Designing Finger Orientation Input for Mobile Touchscreens

Sven Mayer, Huy Viet Le, Niels Henze
University of Stuttgart
Stuttgart, Germany
{sven.mayer, huy.le, niels.henze}@vis.uni-stuttgart.de

ABSTRACT
A large number of today's systems use interactive touch surfaces as the main input channel. Current devices reduce the richness of touch input to two-dimensional positions on the screen. A growing body of work develops methods that enrich touch input to provide additional degrees of freedom for touch interaction. In particular, previous work proposed to use the finger's orientation as additional input. To efficiently implement new input techniques which make use of the new input dimensions, we need to understand the limitations of the input. Therefore, we conducted a study to derive the ergonomic constraints for using finger orientation as additional input in a two-handed smartphone scenario. We show that for both hands, the *comfort* and the *non-comfort* zone depend on how the user interacts with a touch surface. For two-handed smartphone scenarios, the range is 33.3 % larger than for tabletop scenarios. We further show that the phone orientation correlates with the finger orientation. Finger orientations which are harder to perform result in phone orientations where the screen does not directly face the user.

ACM Classification Keywords
H.5.2 User Interfaces: Ergonomics

Author Keywords
Finger orientation; touch; surface; mobile; ergonomics; pitch; yaw; ergonomic zone; non-comfort zone.

INTRODUCTION
The age of ubiquitous computing has brought a large number of interactive surfaces into our lives. Interactive surfaces are present in various forms and various contexts from tabletops to mobile devices. While speech input is getting better [1, 22], touch continues to be the dominant input technique. Through direct touch, users can intuitively interact with the user interface (UI). UI controls can simply be selected by touching them. Here, the touchscreen simply relates the 2D touch point retrieved from the fingers position to the UI control.

While a growing body of research aims to enlarge the input space of touchscreens, the input space which is implemented

Figure 1. A participants performing a 32.5° pitch and 45° yaw input with the left hand while being equipped with our 3D printed tracking parts.

in current consumers products is mostly limited to a 2D location. Both Android and iOS use dwell time to implement a long press which serves as a second input mode. Apples 3D Touch is the first successful commercial implementation of an additional input dimension. However, while the sensor is capable of detecting a wide range of force, the implementation lets the user only interact with three different levels of pressure. Limiting the input to three levels is largely due to the just-noticeable difference (JND) of force input performed by a human. Huber et al. [10] showed that two levels of force should not be exceeded for touch interfaces in cars. Colley and Häkkilä [4] and Marquardt et al. [17] proposed to use finger-specific touch as an additional input dimension with up to 10 classes if distinguishing between all fingertips. Moreover, by using more than the fingertip and combining them can increase the number of possible input classes. As these approaches add a discrete number of additional levels they do not enable continuous input. Therefore, a growing body of work is developing means to determine a finger's orientation, which can add up to three continues dimensions: pitch, roll, and yaw. For instance, Wang et al. [27] proposed using the fingers' orientation for tabletops, Kratz et al. [11] for handheld devices, and Xiao et al. [32] for smartwatches and smartphones.

New interaction techniques are bearing the risk of being too complex to perform for the user. Recently, Mayer et al. [19] studied the ergonomic constraints when using the finger orientation as additional input dimensions. Mayer et al. [19] studied the constraints for stationary setups such as tabletops and phones which are laying on a table in front for the user. They concluded that the yaw input space can be divided into a *comfort* zone and a *non-comfort* zone. However, they only considered scenarios where the position and orientation of the screen remain fixed. When interacting with mobile devices, however, the position and orientation of the screen cannot

MobileHCI '18, September 3–6, 2018, Barcelona, Spain

ISBN 978-1-4503-5898-9/18/09. . . $15.00
DOI: https://doi.org/10.1145/3229434.3229444

be restricted. As users hold mobile devices in their hand, it is even likely that they voluntarily change the device's orientation. Therefore, findings from previous work cannot be transferred to the use of mobile devices.

In this paper, we investigate the use of finger orientation in two-handed smartphone interaction scenarios. In detail, we study the ergonomic constraints of finger orientation input for mobile devices. While Mayer et al. [19] investigated finger orientation in a static, restricted tabletop scenario, we extend their work to study how users move the device and how this affects what can comfortably be used for a two-handed interaction scenario. We conducted a study and asked 20 participants to rate the comfort and feasibility of touch actions. Participants aligned their index finger with given pitch and yaw angles while holding the device with their second hand. They were allowed to freely move their finger and the device while we ensured that they could still perceive content on the screen, see Figure 1.

RELATED WORK

With the success of mobile devices, touch-based interaction has become the dominant way to interact with computing systems. However, compared to the use of indirect interaction techniques such as the mouse, direct touch poses certain challenges. One such problem described by Siek et al. [24] is the *fat finger problem*. However, this can also be utilized as an interaction technique, here Boring et al. [2] presented the *fat thumb* interaction technique, where the size of the touch can be used as an input parameter. Holz and Baudisch further found that there is an offset between the point where the user assumes to have touched the surface and their actual finger position [8, 9]. They found that the touch offset is influenced by the angle with which a finger approaches a touchscreen. Holz and Baudisch concluded that touch is not a 2-dimensional interaction technique, but a 6-dimensional one [9], involving the finger position, orientation, and pressure. They showed that direct touch needs to be described by the 3D finger orientation relative to the touch surface for pitch and roll gestures.

Already since the beginning of the touch screen area multiple use cases that utilize the finger's orientation have emerged. Wang et al. [27] proposed to use the finger orientation to interact with interactive tabletops. Wang and Ren [28] proposed use cases, such as selecting items in a pie menu by rotating the finger, to make use of the new input dimension. Later Xiao et al. [32] enlarged the set of use cases to the smart watch domain. *Z-touch* by Takeoaka et al. [25] used finger pitch angle as an input source, for controlling Bezier curves in a drawing application. Xiao et al. [32] proposed new UI controls such as a circular slider where the finger's yaw angle is mapped to a "twist" sensitive control.

