Evaluating design guidelines for hand proximate user interfaces

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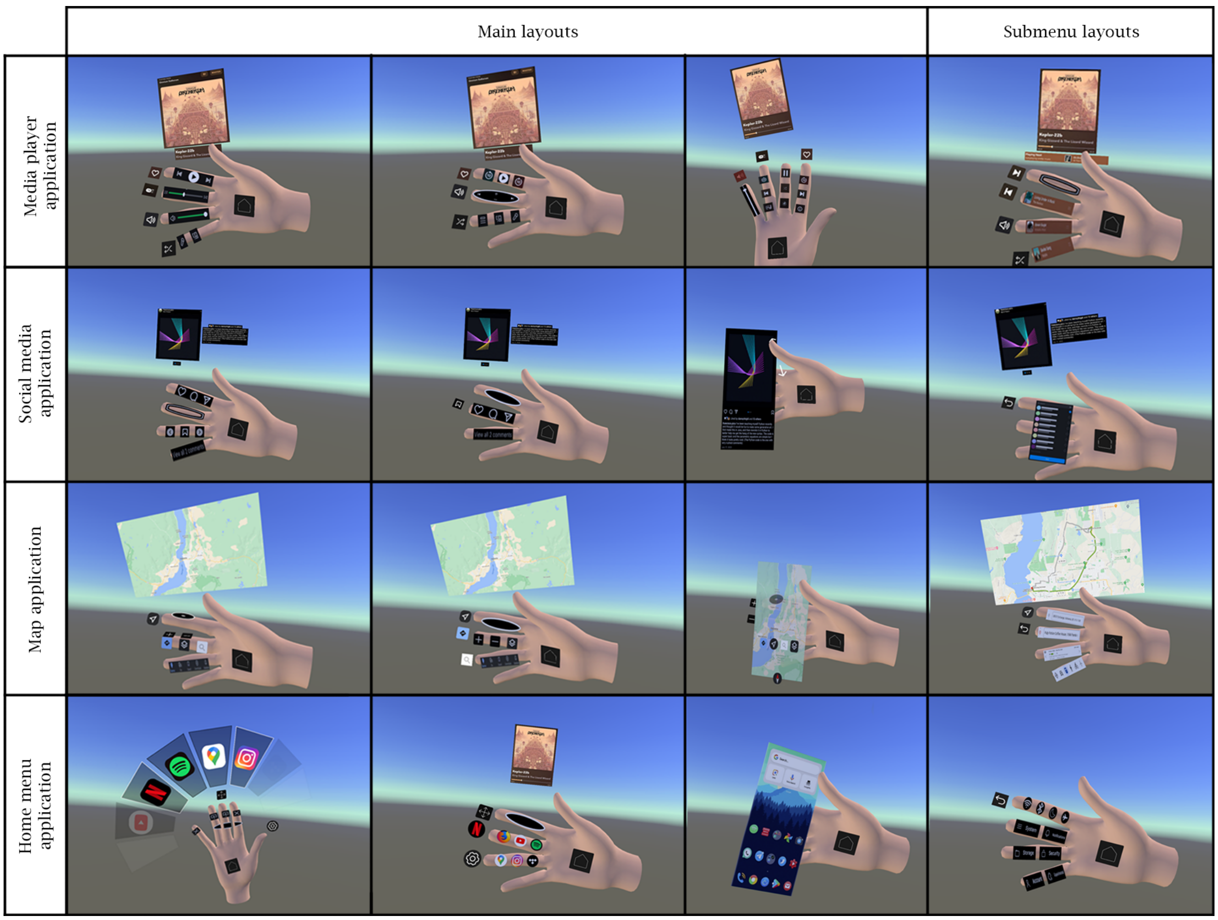

Figure 1: These 16 hand-proximate user interfaces serve as examples to help participants understand the possible designs they can create. The interfaces are organized into different rows, each representing a specific application. For instance, the third row depicts a map application, where the first three columns exhibit distinct map navigation or display styles. The first column demonstrates a detached display with joystick control, the second features a touchpad swipe control, and the third showcases a continuous display and combined input surface. The fourth column portrays a submenu that provides additional options, such as inputting directions.

ABSTRACT

Our study investigates the design practices of Hand-Proximate User Interfaces (HPUI) which are displayed on and around a user's hand in a head-mounted display (HMD). Specifically, we examine one-handed inputs where the main mode of interaction is thumb-to-finger contact. Our focus is on the user interface (UI) design of these displays, and we aim to develop design guidelines and heuristics for this novel design space. To achieve this, we conducted a participatory design study involving 15 participants who provided

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feedback on 120 different design examples, as well as their thoughts surrounding the HPUI design. Participants favored designs that were ergonomically comfortable and flexible, and those that provided clear visibility regardless of hand positioning. Based on this feedback, we developed 7 design guidelines for Hand Proximate User Interfaces. In applying these guidelines we find that common application interfaces can easily be accommodated using HPUI for use on head-mounted displays.

