A Design Space for User Interface Elements using Finger Orientation Input

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ABSTRACT

Despite touchscreens being used by billions of people every day, today's touch-based interactions are limited in their expressiveness as they mostly reduce the rich information of the finger down to a single 2D point. Researchers have proposed using finger orientation as input to overcome these limitations, adding two extra dimensions – the finger's pitch and yaw angles. While finger orientation has been studied in-depth over the last decade, we describe an updated design space. Therefore, we present expert interviews combined with a literature review to describe the wide range of finger orientation input opportunities. First, we present a comprehensive set of finger orientation input enhanced user interface elements supported by expert interviews. Second, we extract design implications as a result of the additional input parameters. Finally, we introduce a design space for finger orientation input.

Figure 1: A mock-up implementation of a circular slider which can be controlled with the finger' yaw. As depicted in this image the users finger controllers the volume using a circular slider.

CCS CONCEPTS

• **Human-centered computing** → **Touch screens**; Empirical studies in HCI; • **Hardware** → *Touch screens*.

KEYWORDS

finger orientation, interfaces, design space, touch devices, interaction, touchscreen, expert interviews

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1 INTRODUCTION

Mobile touch-based devices, such as phones, watches, and tablets, are the dominant computing devices used by billions of people every day. Arguably, touch-based devices have replaced personal computers, such as laptops or desktop workstations, in day-to-day activities such as writing emails and browsing the web. Moreover, they not only replace the traditional personal computer but also extend the range of activities by supporting photography, social media, and instant messaging. This enables millions of users to work mobile and remotely, which was possible only to a limited degree before. Despite these advantages, touchscreens offer only a limited interaction space compared to traditional interactions with mouse and keyboard [22]. Several researchers have proposed various approaches to extend the input space beyond the two-dimensional touchpoint in order to overcome this limitation, e.g., [6, 20, 29].

The more prominent extensions for touch interaction that make use of more information of the finger touching the screen are finger identification [6, 17, 18, 29, 33, 59], finger contact size [3], flat finger interaction [43], taps with different finger parts [20], finger force [2, 7, 14], and finger orientation [45, 51, 58]. They all add new dimensions to the input vector as either categorical data (e.g., finger identification) or numerical values (e.g., force). However, only finger orientation input enriches the input vector by two additional numerical dimensions: the finger's pitch and yaw angles, see Figure 1. Finger roll is commonly treated as a separate input, cf. [46]. Beyond extending touch interaction, which adds a single feature of the touching finger, researchers have also envisioned recognizing large parts of the hand for gesture input [4, 10, 11, 21, 28, 34, 50, 54, 56, 57]; however, this was mostly archived on tabletops. Finally, more exotic approaches extend beyond finger and touch input by recognizing body parts [16, 23]. Further, we argue that finger orientation input has an unmatched potential to enhance touch expressiveness, even making it into a commercial product like Qeexo [44]. In the past, significant efforts have been made to recognize the fingers' orientation, e.g., on tabletops [51, 52], on smartphones [36, 58], and on smartwatches [58]. Even the ergonomic implications of finger orientation have been studied in depth [35, 37], showcasing a rich

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input space. However, while a number of different interaction possibilities have been proposed to make use of finger orientation, no comprehensive study has investigated the space of this user interface element and its use case possibilities. Thus, it is not yet apparent how to use finger orientation input and how the interaction should be designed.

To understand the design space of finger orientation input, we first conducted a literature review to extract previously proposed use cases and user interface elements. In a second step, we conducted expert interviews with user experience (UX) experts inquiring about the design of use cases for finger orientation input and possible design implications. As a result of the literature review and expert interviews, we present user interface elements that utilize finger orientation input. Additionally, we present general design implications on the design of new user interface elements. Finally, we present a design space comprising prior ideas supported by expert interviews to support new designs further.

In this paper, we present a wide range of interfaces and design choices when using finger orientation as additional input. Further, we provide a design space for finger orientation interfaces allowing researchers, practitioners, and designers to benefit from finger orientation input in their designs. Thus, our contribution is three-fold: 1) we present a comprehensive set of interface elements, 2) we present design implications for finger orientation, and 3) we extract a design space allowing us to understand the possibilities of finger orientation in more depth.

2 RELATED WORK

The core research around finger orientation as additional input is two-fold: recognition and ergonomic implications. Both aspects influence how to incorporate finger orientation input into user interface elements and use cases.

Today, various methods have been proposed to realize finger orientation input using a ring [24, 41], smartwatch [53], RGB cameras [8], IR cameras [9, 51, 60, 61], and depth cameras [26, 39, 40]. While Rogers et al. [45] presented the first estimation approach using standalone capacitive sensors, the latest developments integrated the recognition into commodity phones [36, 58], making a step toward finder origination being deployed in standard phones.