Over the last decade, multiples approaches have been developed to determine the a finger's orientation when touching a touchscreen. Initial work on the use of finger orientation as an additional input channel [28, 27] was based on a tabletop setup with back projection and determined the finger orientation from the finger's contact area. Dang and André [5] followed the same approach and improved it further. Later, Kratz et al. [11] proposed the first mobile device capable of detecting the finger orientation. They used a depth camera mounted on tablet and an algorithm to extract the orientation from the 3D point cloud above the screen. Mayer et al. [21] extended the work by Kratz et al. [11] and improved the detection accuracy. To avoid additional sensors, Zaliva [33] used data from a capacitive touch sensor to determine the finger orientation without additional hardware. Rogers et al. [23] built a capacitive sensor array prototype to determine the finger orientation. Xiao et al. [32] trained a Gaussian process (GP) model based on a set of features derived from the capacitive sensor data. Mayer et al. [20] improved the accuracy using a Convolutional Neural Network (CNN) and the raw capacitive sensor data, concluding that better results can be achieved with sensors that have a better capacitive sensor resolution.

Ergonomic constraints have been observed in a number of different prototypes using touch interfaces. Le et al. [14] argue that designers should consider ergonomic constraints when developing single-touch Back-of-Device (BoD) interaction techniques and therefore studies are needed to understand how users interact with devices. Colley and Häkkilä [4] found that when using finger-specific interaction, it is necessary to pay attention to ergonomic limitation. They state, for example, that the ring finger is not suitable for interaction. Le et al. [13] studied the range of the fingers when holding smartphones and areas that can comfortably be reached. They proposed design guidelines to ensure an ergonomic placement of interactive elements on smartphones. Hoggan et al. [7], found that the feasibility of touch rotation depends on the rotation angle, and input becomes harder when the hand rotation increases. Xiao et al. [32] identified additional ergonomic problems when using enriched touch input. Long fingernails made a large pitch unfeasible to perform. Wolf et al. [30] further showed that the feasibility of pitch, yaw, drag, and finger lift gestures on hand-held devices depends on the grip and the touch location. They found that significant deviations from a natural grip cause ergonomic problems, especially for one-handed interaction. Beyond single-touch interactions, Lozano et al. [15] showed that designers need to consider ergonomic factors when designing new multitouch interaction techniques. Mayer et al. [19] investigated the ergonomic constraints of finger orientation as an additional input. In their study, they restricted the touch surface to be mounted flat on a table and allowed participants only to use their right arm for interaction. However, in a mobile usage scenario, the user is not restricted to arm movements nor touch surface orientation.

Overall, previous research highlighted the importance of extending the input space of touch interaction. In particular, determining the finger orientation was extensively studied by previous work. A growing body of work presented use cases for using the finger's orientation as an input technique. While ergonomic constraints have been studied for static tabletop-like scenarios, previous research did not consider two-handed interaction scenarios. This is especially surprising as two-handed interaction is much more common than tabletop interaction. Furthermore, being able to rotate the touchscreen with the hand that holds the device will likely make many finger angles much easier to perform. Therefore, results from previous work cannot be transferred to mobile interaction, the most common application of touchscreens.

HYPOTHESES

Our study investigates the ergonomics of approaching a touch point with different finger orientations and is guided by the hypotheses described below.

Mayer et al. [19] presented work where participants rated the feasibility of finger orientation as input from easy to hard. They found that the *comfort* zone is smaller than the *non-comfort* zone using the finger orientations which were feasible. In their controlled study, the touch surface was flat on a table, and by allowing the user to move and rotate the touch surface, we expect the participants to compensate exhausting body movements by moving and rotating the device. Thus, we constructed the following hypotheses:

Hypothesis 1a (**H1a**): Finger orientation input for a two-handed smartphone interaction is easier than for tabletop interactions.

Hypothesis 1b (**H1b**): The *comfort* zone is larger for two-handed smartphone interaction than for tabletop interactions.

Hypothesis 1c (**H1c**): No finger orientation is infeasible when using both hands to interact with a smartphone.

The finger orientation movement will affect the orientation of the smartphone. Consequently, we infer the following:

Hypothesis 2a (**H2a**): The smartphone orientation varies more in the *comfort* zone than in the *non-comfort* zone.

Hypothesis 2b (**H2b**): The smartphone orientation is reflectively symmetric based on the hand of interaction.

STUDY

To investigate the ergonomic constraints of using the finger orientation as an input for mobile devices we conducted a study with 20 participants. To test the hypotheses, participants were asked to perform touch actions while we systematically manipulated PITCH_{Finger}[1] and YAW_{Finger}[2] of the orientation of the finger in relation to the touch surface. Participants were asked to perform the touch action with one hand while holding the touch surface, a smartphone, with the other hand. We recorded the orientation of the participant's finger, and the phone with a high precision motion tracking system.

Study Design

We used a within-subject design. We asked participants to perform touch actions with their index finger and rate the feasibility of the touch action with the dependent variable RATING. Our overall study design follows the design by Mayer et al. [19]. We use the same independent variables with exactly the same levels. We used the same three independent variables: PITCH_{Finger}, YAW_{Finger}, and HANDs. We used 10°, 32.5°, 55°, and 77.5° for PITCH. For YAW, we covered the full 360° range resulting in 0.0° to 337.5° with 22.5° steps. All combinations of PITCH_{Finger} and YAW_{Finger} were tested with the index finger of both HANDs. Thus, we used a $\text{PITCH}_{Finger} \times \text{YAW}_{Finger} \times \text{HAND} = 4 \times 16 \times 2$ study design resulting in 128 conditions. In addition to the dependent variable RATING, we recorded the smartphone orientation (PITCH_{Phone}, ROLL_{Phone}, and YAW_{Phone}) as additional dependent variables.

