 teachers, 1 assistant for children with special needs, 2 students, 2 beauticians, 2 saleswomen and 1 chief financial officer.

Finger	Nail length	Range of pitch angle	Min pitch angle	Max pitch angle	major axis min
Thumb	0 mm	63.09° [50.58, 73.05]	12.54° [7.08, 22.47]	75.63° [66.60, 81.96]	7.61 dots [7.46, 7.80]
	5 mm	45.93° [41.00, 49.90]	6.20° [4.10, 9.03]	52.13° [47.60, 55.93]	8.16 dots [7.97, 8.40]
	10 mm	29.70° [25.27, 32.40]	5.09° [3.15, 7.65]	34.79° [32.09, 37.86]	9.72 dots [9.43, 10.06]
Index	0 mm	79.98° [72.00, 84.50]	5.25° [2.98, 12.10]	85.23° (CI [78.80, 88.28])	7.07 dots [6.94, 7.18]
	5 mm	49.58° [44.41, 55.49]	4.24° [2.13, 8.97]	53.82° [49.06, 59.33]	7.97 dots [7.61, 9.30]
	10 mm	31.96° [28.00, 39.35]	2.13° [1.03, 4.11]	34.10° [30.39, 41.27]	9.35 dots [9.10, 9.62]

Table 2. Detailed results from study #1 (confidence intervals between brackets).

A PARTICIPANTS OF OUR FORMATIVE QUALITATIVE STUDY (#1)

Table 1 shows the detailed information about the participants from study #1.

B DETAILED RESULTS FROM STUDY #2

Table 2 shows the detailed results from study #2.

For the thumb (Figure 7a), 5 mm (resp. 10 mm) thumbnails lead to a 7.19% (resp. 27.75%) smaller major axis compared to 0 mm thumbnails. For the index finger (Figure 7b), 5 mm (resp. 10 mm) fingernails lead to a 12.73% (resp. 32.24%) smaller major axis compared to 0 mm thumbnails. The 95% CI of the pairwise differences shown in Figures 17a and 17b does not cross the 0 line, showing strong evidence that there is a difference.

Figure 18 shows the predictions of the models computed for each participant, together with the score of each individual model (last column).

C DETAILED RESULTS FROM STUDY #3

C.1 Raw collected areas

Figure 19 shows the raw collected areas.

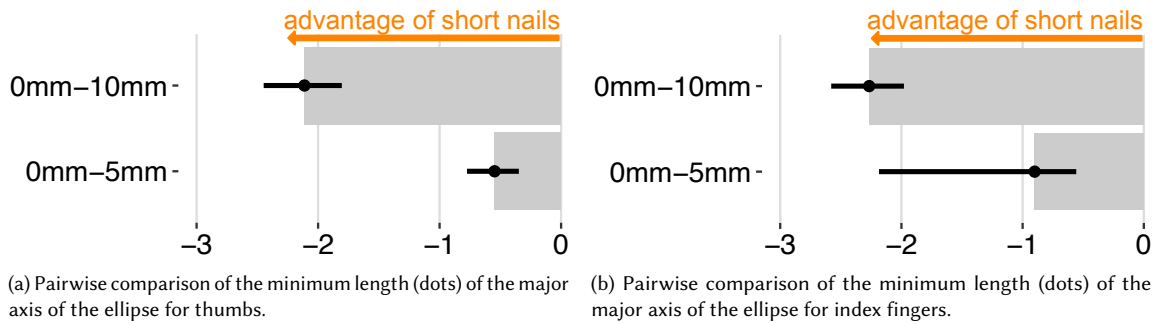


Fig. 17. Pairwise comparisons of the minimum length (dots) of the major axis of the ellipse to 0 mm fingernails, for the index fingers and thumbs. Error Bars indicate Bootstrap 95% CIs.