Although rotating objects are common in the real world, such as doorknobs and steering wheels, actively rotating one's finger is not as common but can be observed during passive actions such as crafting tasks, e.g., pottery. Related work showed that while finger orientations are possible, ergonomic constraints need to be considered in the design process. Here, Xiao et al. [58] first identified ergonomic problems when using enriched touch input using finger orientation input. Long fingernails made a large pitch unfeasible to perform. Wolf et al. [55] 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. Mayer et al. [35, 37] showed the ergonomic limitations of using finger orientation input, finding a feasible comfort zone of 135.0° for tabletops [35] and 180.0° for mobile interaction [37]. Gil et al. [12] presented similar results for smartwatches. Later, Goguey et al. [13] presented an atomic analysis of pitch, roll, and yaw inputs informing design about the impact on different settings.

In conclusion, we saw a long development phase from the first finger orientation conceptualization in 1978 [22] to today's deep-learning recognition approach. Additionally, in the last years, we have seen an uptake in investigations of ergonomic constraints. Both are building the foundation for user interface elements. Moreover, possible scenarios and interface elements arose in this process but only as a showcase for various implementations. Thus, no formal investigation has been presented and the design space has yet to be mapped. Thus, in the next step, we will review the various scattered scenarios researchers have envisioned.

3 LITERATURE REVIEW ON FINGER ORIENTATION SCENARIOS

We have seen many interaction techniques that extend beyond the traditional touch interaction. However, finger orientation is uniquely different as it adds two new continuous input dimensions: pitch and yaw. Therefore, we solely explore the interaction possibilities for new interfaces in conjunction with finger orientation input.

3.1 Methodology

In the following, we present the proposed use case scenarios for finger orientation. For this literature review, we compiled a list of papers related to the keywords "finger orientation," "3D angle," "yaw input," and "pitch input." We used the ACM DL and Google Scholar as search bases. We only included papers that presented a use case of finger origination in the form of an enriched user interface. Thus, we excluded all papers that only tackled topics like recognition, comparison of different approaches, and ergonomic constraints. After excluding all out-of-score papers, we had a list of only 10 papers that presented specific user interface considerations. In contrast, 14 papers addressed recognition possibilities. In their papers, the authors use different recognition techniques and implement them on different device form factors. In the next step, we dissected the papers into the core user interface elements. Two researchers classified and categorized the different capabilities into four different groups based on following functionalities: value manipulation, menu selection, target selection, and special applications.

3.2 Value Manipulation

Value manipulation is one of the rudimentary functions of user interfaces (UIs), such as manipulating a slider as well as viewport manipulations, e.g., zooming. Thus, the researcher envisioned various options to extend interaction with the UI:

Orientation-sensitive button/slider/dial [44, 51, 53, 58]: Hold down the finger and then use the yaw to set the value for the given button/dial or visualized by a button with a radial dial [53]. **Zoom** [32, 44, 58]: The fingers' yaw orientation has been envisioned to be used to zoom in and out of objects and maps. An enhanced version allows **rotation and zoom** [53, 58] where the fingers' orientation is used to rotate and zoom simultaneously using both dimensions; for example, a map application or navigating a photo album viewer using only finger orientation. Alternatively, others have explored **rotation** only [27]. While gaming console controls have a long tradition of incorporating **joysticks**, similar implantation is hard to achieve due to the nature of touchscreens. Thus, researchers [45, 52, 58] envisioned using finger orientation that allowed a joystick-like input on touchscreens. Here, the finger is interpreted as a 3D vector to control 3D environments, such as a flight direction or the orientation of a camera. Lastly, **3D manipulation** [1, 44, 58] enables users to manipulate 3D elements or cameras within a 3D scene such as in augmented reality (AR) or virtual reality (VR) . In particular, changing the object's orientation can benefit from using finger orientation.

3.3 Menu Selection

Menu and item selections are fundamental actions in UIs. While various layout menus have been proposed in the last decades, e.g., pie menus, they are rarely used in UIs. However, with touchscreens enabling finger orientation input, there are possibilities to extend over the common 2D selection.

When using **pie/torus menus**, researchers [25, 51, 52] proposed that the user holds the finger down and then a menu pops up, with which the user can interact using finger orientation. Moreover, Rogers et al. [45] envisioned **rolling context menus**, enabling scrolling through a context menu using the fingers' pitch angle. The menu itself scrolls up and down depending on the pitch angle.

3.4 Target Selection

While target selection at first seems straightforward, especially on larger form factors such as tabletops and large display walls, target selection can be cumbersome. Thus, two interactions are envisioned to extend target selection to more distant targets.

With the **cross-ray selection** [45, 51, 52], researchers envisioned using the pitch and yaw of two fingers simultaneously for object selection at the point where the projected rays of the fingers meet. Moreover, Wang et al. [51] proposed **distant element selection** allowing the user to control a ray can after touching the screen to select elements in the distance. Here, pitch and yaw are mapped to length and orientation, respectively. However, this method requires both hands and, thus, is not feasible in mobile scenarios.