In contrast to previous work, participants were allowed to freely move the touch surface, their finger and their body to perform the touch action.

[1] In this paper, we define PITCH_{Finger} as the angle between the finger and the horizontal touch surface. PITCH is 0° when the finger is parallel to the touch surface, i.e., the entire finger touches the surface.

[2] In this paper, we define YAW_{Finger} as the angle between the finger and a mid-axis parallel the longer edge of the phone (when in horizontal mode). YAW is 0° when the finger is parallel to the long edge of the phone and increases when the finger is rotated counterclockwise.

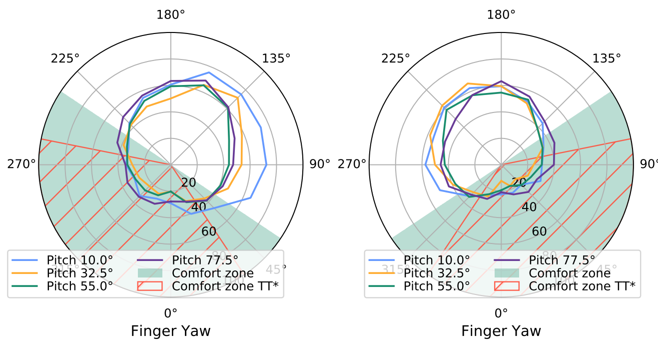
Figure 2. The setup with the 6DOF tracking system, the four pitch stabilizer on the left and the Motorola Nexus 6 with markers.

Apparatus

The apparatus consists of a Motorola Nexus 6 running the study application, a 6DOF tracking system (see 2), and four pitch stabilizers (see Figure 3). The application shows the next to perform touch action as well as a rating scale where participants had to rate the feasibility of the touch action. Furthermore, to ensure that participants were able to read content on the screen we presented them a word which they had to remember and make a one out of three choices when the rating scale was presented. We used all nouns out of the phrase set by MacKenzie and Soukoreff [16]. However, we removed the plural form of the noun if the singular version was also in the phrase set.

(a) (b)

Figure 3. (a) The four pitch stabilizers with the copper plate and the wire, we used in the study to limit PITCH to 77.5°, 55°, 32.5° and 10° presented from left to right. (b) A CAD model of a pitch stabilizer, revealing the wiring and the copper plate in the base.



(a) Left hand rating (b) Right hand rating

Figure 4. The average feasibility RATING (from 0 = "*easy*" to 100 = "*hard*") for the different PITCH$_{Finger}$ inputs. The green areas represent the *comfort* zone in a two-handed smartphone scenario. * the red striped areas represent the *comfort* zone for tabletops by Mayer et al. [19].

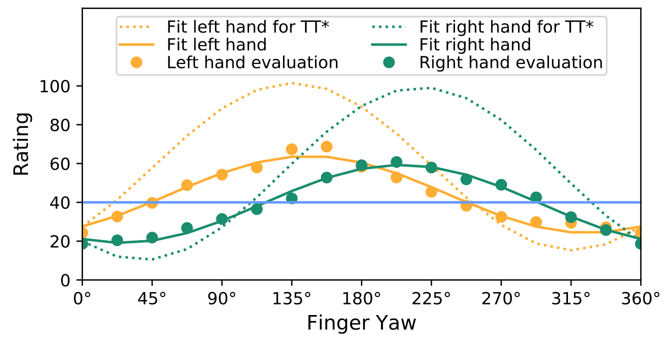


Figure 5. The average feasibility RATING (from 0 = "*easy*" to 100 = "*hard*") for the different YAW$_{Finger}$ inputs averaged over all PITCH$_{Finger}$. The figure also shows the fitted sin curve representing the RATINGs. The blue line indicates the threshold between *comfort* and *non-comfort* zones as defined by Mayer et al. [19]. * approximated rating for tabletops by Mayer et al. [19].

The study application first presented a red crosshair in the center of the screen with one longer line to indicate the yaw orientation participants had to perform. Then, the application presented a rating scale where participants had to rate the feasibility of the performed touch action with a slider control on a scale with 100 steps from "*easy*" to "*hard*". We used a continuous rating scale with a long history in psychophysical measurement, and that enables a robust evaluation [26]. Further, we chose a slider with no ticks as Matejka et al. [18] showed that specific ticks influence the distribution of the results. As Mayer et al. [19] showed that touch action might be impossible to perform we also added the opportunity to tick a checkbox indicating that the input was not feasible. The checkbox enabled the participants to distinguish between very hard but possible and physically impossible touch actions.