CCS CONCEPTS

• **Human-centered computing → User studies**; **Participatory design**.

KEYWORDS

Design Guidelines,Hand Proximate User Interface, Head Mounted Displays

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1 INTRODUCTION

With the acceleration of adoption and development of Head Mounted Displays (HMDs) to be used for both virtual reality (VR) and Mixed Reality (MR), many solutions have been developed for interactions with virtual applications. When it comes to commonly used applications, developers have opted to extend the current desktop GUI paradigm with flat-screen projection and point-and-click controls. This technique, however, is not always purpose-built for MR inputs, and other alternatives could be more effective [15]. Consequently, novel interaction techniques that diverge from the current desktop-based paradigm are cropping up to push UI to better adapt to MR.

The design space of Hand Proximate User Interfaces (HPUI) [20] uses the hand as an input and output space for single-handed interactions. It allows us to make the most out of that interaction space while allowing the user to still interact with their physical environments [20] with another hand. As a fully virtual interface, it also affords unencumbered interaction, while also being less fatiguing to use [26], both physically and socially. As it builds on the body of work on thumb-to-finger interactions [45] and microgestures [10], and following the observations of how smartphones are being used, it can be more expressive compared to controller-based or mid-air interactions. Even though it builds on gestures, it also has the advantage of discoverability similar to graphical user interfaces [13] as it uses direct input [43].

Despite its strengths, due to its unique characteristics, how one could develop an application with HPUI is not immediately obvious, and it is unclear how the existing knowledge on designing good interfaces would translate to HPUI. The already non-contiguous and non-planar surface of HPUI would also be constantly deforming as the fingers move during thumb-to-finger interactions. This limits directly applying design principles from devices with planar surfaces such as mobile devices. Prior work also shows the relative comfort within the design space HPUI is also non-uniform [17, 20, 27]. As ergonomics and user comfort are vital factors for a good user interface, it is unclear how these results would interact with any guidelines borrowed from other paradigms. Since HPUI also has a visual component, guidelines associated with gestures are also not directly applicable.

This work aims to address this gap. More concretely, we aim to develop design guidelines for HPUI. To address this, we look at prior work in UI guideline development, as well as our exploratory findings to formulate preliminary guidelines. We then develop multiple mockups for different applications for the HPUI. These mock-ups provide a blueprint for the interfaces that could be designed from preexisting mobile UI. We then first conduct a participatory design session, with individuals of various experience levels in traditional UI to design applications for HPUI on paper. Following that, we use the data from the evaluations and the placements of UI elements to determine which common rules emerge from the participants' designs and further refine our guidelines.

The contributions we offer are the following: **(1)** Characterization of designing applications for HPUI, where we define why existing design guidelines are not directly applicable. **(2)** Design study and accompanying analysis which provide insight into how the design space of HPUI can be best utilized to design applications. **(3)** Guidelines for designing applications with HPUI, first developed from prior knowledge, then further refined with the results and observations from the design study.

2 RELATED WORK

We begin by examining works that explore using the surface of the hand as an input device, and how it can be done effectively.

2.1 Hands as Controllers

The current paradigm of MR interaction involves using hardware controllers for input. These hardware solutions have expanded to utilizing the hands for novel controller interaction. Studies have been conducted that use peripherals to track basic gestures, such as smart-watches that use radar for tracking [39], optical tracking gloves [28], and fingertip touchpads [11]. Further studies in hand-tracking technology have opened up the possibility of using only one's hands instead of tailored peripherals [2, 14]. Prior research has explored user interfaces that utilize the hand of the user in various ways. The hand of a user can be can be a controller through motion or by mimicking a physical object [42], with studies being conducted to assess the potential ubiquity of hand-gesture controls and their surrounding vocabulary [19]. These gesture interfaces have covered additional modalities that stray from simple motions or hand shapes. In a particular example, Dezfuli et al. [18] explore utilizing the hand as a remote control for the television, using one hand as the input surface and the other as the pointer. Research by Gustafson et al. [23] highlights the benefits of such displays, as the input pointer and surface feel each other and allow the interfaces to be used without the need to look directly at the interface with practice. Relevant findings have been taken into account to develop new forms of gesture-based interaction on the skin, expanding the dimension for input [5, 8, 12].

Using the skin itself as an input surface, we can develop on-hand interactions. Many solutions have been adapted to suit single-handed interactions by adapting hand-to-hand input as thumb-to-finger input [17, 45, 46]. These studies have shown that using a single hand can make interfaces more comfortable and convenient for extended use. By using sensitive hand-tracking solutions, studies have developed a method to use microgestures in thumb-to-finger interactions. Previously tested on physical interfaces [52], thumb-to-finger microgestures allow users to tap, swipe, or perform any other gesture available on a conventional touch screen on the hand itself [10, 45, 46]. Faleel et al. [20] expand on this idea by identifying regions for the comfortable thumb-to-finger interaction with their hand-proximate user interfaces: input surfaces that are displayed directly on the fingers of the hand and are reachable by the thumb. However, there is a need to determine how user interfaces can be created for day-to-day user tasks such as content navigation and how to display them.