3.5 Special Applications

Lastly, we found various special applications that do not have a general interaction purpose but rather serve to support during particular tasks. Bézier curves are problematic to handle on touchscreens [15]. Therefore, Takeoka et al. [49] proposed **Bézier curve controls**. Here, a Bézier curve support point can be controlled with pitch and yaw, and mapped to length and angle, respectively. In the creative domain, Wilkinson et al. [53] envisioned changing the **stroke width** itself using the additional input dimension. With **hidden flaps**, Rogers et al. [45] imitate the "peeking at a note" gesture with all fingers lifted from the screen. Finally, Mayer et al. [35] used the fact that some inputs are less comfortable. Specifically, they envisioned **safety-critical input** as the less comfortable input that will foster users' awareness of actions like a factory reset. Finally, Wang et al. [51] envisioned an **occlusion-aware interface** where menus avoid the space beneath the finger, allowing users to better observe the content. Thus, they proposed an interface adaption that is not an input itself.

3.6 Summary

In our investigation to find all proposed user interface elements that made the use of finger orientation, we found only 10 papers that showcased the potential of finger orientation. Moreover, we found these papers' core contribution was not the design of the user interface element but rather to showcase the new input's potential. This is further reflected in the larger number of papers that recognize the finger orientation and do not perform in-depth use-case evaluations (e.g., user feedback, undo possibilities, relative vs. absolute input). Therefore, we decided to conduct expert interviews with UX experts to understand better the potential and possible user interface designs.

4 EXPERT INTERVIEW

The goal of the expert interviews was to find innovative ideas, designs, and elements that use finger orientation as an additional input. We used open-ended questions on which we followed-up to clarify possible misunderstandings. This allowed gaining better in-depth insights than following a closed-form script [47]. Therefore, we designed 15 leading questions as presented in Table 1. These allowed us to explore different aspects such as interaction, visual appearance, and feedback. We considered these aspects from the literature to be important as they are often not clearly articulated in related works.

4.1 Procedure

After introducing the interviewees to the interview's overall topic, we asked them to sign the consent form and fill in a demographic questionnaire.

All questions were formulated around the main objective: *How can we facilitate new interaction paradigms using finger orientation?* As a first step, we ensured that every expert understood what finger orientation input is. Therefore, we showed the video figure[1] of Xiao et al. [58] and further explained how finger orientation can be implemented and potentially used if needed. At the core of the interview was the fundamental question on what use cases the UX expert could envision. Thus, we started by asking them about their ideas. We then discussed each idea individually in order to understand their specific implementation. We explored different usage scenarios, visualizations, interactions, feedback mechanisms, and possible evaluation methods for each of them. We guided the interview along 15 base questions to explore these points, see Table 1. However, we added questions if further information seemed essential to obtain a holistic picture. We gave interviewees pen and paper to encourage them to sketch or draw, for instance, the interaction, the given feedback, or the visualization to better support the resulting design set. All interviews were audio-recorded. The interviews were conducted in person, if possible, or via video chat.

[1] FingerAngle on YouTube: https://www.youtube.com/watch?v=hLYBEBJHFYY

Table 1: The 15 guiding interview questions.

	Question
1	What would the goal be?
2	How is the concept visualized on the screen?
3	Which motion would be performed?
4	Where on the screen would the motion be performed?
5	What happens during the interaction?
6	What happens after the interaction?
7	Will feedback be given, if so how does it look like?
8	What happens when a mistake is made?
9	How can this be used by existing apps?
10	Could this be helpful if enabled system-wide?
11	How would the user learn about it?
12	How does the user know finger orientation input is available?
13	Would you say this is intuitive? and why?
14	How feasible is this on other devices like smartwatches and tablets?
15	How can this be studied in more depth?

4.2 Participants

Eleven UX experts took part in the interviews, all from various research labs all over Europe. We only recruited experts with a UX background and either working in academia or in industry (no students). Participants were, on average, 33.1-years-old ($median$ = 31, SD = 6.9, range 27 to 52; 1 female and 10 males). The interviewed experts had an average experience of 8.1 years (SD = 7.5, min = 3, max = 30) in human-computer interaction (HCI) with a strong interface and interaction design background.

4.3 Transcription and Analyses

We conducted 11 expert interviews lasting an average length of about 60 minutes. We transcribed the interviews literally to avoid losing information, which often occurs when summarizing participants' statements. We excluded phrase breaks, later corrected statements, or clarification questions made by the participants. Thus, we collected the core feedback of the experts. Next, we extracted all atomic statements from the transcript. If a further explanation was needed, then we added an explaining statement enclosed by brackets to the expert's statement, allowing us to classify the statements in-depth, even without a greater context. Finally, three researchers used affinity diagrams to sort and categorize these atomic statements [19]. Specifically, we found two classes of feedback: specific **User Interface Elements** and general **Design Implications**, which we will describe in the following sections.