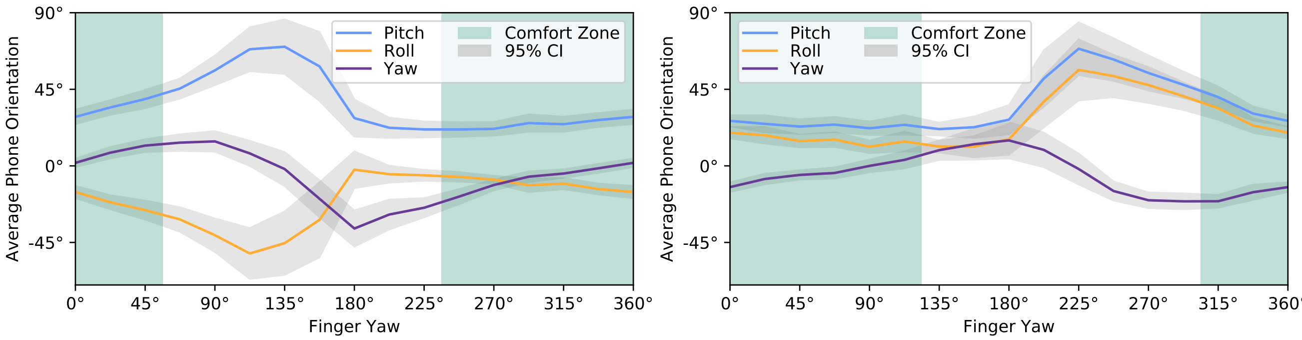
To track the phone and finger, we used a high precision marker-based 6DOF tracking system. The system consisted of 8 *OptiTrack Prime 13W* cameras. After calibration, the system reported a residual mean error of $.2\,mm$.

To guarantee a perfect pitch angle we manufactured pitch stabilizers similar to Mayer et al. [19], with a PITCH$_{Finger}$ of 10°, 32.5°, 55°, and 77.5° as presented in Figure 3. However, we further improved the design by Mayer et al. to enable tracking of the stabilizer through the touchscreen. Therefore we integrated a copper plate into the base of the stabilizer and an electric wire from the copper plate to the slide of the stabilizer where the participant's finger touches the wire. This generated a touch event underneath the stabilizer similar to the WebClip by Kubitza et al. [12] but without any electronic circuit similar to Wolf et al. [31]. Additionally, we added a velcro fastener to allow free movements of the participants (see Figure 3).

Procedure
We followed the instructions and procedure that Mayer et al. [19] used. After welcoming a participant, we explained the procedure of the study and asked them to fill an informed consent. Then we introduced them to the system. We explained that they had to hold the phone with one hand while touching the screen with the other. We explained that they had to touch the red crosshair and align the finger's yaw orientation with the long red line. Participants had to touch on the red crosshair three times. To ensure they had visual contact we extended the procedure to also read one word on the screen. They had to remember the word and then rate the input feasibility. Here we explain in detail how to understand the scale to match it. The application presented the question *How feasible was it to perform the touch action?*. Additionally, we explained the meaning of "*easy*" and "*hard*" as defined by Mayer et al. as *the effort required to perform the touch action* [19]. After participants were familiar with the procedure, we started the app to collect demographic data and initialize the randomization. Then we equipped the participants with the finger marker and the pitch stabilizer needed for the condition, see Figure 1. After each condition, a pop-up told the participants to change the condition settings, and here the experimenter helped to switch the stabilizer.

Participants
We recruited participants from our university's volunteer pool. In total, 20 participants took part in the study (14 male, and 6 female). The age range was between 20 and 27 years ($M = 23.7$, $SD = 1.9$). All participants were right-handed, and none had locomotor coordination problems. We reimbursed the participants with 10 EUR.

RESULTS
We collected 2,560 ratings from 20 participants. The average RATING was 41.8 ($SD = 24.7$). From our 2,560 ratings, none was marked by the participants as not feasible to perform. Further, 41 (1.6 %) of the words were wrongly selected by participants. The RATING for these wrongly selected words was $M = 56.4$ ($SD = 24.2$). To ensure that only samples were going into the analysis where the participants had been able to read the text, we removed all samples with wrongly selected words.



(a) Left-handed interaction

(b) Right-handed interaction

Figure 6. The average phone orientation in a two-handed smartphone interaction scenario.

Rating

To conduct a repeated measures analysis of variance (RM-ANOVA), we applied the Aligned Rank Transform (ART) [29] procedure to the feasible RATINGs, using the ARTool toolkit[3] to align and rank our data.

We conducted a three-way RM-ANOVA to determine whether the independent variables significantly influenced the perceived feasibility of performing the touch action. Our analysis revealed significant main effects for PITCH_{Finger}, YAW_{Finger}, and HAND on feasibility ($F_{(3,2371)} = 18.15$, $p < .001$; $F_{(15,2371)} = 81.17$, $p < .001$; $F_{(1,2371)} = 38.45$, $p < .001$, respectively). Further, we found significant two-way interaction between $\text{YAW}_{Finger} \times \text{HAND}$ ($F_{(15,2371)} = 29.37$, $p < .001$). However, there were no significant two-way interactions between $\text{PITCH}_{Finger} \times \text{HAND}$ and $\text{PITCH}_{Finger} \times \text{YAW}_{Finger}$ ($F_{(3,2371)} = 1.598$, $p = .19$; $F_{(45,2371)} = .942$, $p = .58$, respectively). Lastly, we found a significant three-way interaction between PITCH_{Finger}, YAW_{Finger}, and HAND ($F_{(45,2371)} = 2.08$, $p < .001$).

Figure 4 presents the distribution of feasibility RATINGs for all finger YAWs and both HANDs. We employed further comparisons to investigate how the different variables influenced the results.

We calculated a sine regression to model the RATING based on YAW_{Finger}. Therefore we can model the rating for the right hand using $\text{RATING} = 39.16 - 20.17 sin(\text{YAW}_{Finger} + 1.11)$ and the left hand using $\text{RATING} = 43.91 + 19.73 sin(\text{YAW}_{Finger} - .98)$. The fitness for the right hand is $R^2 = .98$ and for the left hand $R^2 = .96$. We compared our functions with the function by Mayer et al. [19] using t-tests. For the left hand model functions there was a significant difference in the modeled RATING for our new function ($M = 42.1$, $SD = 13.6$) and the tabletop function ($M = 56.2$, $SD = 29.5$); ($t_{(15)} = -3.2$, $p = .006$). For the right hand model functions there was also a significant difference in the modeled RATING for our new function ($M = 38.9$, $SD = 15.5$) and the tabletop function ($M = 54.8$, $SD = 34.4$); ($t_{(15)} = -3.2$, $p = .005$).