2.2 Hands as Displays

Hand-based displays can vary from displaying UI around the hand to directly on the surface of the hand. For one-handed interfaces, both of these alternatives have yielded promising results. Xu et al. [53] developed a display that projects around the hand, and can be interacted with through small wrist motions and pointing. The benefit of this system is that the information is easily legible and does not take up as much space in the field of view. However, this solution does not take advantage of the surface of the hand as an input plane and therefore lacks flexibility. An alternative solution was proposed by Faleel et al. [20] which displayed UI directly on the hand, with displays that bend alongside the fingers using deforming spline surfaces. Their findings showed that having displays that bend alongside the surfaces of the hand allowed for easier reach of all items rendered for interaction

2.3 Adapting Mobile UI to MR

The main corpus of research involving porting mobile interfaces into MR interactions has centered around translating a traditional smartphone into MR. A recent example is a method proposed by Bai et al. [3], which tracks a smartphone in virtual reality and mimics what the real screen is displaying on the virtual twin. Multiple other methods cover using a smartphone in MR environments this method still uses a physical phone for control, but the concept of quickly accessing the convenience and reliability of a smartphone in MR can help inform application development for on-hand interfaces. A major factor in the design decisions regarding one-handed HPUI is the ability to interact with an MR interface with the same one-handed convenience as using a mobile device. Understanding how we interact with and design for our mobile devices, such as how Karlson et al. [31] allows us to make more informed design decisions in an MR context.

2.4 Guideline Design

The advent of HMDs and hand-tracking interfaces has necessitated the re-evaluation of current UI design heuristics and rules. Usability Heuristics such as those proposed by Nielsen and Molich [41] can be applied to the design of HPUI, as with most UI, but more specific guidelines must be developed to account for the minutia of the HPUI design space as designers need to take new factors into account. Broad usability heuristics cannot cover all facets of an interface, especially if it is not traditional a traditional UI. [30] Furthermore, concepts such as Fitts' Law are difficult to implement for hand gestures and on-hand touch displays [20]. Therefore, new guidelines must be developed for MR applications on hand interfaces that take into account the unique features they present. Prior studies have identified guidelines for MR applications, both for interaction and information display [33, 49]. Furthermore, some concepts in multi-modal touchscreen interface design [22] can be adapted to on-hand UI implementations [1]. These results provide insight to create preliminary guidelines for the development of on-hand UI. To further refine these guidelines, we turn to a design study, which has been previously leveraged both using researchers and participants to develop design knowledge from multiple perspectives [47].

3 CHARACTERISTICS OF HPUI

Here we discuss the characteristics of HPUI that affect the applicability of existing design guidelines.

- *Non-rectilinear and non-planer:* Prior work on UI for HMDs has looked at distributing icons layouts on non-standard or complex surfaces [9, 35, 37]. But these are primarily with discrete elements. When elements that cannot be discretized, such as images, 2D maps or large text segments are considered, they are still displayed in a rectilinear plane. Designs that consider the hand as a flat surface also mostly follow this convention where a rectilinear element is fitted on the space on the hand when it is held flat [4, 24, 32]. As content will need to be displayed on the regions of the fingers, using such rectilinear elements would not be ideal.
- *Dynamic surface:* With the fingers constantly moving to allow the thumb to reach different segments of the fingers, the design space will be constantly changing. This also results in parts of the UI being occluded. Apart from the thumb occluding segments of the fingers, as seen with smartphones as well [7], the viewing angle to some of the segments changes significantly. For example, consider an icon displayed on the tip of the index finger. When the thumb has to reach the index segment, in addition to the thumb occlusion, the icon on the index finger would most likely form an extreme viewing angle. If the icons were made to always face the user, this would result in the elements overlapping each other as the finger moves toward the thumb. These can potentially severely affect legibility.
- *Non-contiguous:* Another outcome of thumb-to-finger interactions is the interactive surfaces in the fingers are not contiguous between the fingers. Within the design space of HPUI proposed by Faleel et al. [20], this is captured by multiple factors. *Workspace styles* consider elements that can be discretized and that cannot be, such as images. The *Display frame of reference* considers if a given element would be anchored to the whole hand, a single phalanx, one finger or multiple fingers. Which combination of these would suit which application scenario is not immediately obvious.

- *Limited interactive space:* Compared to other UI modalities, the interactive real estate on the fingers is quite limited. Considering the fat finger problem [6], legibility and limited spatial acuity of the thumb-to-finger interactions [27], designers will have to be careful about how to efficiently display on the hand.