5 EXPERT INTERVIEW RESULTS: USER INTERFACE ELEMENTS

From our interviews with UX experts, we extracted a number of implementations, see Figure 3. We will present user interface elements and use cases for using finger orientation as additional input. We present use cases suggested by our experts, complementing them and filling the gaps with related literature from our literature review to cover the entire spectrum of possible user interface elements.

5.1 General Single Value Input

5.1.1 Circular Slider. Sliders are available in all leading touch interfaces, cf., Android, iOS, Windows. However, sliders are traditionally implemented linearly. The original Apple iPod was a tremendous commercial success with a circular input; however, the visual representation was linear. Finger orientation input again enables circular sliders; see Figure 1, 2, and 3a. Specifically, the finger's yaw is used to set the value of the slider. (Proposed by P2, P3, P7–P9, P11 and [44, 51, 53, 58]).

There are two different approaches for implementing a circular slider, namely, absolute and relative input. Absolute input directly links the yaw value to the user element such as the slider position, in contrast, relative input changes the slider value with respect to the previous slider value.

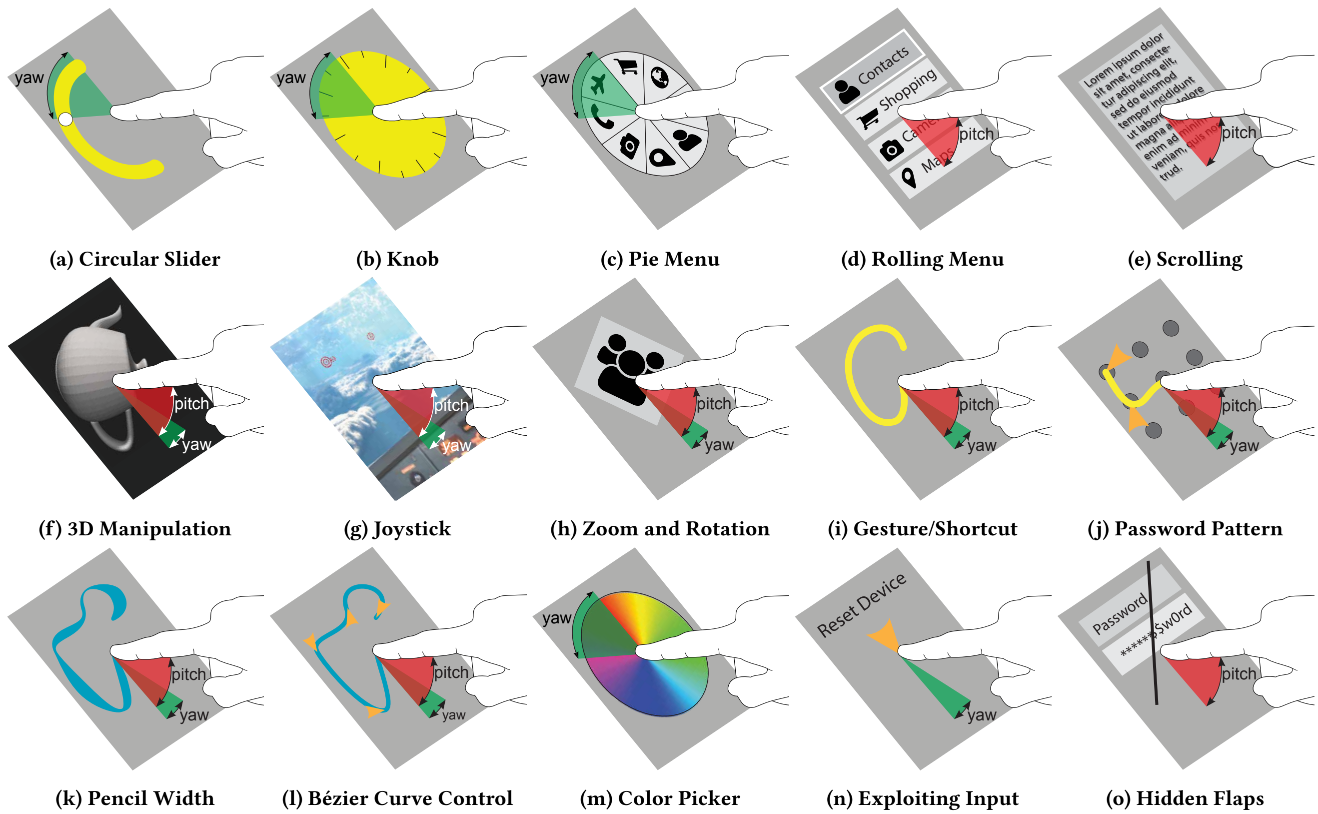
The visual representation of a circular slider should convey the notion of the range of possible values, especially maximum and minimum values. In the particular case of a discrete scale, the slider should visually indicate the steps.