[3] depts.washington.edu/madlab/proj/art/index.html last accessed: 2018-05-25

Mayer et al. [19] divided the YAW_{Finger} input space into a *comfort* zone and a *non-comfort* zone. They argued for their split based on input rated as not feasible to perform. None of our participants rated a single input as not feasible; however, our results as presented in Figures 4 and 5 follow the same trend. Consequently, we used the same threshold of 40 to divide the *comfort* zone and a *non-comfort* zone.

The *comfort* zone for the right HAND ranges from 303.75° to 123.75° and the *comfort* zone for the left HAND ranges from 236.25° to 56.25°. Therefore the span of both *comfort* zones is equal to 180.0° for both hands and two *comfort* zones overlap by 112.5°. Thus the *non-comfort* zones are also 180.0° wide.

Phone Orientation

We matched the motion tracking data and the touch data using the timestamps of the touch events and the motion tracking data. We filtered all samples where the time distance was larger than $30ms$. This resulted in a loss of 177 (2.36%) filtered samples. The remaining time difference was $M = .36ms$ with an SD of 1.98. Thus, the following analysis is based on the remaining 7,324 touch samples.

In the following the 0° orientation of the phone for all 3 axes (PITCH_{Phone}, ROLL_{Phone}, and YAW_{Phone}) is defined as the phone laying flat in portrait mode with the screen up in front of the participant. Further, the rotation direction of the axes are defined to be positive when rotating clockwise and negative when rotating counterclockwise.

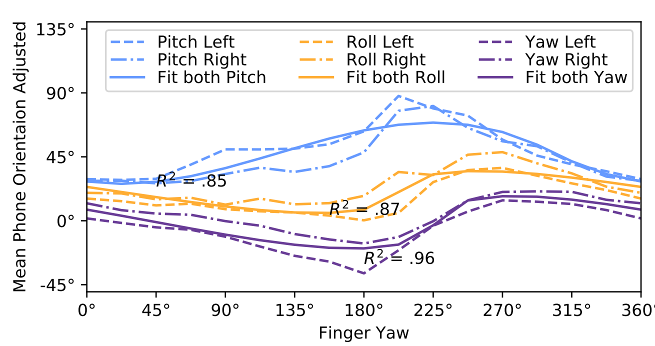


Figure 7. The average phone orientation adjusted to be hand invariant.

We conducted three one-way RM-ANOVAs for each HAND to determine whether ZONE within HAND significantly influenced the orientation of the phone (PITCH_{Phone}, ROLL_{Phone}, and YAW_{Phone}). As Table 1 shows, we found significant effects for all six one-way RM-ANOVAs. The orientations are presented in Figure 6.

Lastly, we mirrored the data of the phone orientation for the left-handed interaction, resulting in a dataset that mimics right-hand usage data, as shown in Figure 7. We first modeled the orientation of the phone using a sine function, resulting in an average R^2 of .83, for PITCH_{Phone}, ROLL_{Phone}, and YAW_{Phone} R^2 is .83, .79, and .83 respectively. We then modeled the orientation with a skewed Sinus function, a Clausen function [3].

$$S_n(x) = \sum_{k=0}^{\infty} \frac{sin(kx)}{k^n} \tag{1}$$

To fit the skewed Sinus function to the data, we added fitting parameters to stretch or compress the function if needed. We again used ordinary least squares to estimate the fitting parameters a to e for our fitting function:

$$fit(x) = aS_b(c(x-d)) + e \tag{2}$$

Using a skewed Sinus function we achieved an average fit of $R^2 = .89$, for PITCH_{Phone}, ROLL_{Phone}, and YAW_{Phone} R^2 is .85, .86, and .96 respectively. The fitted functions are presented in Figure 7.

Pointing Accuracy
We first filtered 54 (.7%) of the 7,680 touch events where the distance to the center is larger than the mean plus 3 times the SD. The remaining average distance to the target was $M = 2.9mm$ ($SD = 1.75$). We conducted a three-way RM-ANOVA to determine whether the independent variables significantly influenced the touch accuracy. Our analysis revealed significant main effects for PITCH_{Finger} and YAW_{Finger} on distance ($F_{(3,2363)} = 483.493$, $p < .001$; $F_{(15,2363)} =$ 10.03, respectively), however, not for HAND ($p < .001$; $F_{(1,2363)} =$ 1.243, $p = .264$). Further, we found significant two-way interactions between $\text{PITCH}_{Finger} \times$ HAND and $\text{PITCH}_{Finger} \times \text{YAW}_{Finger}$ ($F_{(3,2363)} = 15.659$, $p =< .001$; $F_{(45,2363)} = 1.724$, $p < .003$, respectively). However, there was no significant two-way interaction between HAND $\times$ YAW_{Finger} ($F_{(15,2363)} = .564$, $p = .904$). Lastly, we found a significant three-way interaction between PITCH_{Finger}, YAW_{Finger}, and HAND ($F_{(45,2363)} = 1.512$, $p = .016$).

Axes	HAND	df	F	p
PITCH_{Phone}	right	1, 19	38.47	<.001
PITCH_{Phone}	left	1, 19	30.21	<.001
ROLL_{Phone}	right	1, 19	18.31	<.001
ROLL_{Phone}	left	1, 19	25.38	<.001
YAW_{Phone}	right	1, 19	7.61	.012
YAW_{Phone}	left	1, 19	14.54	<.002

Table 1. One-way RM-ANOVAs to determine if the phones' orientation is depended on ZONE within HAND.