As a result of these characteristics, we cannot directly apply existing guidelines on how to build applications. We develop a set of guidelines that were informed by the literature and iterative testing while exploring how existing applications can be presented on HPUI. This is an early exploration of how to design applications for HPUI while broadly considering all dimensions (including input and output) of this interface. To further validate these guidelines, we use a participatory design study. The participants of the study are not made aware of the guidelines initially developed. They are asked to consider the characteristics and design application layouts. By having participants design and evaluate their own HPUI without giving them any guidelines, the patterns that emerge from their designs and their observations on the usability of their HPUI can be aggregated into heuristic evaluations to refine the guidelines, which we present the guidelines in Section 5.

4 DESIGN STUDY

We employ a design study where we ask participants to design applications for HPUI. We first developed mockup designs of four applications (see Section 4.1), which were used to give participants a first-hand experience of using HPUI which would inform the designs they consequently make. To present these mockups, we followed a similar approach to Faleel et al. [20]. The applications the participants consequently designed were also for the same four applications. The mockups were developed using Unity, with the application running through Oculus Link on an Oculus Quest 2 headset. We used a Vicon motion tracking system to have high-fidelity hand tracking to give the participants a more complete experience (see Figure 2). Note that during the design sessions, the applications did not have any interactions, i.e. they were visual mockups with no interactivity.

4.1 Applications

We used four applications for the study. These were selected to provide coverage of the different UI components [36] and UI topics [1, 34]. These were also chosen to be commonly used applications by users. This would allow participants to make more informed design decisions during the study. We further limited the number of applications to four to avoid fatiguing the participants.

The applications chosen were as follows:

- *Media player*: This covers applications that have a small number of very frequently used interactive elements, while the most dominant UI element is dedicated to output such as album art or video. Note that we consider videos and images as "output", where the user does not have to provide any input to these elements. The larger design space of HMDs affords to make this distinction. Further, the media player also includes elements such as sliders for volume, which can be seen as a one-dimensional continuous interactive element, while no direct navigation like other applications.

Figure 2: The setup used to demonstrate the example applications during the study. We used a Oculus Quest 2 HMD with a Unity application being executed with Oculus Link. A Vicon motion tracking system was used to track the motion of the HDM and the hands with optical markers.

- *Social media*: This is representative of most content ordered as a large (or infinite) list, where each element also contains additional interactions and information attached to them.
- *Maps*: This represents applications that require interacting with a continuous interface. It is also an interface that involves 2-dimensional navigation.
- *Home menu*: This is an interface that has a large number of discretized elements. Note that, discretized/continuous as used here is based on the definitions used by Faleel et al. [20], where continuous UI elements are ones components that are constrained by where they can be placed in relation to each other.

For each of the applications, we designed 3 example layouts. This was done to allow participants to familiarize themselves with the design space and characteristics of HPUI and further encourage being critical of the designs they propose. We also included one sample second layout of another view or submenu within the application in the mockups. We refer to these as *submenus* in the remainder of the paper. These were secondary layouts meant to encourage participants to consider navigation between different parts of applications. As submenus, for the media player we used the playlist queue, for social media we used a list of contacts to share, for maps we used the "get directions" view, and for the home menu, we used the settings menu.

We also include 3 navigational elements throughout the applications with an accompanying visual element. These can be interpreted as microgesture control widgets. The first is a circular scroll. This is similar to the circular touchpad that was commonly found in the early iPods. The interaction on this would be similar to the circular gesture used by Huang et al. [27] but limited to a single finger. The Second is a swipe control surface. This is a dedicated surface where users could perform swipe gestures. Third is a joystick control. This is similar to the TrackPoint control on Lenovo laptops [1]. The user would swipe and hold to move in a given direction.

4.2 Participants

Fifteen participants volunteered for this study (12 males, and 3 females. Aged between 19 and 22 (M=20.8, SD=0.86)). Nine of the participants had never worn a virtual reality headset before. Three of the participants were left-handed. Four participants had experience with virtual reality UI development.

4.3 Study Design

To accurately represent the UI on the hand of the participants, they will be asked to wear the HMD and Vicon motion tracking glove to allow them to see the UI in motion. Each group of participants viewed applications in Section 4.1 in a random order before the design session started. The participants were allowed to ask probing questions while viewing the different application layouts. Consequently, they are asked to redesign the applications with their own layouts. They would design the main layout as well as a submenu of their choosing. The designs from the main layout would provide us with data that would allow us to directly compare the layouts. The submenu designs were used to allow participants with more freedom with coming up with new layouts and designs.

4.4 Procedure

The study is conducted in groups of 3 participants at a time. We used groups as we believe the participants would collaborate to derive better designs. On arrival, all participants are asked to complete a consent form and pre-study questionnaire. The participants are then introduced to HPUI and we provide them with an overview of the applications and layouts they will experience in VR in a brief 5-minute video. The video was used as initial stimuli, to reduce the total time taken for the study. The participants were allowed to ask questions at the end of the video.