5.1.2 Knob. The overall interaction of a knob closely resembles the circular slider interaction, see Figure 3b. However, knobs have an intrinsic difference in meaning. Typical knobs can have limits or steps, e.g., a volume knob. However, the affordance of a knob has no minimum or maximum value but only a rotational state. Thus, a knob can perform 360° rotations or even more, e.g. a radio tuner. Ergonomic constraints, however, render parts of the input range not physically feasible. Thus, knobs should be implemented only using a relative interaction approach. (Proposed by P4, P5, P7–P11 and [44, 51, 53, 58])

5.1.3 Context Menu. Context menus can be controlled with different finger orientation methods, depending on the type of menu. For example, a *rolling menu* can use the finger's pitch, while the yaw angle is more convenient to control a *pie menu*.

The *rolling menu* is a variation of a linear menu, see Figure 3d. Menu options are in a linear order. However, scrolling through all menu options is mapped to a change in pitch. This can be very handy, especially on small screens and long lists. Relative input

Figure 2: Finger orientation can enable slider value selection on small screens like smartwatches. As shown here, the yaw of the finger is used to manipulate a round slider changing the volume level



(a) Circular Slider (b) Knob (c) Pie Menu (d) Rolling Menu (e) Scrolling
(f) 3D Manipulation (g) Joystick (h) Zoom and Rotation (i) Gesture/Shortcut (j) Password Pattern
(k) Pencil Width (l) Bézier Curve Control (m) Color Picker (n) Exploiting Input (o) Hidden Flaps

Figure 3: Sketches of the different finger orientation enabled user interfaces.

would further enable long scrolling lists by clutching the finger orientation. (Proposed by P1, P6, P9, P11 and [45])

Pie menus arrange the options in a circular configuration around the center of the menu, see Figure 3c. This arrangement is excellent for scrolling and selecting the option using yaw input. Here, yaw input could effectively substitute commercial products such as the Microsoft Surface Dial[2]. (Proposed by P1–P7, P9, P11 and [25, 51, 52])

5.1.4 Scrolling. Pitch input can be utilized to scroll through lists and websites, see Figure 3e. While one-finger touch scrolling on touchscreens offers a simple and effective way to scroll the screen's length, continuous scrolling, as allowed by computer keyboard arrows, is impossible using traditional touch interaction. By utilizing pitch input to scroll, continuous scrolling can be easily achieved. Here, 45° could be implemented as the resting point (no movement) while 0° scrolls the page down and 90° up. Moreover, intermediate pitch values can even offer control over the scrolling speed. (Proposed by P4, P9)

5.2 General Dual Value Input

5.2.1 3D Manipulations. Computer-aided design (CAD) software heavily relies on 3D object manipulations, cf. Shapr3D for iPad[3]. While panning and zooming have become standard interactions, changing an object's orientation exceeds the number of traditionally available input dimensions, rendering the interaction cumbersome. Here, finger orientation adds the necessary means by adding two more dimensions to the input vector. Thus, finger orientation enables fast object reorientation or changing the view direction of the 3D camera within the CAD scene, see Figure 3f. (Proposed by P1–P7, P9, P11 and [1, 44, 58])

5.2.2 Joystick. In *first-person shooter* games and flight simulators, controlling the character or vehicle (i.e., the camera position) in the 3D environment is an integral part of the interaction. Pitch and yaw can be mapped to rotation in their respective planes, allowing the user to navigate the virtual world, see Figure 3g. Furthermore, racing games can benefit from extra input dimensions. For instance, the gas pedal can be linked to the pitch angle, building an intuitive mapping between in-game dynamics and physical input. Besides gaming, joystick input using finger orientation can also be used to navigate 3D landscapes such as 3D maps, street view images, and 3D architectural design software for buildings. Furthermore, finger input can replace joysticks in real-world applications such as controlling vehicles, cranes, robot arms, and other electromechanical systems that require high-precision and complex controls. (Proposed by P1, P3–P5, P7, P8 and [45, 52, 58])

5.2.3 Rotate and Zoom. For 2D content representations, such as maps and images, finger orientation can be a convenient aid to

[2]Surface Dial: https://www.microsoft.com/en-us/p/surface-dial/925r551sktgn
[3]Shapr3D: https://www.shapr3d.com/

manipulate content, see Figure 3h and 4. Here, the methodical link between yaw input and the content's orientation to rotate the content can result in intuitive and versatile interactions. Similarly, magnification of a map or image can be linked to the finger's pitch, resonating with the concept of the mouse wheel. (Proposed by P1–P3, P5, P10, P11 and [32, 44, 45, 53, 58])

5.3 Free Movements

5.3.1 Gestures. Generally, gestures can be enriched by two additional dimensions, namely, pitch and yaw, see Figure 3i. However, complex gestures can be hard to remember. Therefore, gestures using finger orientation should be used sparsely. The creation of methodical links can increase memorability. An example could be the use of a low pitch to represent an eraser in a graphic editor application. Another example could be the use of gestures on soft-keyboards, linking second-level characters, such as numbers and symbols, to a pitch below a given threshold. (Proposed by P1, P2, P4, P6–P9, P11)