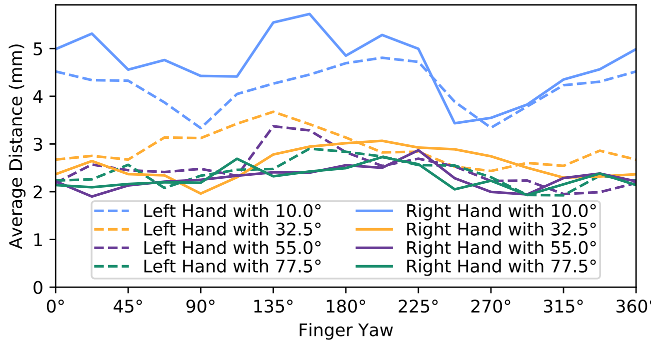


Figure 8. The average diatnce bewtween the touch point of the finger tip and the cross hair on the screen.

A Tukey's HSD post hoc test on PITCH_{Finger} with Bonferroni correction applied only showed a significant difference (all p < .05) between 10° and all other pitch values. We did not conduct the post hoc test for YAW_{Finger} due to the number of comparisons which likely lead to no insights which we support by a visual analysis of Figure 8.

DISCUSSION
We first modeled the RATING using a sine wave. We conclude that the overall trend of how the rating correlates with the finger yaw orientation is in line with the findings by Mayer et al. [19]. However, the modeled ratings for both hands are significantly easier than in the tabletop scenario. Therefore we confirm **H1a**. Thus, allowing the users to move the device and the fingers makes the input easier to perform, despite the fact that the participants had to control more degrees-of-freedom.

We used the same rating threshold of 40 to distinguish between the *comfort* zone and the *non-comfort* zone similar to Mayer et al. [19]. The *comfort* zone for two-handed interaction was 180.0° and therefore 33.3 % larger than in the tabletop scenario. Thus, we confirm **H1b**. This allows designers to use a larger input range for yaw inputs. Furthermore, the overlap of the left and the right hand's *comfort* zones is 66.7 % larger, enabling designers to implement yaw without adjusting for handedness.

We carried out our study in the same ways as described in previous work [19]. However, in contrast to the tabletop results, for our two-handed scenario, we did not observe infeasible input. Therefore, we can confirm **H1c**. For tabletop scenarios the *non-comfort* zone describes inputs which might not be feasible to perform by users, in the two-handed scenario the *non-comfort* zone can be used to gain attention for safety-critical input without making the input too hard.

Our analysis revealed a significant effect of YAW on the smartphone's orientation. In detail, we found that the smartphone orientation changes more in the *non-comfort* zones than in the *comfort* zones confirming **H2a**. While we expect that the screen was readable at all time due to the low error rate when selecting words, the change in orientation shows that the screen was not always perfectly facing the participant. Therefore, while reading a single word remains possible, designers need to be aware that using the finger orientation as the input changes the orientation of the display. Especially when exceeding the *comfort* zone, the readability will decrease.

We modeled the smartphone orientation using a Clausen function and achieved an average R^2 of .89 when the left-hand data is mirrored. This shows that the smartphone orientation can be modeled for both hands with one function for each degree-of-freedom. Thus, we confirm **H2b**. The function enables us to model the smartphone orientation for each finger orientation. Further, this allows designers to understand how possible inputs would affect the smartphone orientation and thus influence the readability of the content displayed on the smartphone.

Lastly, our analysis revealed that the offset between the input and the target is significantly different for a pitch of 10° compared to all other conditions. Holz and Baudisch [8] found significant differences between all of their 5 conditions ranging from 15° to 90°. However, they studied only 2 levels of YAW_{Finger}, while our analysis also revealed significant main effects for 16 levels of YAW_{Finger} and both HANDs. Thus, we conclude that today's touchscreens are not well suited for 50 % of the finger orientations. While Henze et al. [6] presented a model to improve touch input, taking the finger orientation into account would further improve single touch input.

In line with Mayer et al. [19], we showed that the feasibility RATING for finger orientation with two-hands can also be modeled using a sine function. However, we found that finger orientation is easier when the user is allowed to move and rotate the phone with the second hand than in the tabletop scenario. As a consequence, this leads to a phone orientation which is not perfectly in sight of the user.

In our study, we did not control if participants bent their finger on the Proximal Interphalangeal (PIP) joint or the Metacarpophalangeal (MCP) joint of the index finger. However, the two 3D printed parts controlled for the distal interphalangeal (DIP) joint of the index finger. As the DIP has a limited movement range, we assume that our results can be transferred to situations where users can bend all joints.

CONCLUSION

We investigated the ergonomic constraints of using finger orientation as additional input dimension for mobile touchscreens. In detail, we conducted a study to investigate the feasibility of using finger orientation in a two-handed interaction scenario where the user is holding the device in one hand while touching it with the other hand. We systematically varied the finger orientations using 4 different pitch and 16 different yaw angles while ensuring that the screen was visible to the participant during the interaction. Further, participants were able to perform all combinations with the index finger of both the right and the left hand. In line with Mayer et al. [19], we found that the feasibility can be modeled using a sine function. However, we found that finger orientation input is harder in tabletop scenarios than in two-handed interaction scenarios. A motion tracking system enabled us to also study the resulting phone orientation. We showed that the feasibility rating correlated to the phone orientation. A harder feasibility rating, therefore, results in a phone orientation tilted away from the user.