Following that, each participant gets to view the applications in VR with the motion tracking system driving their hand movements. For this session, only one participant can experience the demo at a time. This was primarily due to only being able to track one hand within the motion capture volume at a time, as tracking thumb-to-finger interactions with optical markers requires a larger number of cameras to cover all possible locations for the markers on the marker glove. For each participant, they first put on the tracking glove on top of a rubber glove and Oculus Quest 2 HMD and seated within the tracking volume. Then the Unity application with the example application layouts was launched. For each example, participants are asked to try to reach every element and mimic every action they might think to make on such an application, to inform them of the personal comfort of each layout. Once the participant has viewed every example design, they are asked to remove the HMD and gloves and return to their seat at the table.

Once all three participants have experienced the example application layouts, they are instructed on their first application layouts to design. They are given 20 minutes to sketch a design for both a main and submenu for the application on sheets provided to them. The sheets had a sketch of the hand printed on them (see Figure 8). Following this, there is a 10-minute discussion section where each participant takes about 3 minutes to explain their main and submenu designs. The session is divided as such to allow each participant to first derive their own designs before discussing them with the group. We record the participant discussion and ask them questions regarding their design choices to understand their reasoning. The questions asked by the researchers were primarily to encourage the participants to provide further rationale for their designs, such as why they chose a given location on HPUI or if they think it would be something appropriate to use in a public setting. During this phase, the participants are also encouraged to discuss their designs amongst themselves. Throughout these sessions, on a monitor, they were shown the corresponding layouts they saw previously for reference, the list of interactions they would have to have for each application, and the instructions. Figure 3 shows this information page for the social media application. All instruction pages shown to users can be seen in the Appendix A. These design and presentation sections are repeated for each application type, with a 5-minute break between the third and fourth sections.

At the end of the 4 design sections, participants are asked to fill out an exit questionnaire, after which the study concludes. The study took roughly 2 hours and 30 minutes to complete.

4.5 Results

From the 15 participants, we gathered 15 different designs for both the main interface and submenu of the Media, Social Media, Map and Home Menus. In total, we gathered 120 distinct designs that leverage HPUI as an interaction method, 60 main layouts and 60 submenu layouts.

4.5.1 Discrete Interaction Placement. By tagging the hand segments where the participants placed interaction elements in the main layouts for each application, we can observe patterns in their placement. For each application, we have generated heatmaps on a hand diagram to visualize which spaces of HPUI are utilized. The results were aggregated into a single total placement heatmap for all designs (Figure 4).

The primary interaction surfaces in the participants' designs are the volar sides of each finger phalanx as well as the off-finger position past the tip. These segments account for 68.4% of all placed interface elements by the participants. In terms of finger preference, the participants leaned most toward the index and middle fingers for their interactions. A decline in placements can be seen in the ring and pinky fingers, neither one surpassing the latter two in any of the applications. Preferences are less clear-cut between the index and middle fingers, as for most applications, there is less deviation in placement frequency. The home menu stands out between the two top fingers because the middle finger saw significantly more use in this application compared to the index finger.

The media player HPUI had a total of 265 elements placed spanning every participant's designs. Similarly, the social media application had 214, the maps application had a total of 214, and the home application had 205 placed elements.

We also generated heatmaps for each application displaying the top three most used elements in the designs (Figure 5a). For the media player, these elements are the *play*, *skip forward*, and *skip back* inputs. The social media application has the *like*, *next image*, and