C.2 Location of areas

To study the location of the areas on the screen, we study the location of their centroid. The centroid of the comfortable area is 94.99 px away with 5 mm thumbnails compared to 0 mm thumbnails (CI [114.76, 79.34]), and 125.66 px away with 10 mm thumbnails compared to 0 mm thumbnails (CI [167.23, 97.58]). The centroid of the useful area is 26.32 px away with 5 mm thumbnails compared to 0 mm thumbnails (CI [34.61, 20.66]), and 29.10 px away with 10 mm thumbnails compared to 0 mm thumbnails (CI [36.94, 22.69]). Figures 20a and 20b show the pairwise distance from the centroid of the reachable area obtained with long fingernails to the centroid of the reachable area obtained with the 0 mm fingernail. Figures 20a and 20b show that the location of the comfortable and useful area with longer thumbnails moves away from the location of the 0 mm thumbnail (the 95% CI does not cross the 0 line). However, the effect size is larger for the comfortable area. The centroid of the comfortable area moves towards the top right of the screen as the thumbnail length increases. This shows that it is more difficult for our (right-handed) participants to comfortably reach the area at the bottom left of their 0 mm comfortable area.

C.3 Thumb contact angle on the touchscreen

Participants commented on the angle of their thumb when touching the screen. P1-4, P6, P9, and P12 reported turning their finger to the side. E.g., (P3) “When the area is close [to the palm], I use the side of the thumb because I can’t bend my finger”. More importantly, P2-4 and P6-10 reported using their finger pad to be able to touch the screen with a long thumbnail, as suggested in our formative study. To illustrate this, we divided our pitch angle data into nine subparts of the screen. Figure 21 shows the mean pitch angle of the thumb when drawing each AREA depending on the location on the screen. On Figure 21a we can see that the mean pitch angle around the touchscreen for the comfortable area ranges from 35° in the middle left part to 61° in the bottom right corner with 0 mm thumbnails. With 10 mm thumbnails, the mean pitch angle around the touchscreen ranges from 21° in the top left part to 36° in the bottom right corner.

C.4 Relocation of the hand, effort, and rapidity

To illustrate participants’ comments on the relocation of their hand (Figure 21b), we analyze the central part of the touchscreen separately as only P8 with the shortest thumb had to draw in this area. Figure 21b shows that the mean pitch angle around the touchscreen for the useful area ranges from 40° in the left part to 55° at the bottom right corner with 0 mm thumbnails. With 10 mm thumbnails, the mean pitch angle around the touchscreen ranges from 21° at