The presented analysis shows that the *comfort* zones are different between the tabletop scenario and the two-handed interaction scenario. In the future, we would like to investigate the two-handed interaction scenario in detail by studying the impact of standing and walking onto the *comfort* zones, we hypothesis that the *comfort* zones for standing and walking will be smaller than in the sitting two-handed interaction scenario. Furthermore, we hope that by highlighting the ergonomic restrictions designers can use the finger's orientation as input. As we developed an understanding of the ergonomic constraints, we would like to investigate the throughput of using finger orientation in smartphones and compare it to other techniques like force press and long press as two well-established input techniques. Lastly, we believe that communicating new touchscreen interactions to users poses a major challenge that needs to be addressed in future work.

ACKNOWLEDGMENTS

This work is financially supported by the German Research Foundation (DFG) within Cluster of Excellence in Simulation Technology (EXC 310/2) at the University of Stuttgart, the project C04 of SFB/Transregio 161, and the MWK Baden-Württemberg within the Juniorprofessuren-Programm.

REFERENCES

1. Michiel Bacchiani, Françoise Beaufays, Alexander Gruenstein, Pedro Moreno, Johan Schalkwyk, Trevor Strohman, and Heiga Zen. 2017. Speech Research at Google to Enable Universal Speech Interfaces. In *New Era for Robust Speech Recognition: Exploiting Deep Learning*, Shinji Watanabe, Marc Delcroix, Florian Metze, and John R. Hershey (Eds.). Springer International Publishing, Cham, 385–399. DOI: http://dx.doi.org/10.1007/978-3-319-64680-0_18

2. Sebastian Boring, David Ledo, Xiang 'Anthony' Chen, Nicolai Marquardt, Anthony Tang, and Saul Greenberg. 2012. The Fat Thumb: Using the Thumb's Contact Size for Single-handed Mobile Interaction. In *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services (MobileHCI '12)*. ACM, New York, NY, USA, 39–48. DOI:http://dx.doi.org/10.1145/2371574.2371582

3. Thomas Clausen. 1832. Über die Function $sin(\varphi) + \frac{1}{2^2}sin(2\varphi) + \frac{1}{3^2}sin(3\varphi) +$ etc.. In *Journal für die reine und angewandte Mathematik*. Duncker und Humblot, Berlin, Germany, 298–300.

4. Ashley Colley and Jonna Häkkilä. 2014. Exploring Finger Specific Touch Screen Interaction for Mobile Phone User Interfaces. In *Proceedings of the 26th Australian Computer-Human Interaction Conference on Designing Futures: The Future of Design (OzCHI '14)*. ACM, New York, NY, USA, 539–548. DOI: http://dx.doi.org/10.1145/2686612.2686699

5. Chi Tai Dang and Elisabeth André. 2011. Usage and Recognition of Finger Orientation for Multi-Touch Tabletop Interaction. In *Human-Computer Interaction – INTERACT 2011*. Springer Berlin Heidelberg, Berlin, Heidelberg, 409–426.

6. Niels Henze, Enrico Rukzio, and Susanne Boll. 2011. 100,000,000 Taps: Analysis and Improvement of Touch Performance in the Large. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '11)*. ACM, New York, NY, USA, 133–142. DOI:http://dx.doi.org/10.1145/2037373.2037395

7. Eve Hoggan, John Williamson, Antti Oulasvirta, Miguel Nacenta, Per Ola Kristensson, and Anu Lehtiö. 2013. Multi-touch Rotation Gestures: Performance and Ergonomics. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 3047–3050. DOI: http://dx.doi.org/10.1145/2470654.2481423

8. Christian Holz and Patrick Baudisch. 2010. The Generalized Perceived Input Point Model and How to Double Touch Accuracy by Extracting Fingerprints. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 581–590. DOI: http://dx.doi.org/10.1145/1753326.1753413

9. Christian Holz and Patrick Baudisch. 2011. Understanding Touch. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2501–2510. DOI: http://dx.doi.org/10.1145/1978942.1979308

10. Jochen Huber, Mohamed Sheik-Nainar, and Nada Matic. 2017. Force-enabled Touch Input on the Steering Wheel: An Elicitation Study. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct (AutomotiveUI '17)*. ACM, New York, NY, USA, 168–172. DOI: http://dx.doi.org/10.1145/3131726.3131740

11. Sven Kratz, Patrick Chiu, and Maribeth Back. 2013. PointPose: Finger Pose Estimation for Touch Input on Mobile Devices Using a Depth Sensor. In *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces (ITS '13)*. ACM, New York, NY, USA, 223–230. DOI: http://dx.doi.org/10.1145/2512349.2512824

12. Thomas Kubitza, Norman Pohl, Tilman Dingler, and Albrecht Schmidt. 2013. WebClip: A Connector for Ubiquitous Physical Input and Output for Touch Screen Devices. In *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp '13)*. ACM, New York, NY, USA, 387–390. DOI:http://dx.doi.org/10.1145/2493432.2493520

13. Huy Viet Le, Sven Mayer, Patrick Bader, and Niels Henze. 2018. Fingers' Range and Comfortable Area for One-Handed Smartphone Interaction Beyond the Touchscreen. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI'18)*. ACM, New York, NY, USA. DOI: http://dx.doi.org/10.1145/3173574.3173605

14. Huy Viet Le, Sven Mayer, Katrin Wolf, and Niels Henze. 2016. Finger Placement and Hand Grasp During Smartphone Interaction. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '16)*. ACM, New York, NY, USA, 2576–2584. DOI: http://dx.doi.org/10.1145/2851581.2892462

15. Cecil Lozano, Devin Jindrich, and Kanav Kahol. 2011. The Impact on Musculoskeletal System During Multitouch Tablet Interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 825–828. DOI:http://dx.doi.org/10.1145/1978942.1979062

16. I. Scott MacKenzie and R. William Soukoreff. 2003. Phrase Sets for Evaluating Text Entry Techniques. In *CHI '03 Extended Abstracts on Human Factors in Computing Systems (CHI EA '03)*. ACM, New York, NY, USA, 754–755. DOI:http://dx.doi.org/10.1145/765891.765971