[1]https://patents.google.com/patent/US6115030A/en

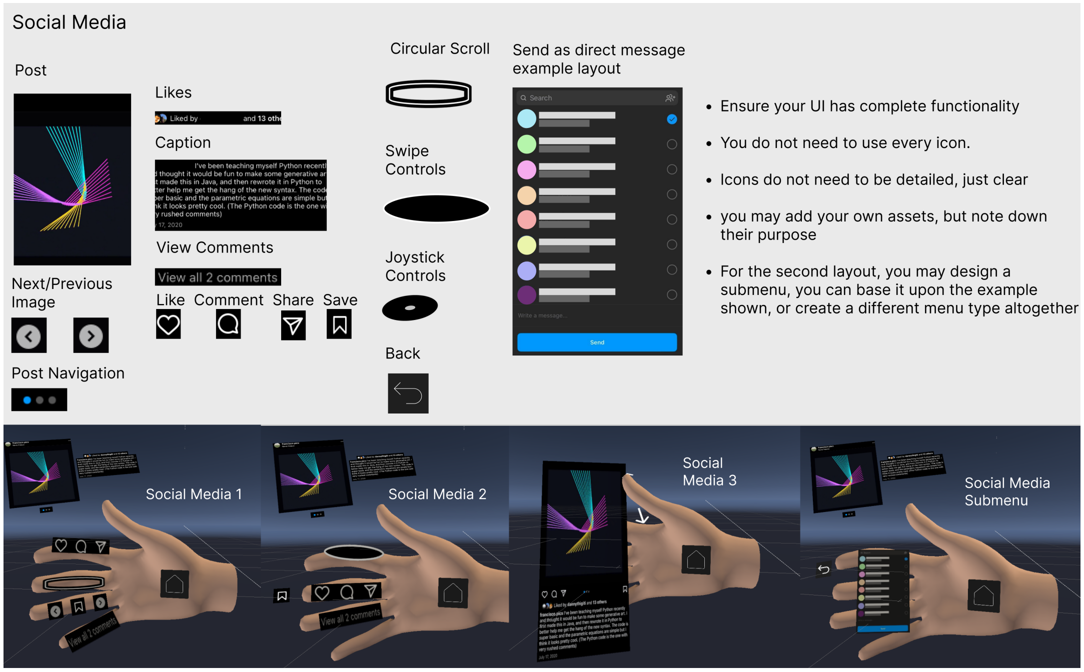


Figure 3: Information page is shown to the participants when they are designing their own layouts. Includes the example layouts they were shown, the necessary elements of the interface and instructions. Each application had a similar information page.

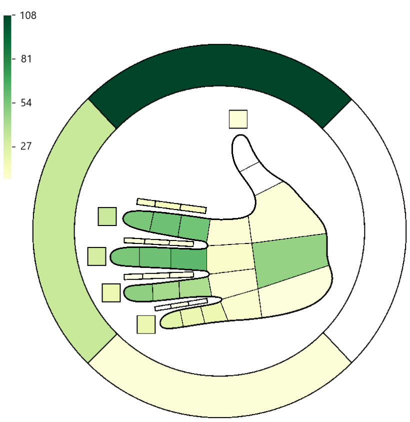
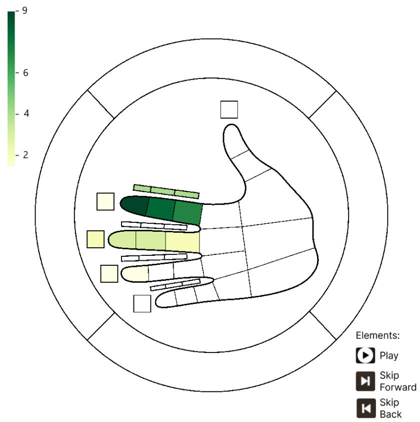


Figure 4: Total interaction placements for all designs

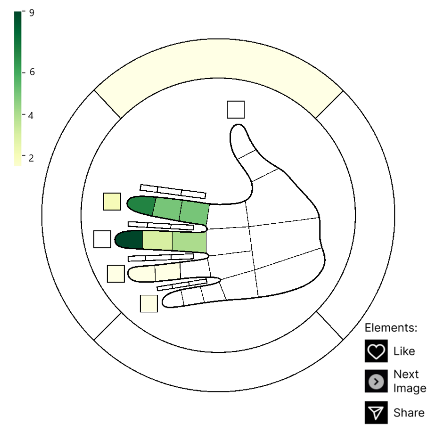
share inputs. The maps application has the *directions*, *center*, and *navigation* inputs, and finally, the home application has the *applications*, *settings menu*, and *navigation* inputs. These most frequently used inputs were determined by the participant presentations and the number of times these elements are included in participant designs. From the heatmaps, we can determine a preference for the index and middle fingers for all 4 applications, with the media player and social media applications particularly lacking frequent-use elements in the ring and pinky fingers. The maps and home menu applications exhibit more frequent-use elements in those fingers, mainly because their frequent-use elements, apart from the navigation, do not need to be interacted with as often. A user may skip a song multiple times in succession in the media player, but they only need to select directions once on the map application.

4.6 Continuous Display Placement

A continuous deformable display was also provided as a design option for participants based on the work of Faleel et al. [20]. Only five participants designed interfaces with continuous displays. 3 displays were designed for the social media app, and 3 for the Maps app, with none of the participants making any continuous displays for the media player or home menus. Some Participants expressed unwillingness to use the deformable displays for most of their designs citing legibility, control over the deformation of the surface, and aesthetics as primary concerns for the implementation of these displays. Participant 3 explained their dislike for displaying images on a continuous surface citing a need to "make an extra effort of keeping it as flat" when trying to view one. Participants 7 and 8 echo that sentiment, both agreeing that the relaxed position of their fingers makes the surface illegible. Participant 11 simply stated they disliked the continuous surface, hesitating to cite its problem as being too similar to a mobile device, and concluding that the way it deforms is just "really weird". Participant 14 implemented a continuous display but eschewed the deformation because "it didn't look quite as good" and "deformed into itself".