5.3.2 Shortcuts. In the context of finger orientation input, shortcuts can be considered as a special category of gestures. As discussed, complex gestures are harder to remember; however, system-wide gestures have a high acceptance rate and are common in today's UIs, and becoming increasingly popular (Android and iOS enable app switching with gestures). Frequent actions, like share, copy, and paste, have the affordance to be substituted by a finger orientation gesture, see Figure 3i. (Proposed by P1-–P3, P5, P6, P8)

5.4 Special Applications

5.4.1 Enhanced Password Pattern. While face unlocks and fingerprint unlocks are secure and easy to use, the standard fallback is still a password pattern. Default patterns with 9-point matrices have a very limited input space and can easily be sneak-peeked by bystanders. Finger orientation input adds an extra input dimension and, thus, an extra level of security to the pattern input by relying on the position in the matrix and the pitch and yaw for each of the pattern points, see Figure 3j. (Proposed by P1, P3, P5, P8)

Figure 4: For images or maps, pitch and yaw can be used to rotate and zoom the object. We present a mock-up to demonstrate how rotate and zoom works in a gallery on a wall-sized display.

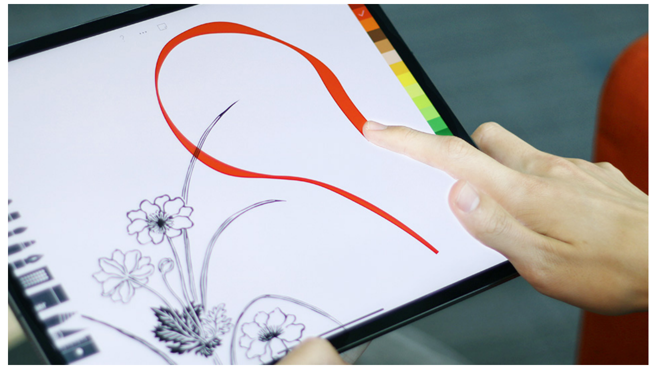


Figure 5: In a drawing app the line width can be controlled by the pitch of the finger. Here, a mock-up shows the red line which has different width as the pitch changed over the course of the stroke.

5.4.2 Pencil Width. Active touch pens like the Apple Pencil[4] offer additional input dimensions like force and angle, which can be mapped, for instance, to the stroke width. Here, finger orientation can expand a simple stroke with the same features, enabling a rich drawing experience on a touch surface without additional hardware; see Figure 3k and 5. (Proposed by P7–P9, P11 and [53])

5.4.3 Bézier Curve Control. Current methods to manipulate Bézier curves rely on handles to control the curve's shape. Thus, each point in the curve requires two separate inputs: the position of the point and turning of the handles. Finger orientation can allow simultaneous control of both metrics, using the contact position to place the point while yaw and pitch can be used to manipulate the handles, see Figure 3l. (Proposed by [49])

5.4.4 Color Wheel Picker. A color wheel has the implicit affordance to be controlled by rotational inputs, such as the Microsoft Surface Dial. Here, we can substitute the hardware component by using finger orientation input. While yaw controls hue, pitch controls the saturation, see Figure 3m. In contrast to touch selection, selecting color using finger orientation prevents the finger from covering the area where the color is selected. Thus, this allows for more precise color selection. Moreover, similar to the knob, a relative input implementation should be preferred due to ergonomic constraints. (Proposed by P17 and P11)

5.4.5 Exploiting Less Comfortable Input. As finger orientation input has ergonomic constraints, this can be exploited to force a conscious interaction, thus counteracting typical operations trained in muscle memory. Here, the factory reset of a device would require a finger orientation on the edge of the comfortable zone to ensure the user is aware of the action and its consequences, see Figure 3n. (Proposed by [35])

5.4.6 Hidden Flaps. Hidden Flaps enable the user to see a password or message without bystanders being able to see the screen. The idea here is that the finger and hand will shield the screen from

[4] https://www.apple.com/apple-pencil/

bystanders. Finger orientation input signals a high pitch to a text field to uncover hidden content, see Figure 3o. (Proposed by P2, P5–P7, P10, and [45])

Current solutions show by default the last entered character in a password field. This can be deactivated by checking a box and, thus, disclosing the complete input string. Revealing everything and showing the last entered character raises security issues, whereas not showing the password increases the chance of misspellings and, consequently, of failed sign-in attempts. Hidden Flaps offers a secure and user-friendly password input and secure message transmission as the fingers physically shield the content.

6 EXPERT INTERVIEW RESULTS: DESIGN IMPLICATIONS

From our transcripts, we gained a large number of possible design implications. In the following, we present the design implications and considerations critical for the design of novel finger orientation input.