17. Nicolai Marquardt, Johannes Kiemer, David Ledo, Sebastian Boring, and Saul Greenberg. 2011. Designing User-, Hand-, and Handpart-aware Tabletop Interactions with the TouchID Toolkit. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '11)*. ACM, New York, NY, USA, 21–30. DOI:http://dx.doi.org/10.1145/2076354.2076358

18. Justin Matejka, Michael Glueck, Tovi Grossman, and George Fitzmaurice. 2016. The Effect of Visual Appearance on the Performance of Continuous Sliders and Visual Analogue Scales. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 5421–5432. DOI: http://dx.doi.org/10.1145/2858036.2858063

19. Sven Mayer, Perihan Gad, Katrin Wolf, Paweł W. Woźniak, and Niels Henze. 2017a. Understanding the Ergonomic Constraints in Designing for Touch Surfaces. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '17)*. ACM, New York, NY, USA, Article 33, 9 pages. DOI: http://dx.doi.org/10.1145/3098279.3098537

20. Sven Mayer, Huy Viet Le, and Niels Henze. 2017b. Estimating the Finger Orientation on Capacitive Touchscreens Using Convolutional Neural Networks. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces (ISS '17)*. ACM, Brighton, United Kingdom, 220–229. DOI: http://dx.doi.org/10.1145/3132272.3134130

21. Sven Mayer, Michael Mayer, and Niels Henze. 2017c. Feasibility Analysis of Detecting the Finger Orientation with Depth Cameras. In *Proceedings of the 19th*

International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct (MobileHCI'17). ACM, New York, NY, USA, 82:1–82:8. DOI:http://dx.doi.org/10.1145/3098279.3122125

22. Kanishka Rao, Haşim Sak, and Rohit Prabhavalkar. 2017. Exploring architectures, data and units for streaming end-to-end speech recognition with RNN-transducer. (Dec 2017). DOI: http://dx.doi.org/10.1109/ASRU.2017.8268935
23. Simon Rogers, John Williamson, Craig Stewart, and Roderick Murray-Smith. 2011. AnglePose: Robust, Precise Capacitive Touch Tracking via 3D Orientation Estimation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 2575–2584. DOI: http://dx.doi.org/10.1145/1978942.1979318
24. Katie A Siek, Yvonne Rogers, and Kay H Connelly. 2005. Fat finger worries: how older and younger users physically interact with PDAs. In *Human-Computer Interaction-INTERACT 2005*, Maria Francesca Costabile and Fabio Paternò (Eds.). Lecture Notes in Computer Science, Vol. 3585. Springer Berlin Heidelberg, Berlin, Heidelberg, 267–280. DOI: http://dx.doi.org/10.1007/11555261_24
25. Yoshiki Takeoka, Takashi Miyaki, and Jun Rekimoto. 2010. Z-touch: An Infrastructure for 3D Gesture Interaction in the Proximity of Tabletop Surfaces. In *ACM International Conference on Interactive Tabletops and Surfaces (ITS '10)*. ACM, New York, NY, USA, 91–94. DOI:http://dx.doi.org/10.1145/1936652.1936668
26. Horst Treiblmaier and Peter Filzmoser. 2011. Benefits from Using Continuous Rating Scales in Online Survey Research. In *Proceedings of the International Conference on Information Systems (ICIS '11)*. Association for Information Systems, 1–15. http://aisel.aisnet.org/icis2011/proceedings/researchmethods/1
27. Feng Wang, Xiang Cao, Xiangshi Ren, and Pourang Irani. 2009. Detecting and Leveraging Finger Orientation for Interaction with Direct-touch Surfaces. In *Proceedings of the 22Nd Annual ACM Symposium on User Interface Software and Technology (UIST '09)*. ACM, New York, NY, USA, 23–32. DOI: http://dx.doi.org/10.1145/1622176.1622182
28. Feng Wang and Xiangshi Ren. 2009. Empirical Evaluation for Finger Input Properties in Multi-touch Interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. ACM, New York, NY, USA, 1063–1072. DOI: http://dx.doi.org/10.1145/1518701.1518864
29. Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11)*. ACM, New York, NY, USA, 143–146. DOI: http://dx.doi.org/10.1145/1978942.1978963
30. Katrin Wolf, Marilyn McGee-Lennon, and Stephen Brewster. 2012. A Study of On-device Gestures. In *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services Companion (MobileHCI '12)*. ACM, New York, NY, USA, 11–16. DOI: http://dx.doi.org/10.1145/2371664.2371669
31. Katrin Wolf, Stefan Schneegass, Niels Henze, Dominik Weber, Valentin Schwind, Pascal Knierim, Sven Mayer, Tilman Dingler, Yomna Abdelrahman, Thomas Kubitza, Markus Funk, Anja Mebus, and Albrecht Schmidt. 2015. TUIs in the Large: Using Paper Tangibles with Mobile Devices. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15)*. ACM, New York, NY, USA, 1579–1584. DOI: http://dx.doi.org/10.1145/2702613.2732863
32. Robert Xiao, Julia Schwarz, and Chris Harrison. 2015. Estimating 3D Finger Angle on Commodity Touchscreens. In *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces (ITS '15)*. ACM, New York, NY, USA, 47–50. DOI: http://dx.doi.org/10.1145/2817721.2817737
33. Vadim Zaliva. 2012. 3D finger posture detection and gesture recognition on touch surfaces. In *12th International Conference on Control Automation Robotics Vision (ICARCV 2012)*. IEEE, 359–364. DOI: http://dx.doi.org/10.1109/ICARCV.2012.6485185