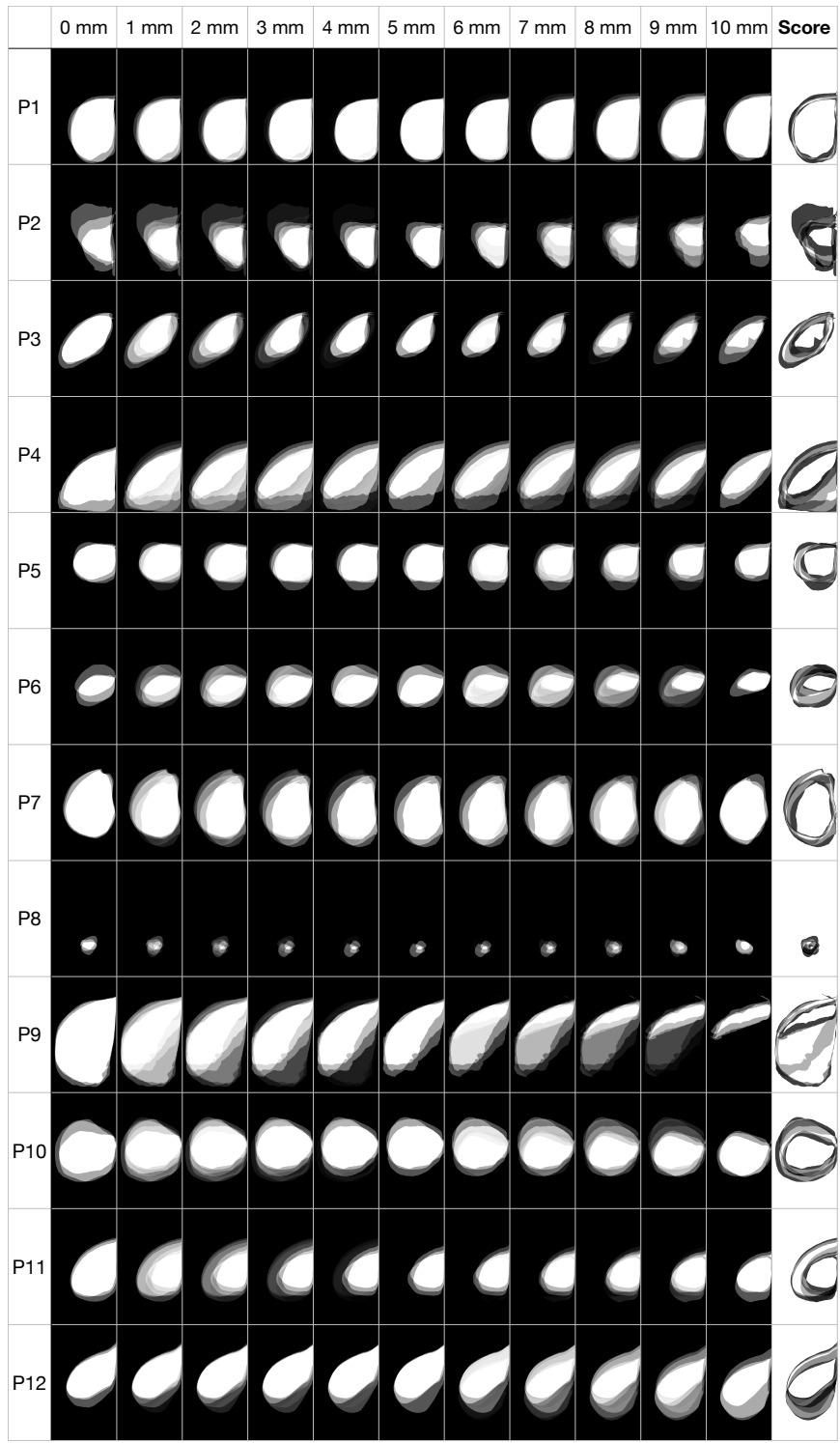
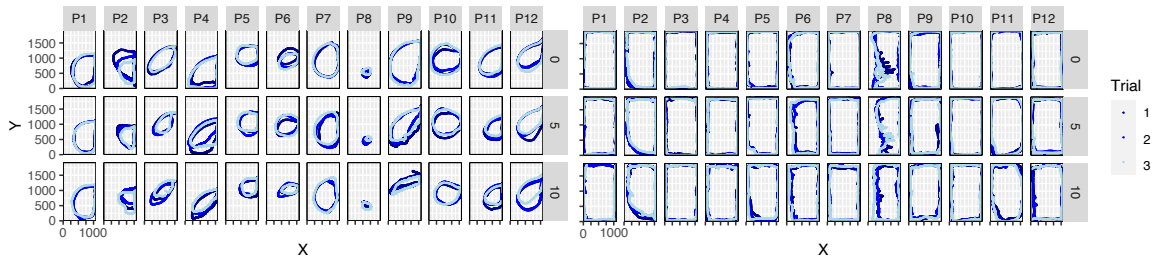
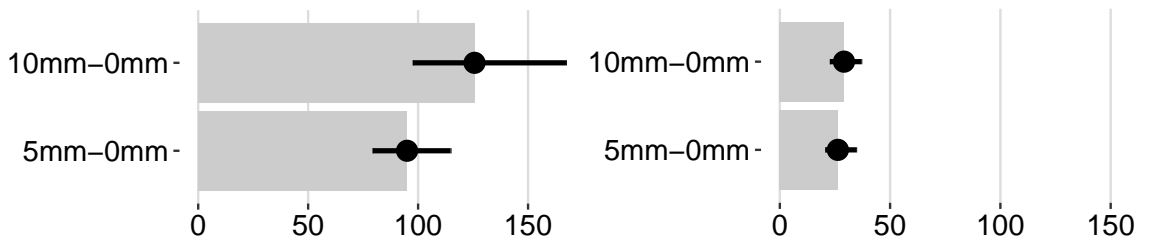


Fig. 18. Images predicted by the individual polynomial models of degree two for the comfortable area for each participant, together with the score of each individual model (last column).