6.1 Absolute vs. Relative Input

The experts elaborated on the mapping of the input to the display as being either absolute or relative. In absolute mapping, the angle between the finger and screen represents a direct input value. On the other hand, when using relative input, the difference between the finger's initial position (when touching the screen) and the current position is the input value for UI manipulation. This allows a clutching mechanism similar to mouse input movements by lifting a finger off the screen and placing it down in a new position.

While absolute has a metaphorical link to the interaction, e.g., pie menu or joystick, the input value range is limited (P4–P6, P8). Thus, to counteract the limited input space often caused by ergonomic constraints, cf. Mayer et al. [35, 37], experts argued to investigate relative input interaction when possible. However, this also addresses ergonomic concerns such as the unwillingness to change their grip during an interaction (P6).

6.2 Form Factor

The consensus among participants was that finger orientation input is useful for mobile touch interaction. While the most frequently proposed use case was always the *smartphone*, the experts saw a high potential for *smartwatches* (see Figure 2), given the limited space on their screens (P2, P3, P5, P6, P8, P9, P11). Moreover, they found that tablets can benefit from the additional input method (P3, P4, P6, P9, P10). Finally, P4 and P5 also suggested that finger orientation input could also enable a wide range of interaction possibilities on touch-sensitive *wall-sized displays*, see Figure 4. Thus, finger orientation can enrich touch-based devices with all form factors, from very small to very large surfaces.

6.3 Context

We found that our experts envisioned four different context-dependent interactions. *Finger position-awareness*: Both the finger and the orientation position affect the interaction, e.g., zooming into a specific position (P3, P5, P7, P10). *Element-aware*: Only the touched element is relevant for the interaction but not the position, e.g., a pie menu selection (P2, P5, P7, P8, P10). *Dominant element*: An element can be the dominant receiver of the orientation input. This can be used for full-screen applications such as games. Moreover, it can be useful to be the main receiver for list and scroll elements or, in general, all other elements that are important in a given context. Only one element can be controlled in this scenario but from all positions on the screen (P1, P4, P6, P9). *Two-stage click and value*: In this two-stage interaction, the user first selects the object and in a second step, the value is changed; all this happens anywhere on the screen. This becomes especially handy when the finger visually obstructs the changed value, e.g., circular slider such as in Figure 1 (P3).

6.4 Ergonomics

All experts but three had comments on possible ergonomics constraints. The general observation was about the limited input range of this method as Mayer et al. [35, 37] investigated. However, interacting while walking was also expressed as a concern (P5, P8) as well as the effect of long nails (P2, P9), an aspect already discussed by Xiao et al. [58].

6.5 Two-handed Interaction

All participants agreed that finger orientation input can only be performed with two hands in a mobile scenario when using the index finger for input. However, in a scenario where the screen is fixed or static (e.g., wall-mounted display), the second hand would not be required to hold the screen. Thus, a one-handed interaction would only be possible in these static situations. Finally, P2, P8, and P9 could imagine that reducing the input to pitch input could only enable one-handed scenarios, especially when considering the thumb and not the index finger.

6.6 Feedback

Our experts advised incorporating feedback during the interaction (P6–P8, P10), thus confirming the design rules by Norman [42] and Schneiderman et al. [48] on feedback. Moreover, P7 suggested not only using visual feedback but also using haptic feedback.

6.7 Explanations

The experts were concerned about informing users about all these new interaction possibilities based on finger orientation. This is in line with research by Mayer et al. [38] as they found three viable methods to communicate the interaction to the user: Tutorial (P1–P6, P8–P10), Pop-up (P1–4, P7, P9), and Depiction (P1–P8). Moreover, P2, P3, and P6 expressed that videos could be a helpful addition when using the Tutorial or Pop-up method. Finally, P2, P5, P6, and P10, recalled Apple's advertisements teaching potential users about new features, which would be an additional indirect method.

7 DESIGN SPACE

In the following, we present the resulting design space. This process is inspired by fundamental work on design space analysis for input devices, cf., [5, 30, 31]. Therefore, two researchers coded and clustered the overlap among all the different interface implementations. We found that the design space can be represented by three axes: *Physical Action*, *Mapping*, and *Interpretation*. Figure 6 illustrates the design space.

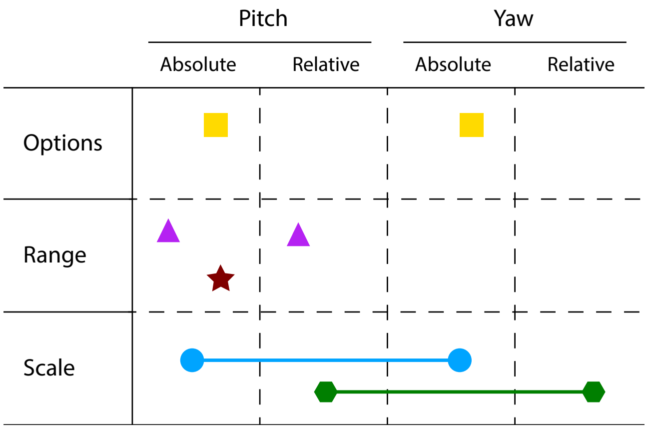


Figure 6: The visual representation of the design space with its three dimensions: *Physical Action*, *Mapping*, and *Interpretation*. Here, we illustrate five interfaces: context menu (yellow square), joystick (green hexagon), hidden flaps (red star), rotate and zoom (blue circle), and pencil width (purple triangle). As indicated here, pitch and yaw are used as a single (no line) or as well as combined input (connected icons with a line). Moreover, absolute and relative can be used as alternative modes depending on the implementation, e.g., Context Menu and Pencil Width.