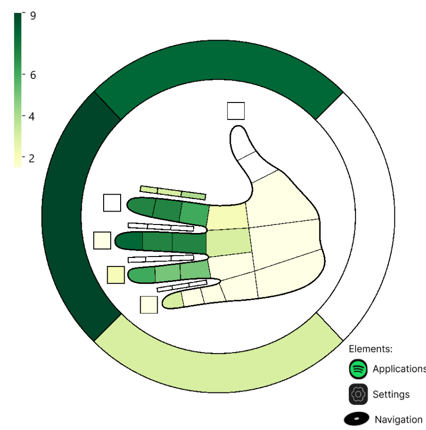


(a) For media player; number of times *play*, *skip forward*, or *skip back* inputs were placed at a given location.



(b) For social media application; number of times *like*, *next image*, or *share* inputs were placed at a given location.

(c) For map application; number of times *directions*, *center*, or *navigation* inputs were placed at a given location.



(d) For home menu application; number of times *applications*, *settings menu*, or *navigation* inputs were placed at a given location.

Figure 5: Within each application, the number of times a given location was used to place one of the top three most used elements.

4.7 Around-hand Displays

Due to the low usage of continuous on-hand displays, the discrete around-hand displays saw far more widespread use with 146 elements being placed in them, amounting to 15.9% of all elements placed. The around-hand displays are separated into 4 quadrants around the hand, one off the radial side of the hand, one off the fingertips, one off the ulnar side of the hand, and one off the base of the wrist. the radial display saw the most use out of all of them, accounting for 108 elements. This is followed by the 33 elements in the off-finger locations and the 5 elements in the ulnar display. No elements were displayed on the wrist display on the palmar plane, however, participant 12 included a wristwatch-style element on the dorsal plane of the wrist as a potential option. These results can be seen in Figure 4.

4.8 Microgesture Control Widgets

Discrete thumb-to-finger interactions were not the only input methods that participants were provided within the examples. Microgesture controls were an additional layer of interactions that participants had at their disposal, such as swiping or circular gestures on the fingers [10, 27]. Microgestures are the primary form of interaction the participants employed for designs that required granular or analog-style controls. Participants mainly used these microgestures for navigating within the applications they were designing for. Larger hand gestures did see some use, however, most participants did not implement them.

Due to the media player traditionally using button controls to skip forwards or backward, only 3 participants implemented navigation microgesture controls for this application, all implementing a swipe touchpad to traverse songs. Additionally, 8 participants used microgesture surfaces as controllable volume bars and 12 used them for scrubbing playback bars. 2 participants implemented hand

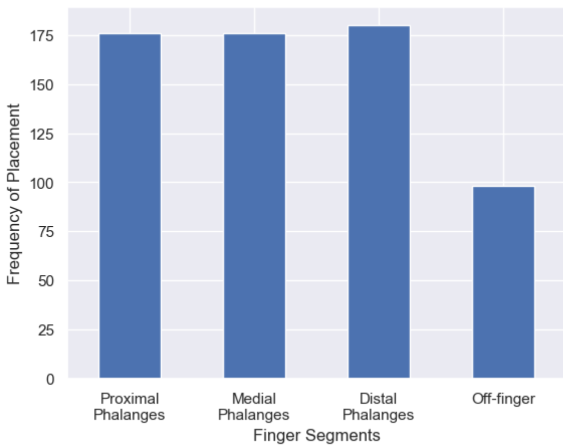


Figure 6: Total number of elements placed on each segment summed across all fingers.

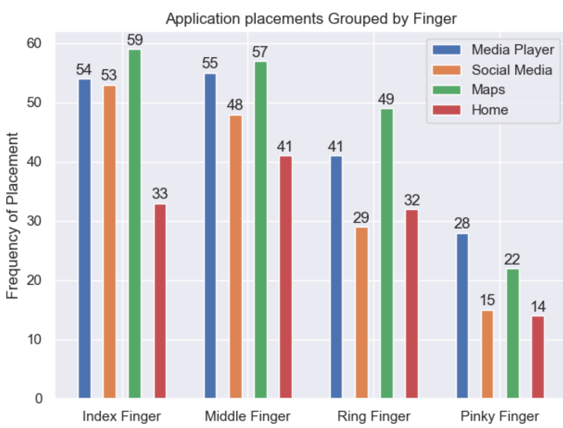


Figure 7: Number of elements placed on a given finger Application placements grouped by finger

gestures, both using the thumb to traverse songs with a vertical motion, a gesture that was presented to them in an example layout for the social media application.

The one-dimensional nature of the social media app navigation meant that all participants needed to provide some way to traverse the application. 9 participants implemented a touchpad for swiping, 3 participants implemented swiping on a continuous surface, and 1 implemented a joystick. 1 participant implemented the thumb gesture previously mentioned for the social media application. Participant 12 did not implement any microgestures for this app, opting to use discrete buttons, however, they implemented an alternate "gun mode" where users selected elements by pointing at them in a gesture representing a gun, and curling the thumb to 'shoot' them.