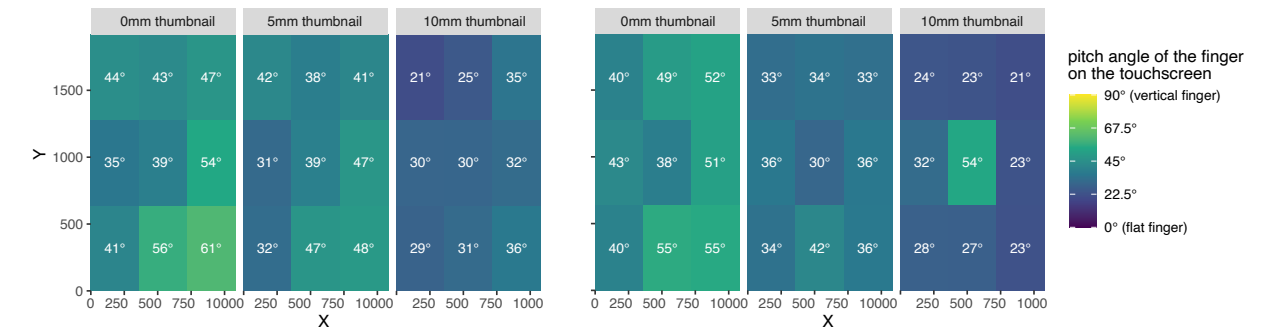
(a) Raw comfortable AREAS according to thumbnail LENGTH and participant. (b) Raw useful AREAS according to thumbnail LENGTH and participant.

Fig. 19. Raw collected reachable AREAS according to thumbnail LENGTH collected in our experiment (P8 has the smallest thumb size).



(a) Pairwise distance (px) to the centroid of the 0 mm fingernails comfortable AREA. (b) Pairwise distance (px) to the centroid of the 0 mm fingernails useful AREA.

Fig. 20. Pairwise distance to the centroid of the AREAS performed with 0 mm thumbnail: (left) comfortable AREA and (right) useful AREA.



(a) Mean pitch angle of the finger drawing the comfortable AREA. (b) Mean pitch angle of the finger drawing the useful AREA.

Fig. 21. Analysis of the mean pitch angle of the finger drawing the reachable AREAS. The closer to 0°, the flatter the finger on the screen, and therefore, the less accurate the finger is when tapping.

the top right corner to 32° in the middle left part. The most vertical thumb is not at the bottom right corner anymore, showing that participants had to relocate their hands more with the 10 mm thumbnails compared to 0 mm thumbnails.

D DETAILED RESULTS OF STUDY #4

D.1 Subjective finger angles.

Confirming our formative study, all 12 participants commented that they had to adapt their finger pitch angle on the surface in order to be able to acquire the targets. Seven participants also commented on their use of the roll angle of their fingers. In particular, P2 mentioned turning the finger to the side so that the contact area between the finger and the screen is smaller in order to be more accurate. In particular, they commented on using the roll angle for specific areas of the screen, as explained below.

D.2 Subjective areas.

For far targets –e.g., at the top left for right-handed participants–, the long fingernails prevented P6 and P7 from touching with the fingertip and required them to perform a gesture with a larger amplitude with their whole hand to touch with the finger pad. Symmetrically to quickly reach the targets in the bottom right area of the screen, the long fingernail prevented P3, P7, P8, and P12 (right-handed participants) from bending their fingers.

D.3 Subjective expertise.

P4, P6 and P8 felt that expertise might be important, e.g., P6 “I will need some training, because 5 mm can happen to me, but not 10 mm” and P4 with 10 mm index fingernail “[has] the impression to be less efficient [...] but maybe it is the habit”. Yet, P3 and P12 felt that expertise and training would not solve their problems: P3 “On a daily basis, I think I could get used to 5 mm, but I couldn’t [get used] to 10 mm” and P12 “I don’t see where I touch, what part of my thumb touches, I can’t improve and rectify”. As P7 summarized –it is “easier with the short nail. Is it really a matter of habit?”– and according to the results of our formative study it is not clear yet if expertise eases target acquisition tasks. Future work needs to study target acquisition with long nails in the long term.

D.4 Exploratory analysis of the touch locations on the touchscreen.