7.1 Physical Action

The additional features of the finger are performed by physical movement. We found that both dimensions (pitch and yaw) were available to make use of the additional input; the majority of interfaces only used one of the two dimensions. However, the second dimension can be ignored when not needed. Moreover, we found that some interfaces used pitch and yaw complementarily depending on their implementation.

7.2 Mapping

The dichotomy between absolute and relative input modes is a separate distinguishing factor in the design space. We found that absolute and relative input can be used for both pitch and yaw. This forms the second layer of the design space for pitch and yaw, see Figure 6. Moreover, the modes could technically be used in a mixed setup (e.g., relative for pitch and absolute for yaw) as they are independent of each other. This depends on the implementation, which is often made based on metaphorical and ergonomic limitations. However, while they are independent, we found that they are never actually implemented in a mixed modes setup.

7.3 Interpretation

Apart from the physical action and the mapping convention, we see the value interpretation as a separate axis in the design space. The human's finger orientation input can trigger actions on three levels: options, range, and scale. Here, options are a set of selectable items. The range is a scale with a minimum and maximum input, for instance, a slider. Finally, scale interpretation is a continuous value input. Examples are knobs or a joystick. Whenever pitch and yaw are used simultaneously, the interpretation for pitch and yaw are always the same.

8 DISCUSSION

Following our literature review, we conducted interviews with UX experts in which we asked them to envision new user interface elements enriched with finger orientation input. As our literature review showed an overlap with the ideas by the experts, we combined both into a reference library. While we speculate that more specific application implementation can be envisioned based on the saturation of new interface elements, we argue that our list covers all general-purpose elements such as circular, slider, and enhanced menus. However, specific scenarios in which they are used are endless and should be explored further in the future.

To help designers in exploring more ideas for specific scenarios, we extracted design implications from the interviews. While some are specific to finger orientation input, others overlap with common user interface design guidelines such as those by Norman [42] and Schneiderman et al. [48]. However, as a whole, our findings will guide designers through the process of designing interactions for specific scenarios. Ultimately the design space serves as a tool to understand what is possible from a functional perspective — Allowing the designer to make the right design choices and pick the right functional implementation. This paper's core contribution is user interface elements and guidelines for designing finger orientation input. Defining the design space and envisioning user interface elements are the initial steps to enable widespread finger orientation adoption. While future work might look at individual concepts in lab studies, we argue that the next step should be large field studies of finger orientation input. We argue that only large in-the-wild studies can yield new insights about the use of finger orientation in everyday situations. Current technologies are not ready to support out-of-the-box everyday use, as today's implementations require modifying commodity smartphones (cf. Mayer et al. [36]). However, we can use such a model to run controlled in-the-wild studies, which are needed to showcase the great potential of finger orientation and spark mass adoption.

While finger orientation with the index finder adds the ability to input more information with a single click, the experts pointed out that in most cases, this requires a two-handed interaction. This drawback is especially present in a mobile scenario [37]. To overcome this, we can envision thumb input, allowing the user to hold the hand in the same hand with which the thumb performs input. However, this would most probably limit the input only to pitch input. Thus, while this alternative would allow for additional input, the input is less rich than when the user holds the device with one hand and operates it with the other hand as in the finger orientation input case.

9 CONCLUSION

We first presented a comprehensive review of prior work investigating possible user interface designs incorporating finger orientation. Because we found that these designs were mostly used to showcase new finger orientation recognition approaches, we decided to conduct interviews with UX experts to investigate the potential of finger orientation input and elicit alternative designs. Based on related work and the interviews, we presented various user interface elements from which designers and developers can choose. Moreover, we presented more general design implications Tattoo enable designers and developers to design even more application-specific interfaces following the presented recommendations. Finally, the design space for finger orientation as an additional input dimension enables other designers and developers to classify their designs and allows comparability among different approaches. Additionally, the design space can be used as a tool to envision new designs.

While UX experts have proposed the presented interface designs, we have not yet formally evaluated them. Therefore, as a next step, we want to implement the proposed design to evaluate them in a lab setting and compare them to today's state-of-the-art alternatives. Moreover, it is also essential that the proposed user interface elements are deployed to commodity smartphones to test them in the wild.

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