The disadvantage of long fingernails is higher for the thumb compared to the index finger. Unfortunately, interacting with the thumb of the same hand holding the phone is a very popular way of using the phone [35]. To explain this disadvantage, we explored the incidental pitch angle and the accuracy according to the comfortable area.

Pitch angle. Figure 22 shows the mean pitch angle of the finger on 9 different areas of the touchscreen. With a 0 mm nail, we can see that both fingers touch the screen more vertically than with a 5 mm nail, and even more vertically than with a 10 mm nail. This demonstrates that the adaptation of the pitch angle measured in our first experiment comes into play when tapping on targets. Due to the grasp, the most vertical angle for the thumb is at the middle rightest position on the screen for 0 mm and 5 mm, while the most vertical angle for the index finger is at the bottom right corner.

The thumb of the hand holding the phone has limited ability to adapt its pitch angle of incidence on the touchscreen compared to the index finger of the opposite hand: While the index finger touches the screen on average from 60.02° (CI [54.12, 64.51]) with 0 mm fingernail to 24.53° (CI [19.86, 29.33]) with 10 mm fingernail, the thumb touches the screen from 61.69° (CI [54.19, 66.24]) with 0 mm fingernail to 32.74° (CI [29.87, 37.86]) with 10 mm fingernail. Figure 22 shows that the thumb and index finger have similarly bright colors with a 0 mm nail, whereas the index finger has darker colors (flatter finger on the screen) than the thumb with a 10 mm nail.

The average pitch angle we found in this 3rd experiment confirms the ranges found in the first experiment. Comparing to them (Figure 6), the index finger with 0 mm nails was able to reach 68.48% of the range in the first experiment, the

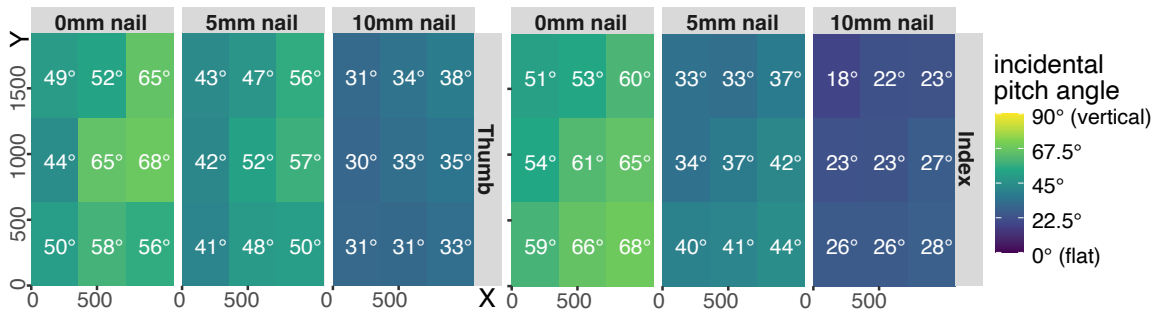


Fig. 22. Pitch angle of the finger on the touchscreen averaged for each section of the touchscreen during the target acquisition experiment.

index finger with 10 mm nails 70.07%, the thumb with 0 mm nails 77.90%, and the thumb with 10 mm nails 93.10%. While the index finger did not have to reach the maximum of the possible range, the thumb with 10 mm nails shows the most effort to reach the maximum, because its range is the most limited (Figure 6).

Holz and Baudisch showed that the finger pitch had an effect on the touch position captured by the system [33]. A finger that touches the screen horizontally, as it does with long fingernails, can cause the device to locate the touch location further away from the target. However, in our experiment, although Figure 22 shows that the index touches more flat with 10 mm, the number of errors for the thumb is higher than for the index finger: the mean number of errors for the thumb is 16.50 (CI [11.33, 24.00]) with 0 mm nail, 22.17 (CI [15.33, 30.00]) with 5 mm nail, and 36.17 (CI [27.17, 48.00]) with 10 mm nail. The mean number of errors for the index finger is 14.33 (CI [9.67, 23.33]) with 0 mm nail, 20.67 (CI [14.00, 31.67]) with 5 mm nail, and 25.33 (CI [17.50, 34.50]) with 10 mm nail. This might be due to the need to change the incidental angle with the thumb constantly: it might be more difficult to build a mental model of the touch location.