The maps application provides a two-dimensional surface to traverse, this spurred a greater use of joystick microgesture widgets, with 11 participants incorporating them into their designs. 3 participants implemented a two-dimensional touchpad to swipe through the map, and one participant implemented a continuous display that could be traversed by swiping on any part of the surface.

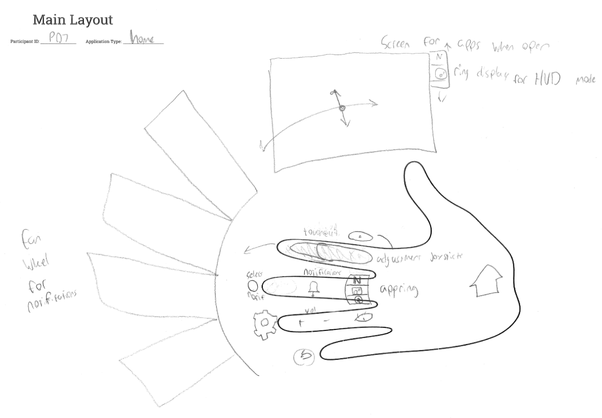
The home menu does not have a specific traversal dimension, so participants implemented a variety of navigation microgestures. 5 participants implemented a one-dimensional swipe microgesture, 4 implemented a two-dimensional touchpad microgesture, 2 participants used a joystick widget, and one participant implemented the one-dimensional circular scroll microgesture widget presented in a social media example. 1 participant did not use any gestures. Additionally, 2 participants implemented hand gestures, with one using wrist rotation to scroll left and right on an app list, and the other participant using a tilting motion on the hand's coronal plane to navigate, followed by a finger curling motion to select.

Some additional microgestures were implemented by participants throughout all of their application layouts. Participant 7 included additional joystick surfaces to transform and resize around-hand displays, as well as a custom secondary microgesture surface on the proximal phalanx of the middle finger that could be spun around to select options, emulating a common smart ring interaction [25]. These additions are repeated in all the participant's designs. Participant 8 implemented a microgesture-based system for selecting additional inputs on a full-finger surface. Their design involved holding down the thumb on the tip of the finger, whereafter the inputs on the surface of the finger change into new options, the user then drags the thumb along the palmar surface and releases it to select.

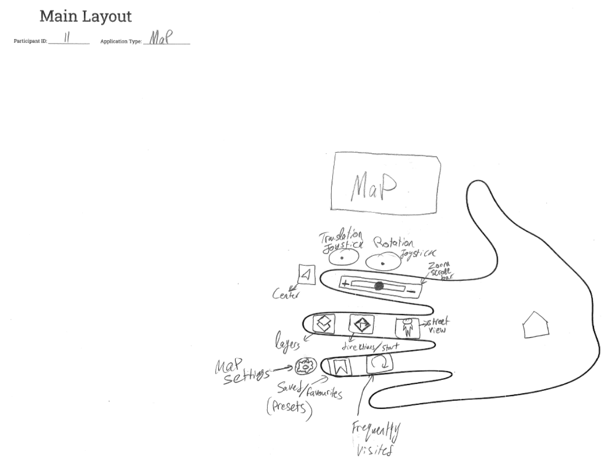
4.9 Participant Comfort

Although preliminary guidelines were set in place before the study, the participants were not informed of these design guidelines to allow them to organically determine the best way to adapt the designs. A result of this approach to design is that participants greatly prioritized comfort in their layouts. Participants found that their hand dexterity and flexibility were all distinct, and so they found certain elements easier to reach. For example, five participants expressed a desire to make their designs customizable, with 2 participants implementing a method to reposition certain elements around the hand or in the HMD view. The primary consensus was that certain overhand displays could not be viewed comfortably depending on the participant. 3 participants suggested locking these displays to headset rotation, so users could view the display from any angle. Also, some participants used vertical layout (layout from the distal side of the hand towards the proximal side of the hand) in 9 instances for the main layouts out of the 60 main layouts designed; 2 for media player, 1 for social media, and 6 for home application.

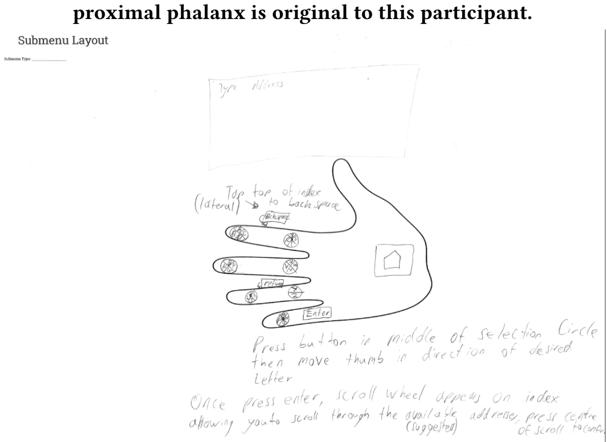
Comfort evaluations also came about from participants' own designs. 9 participants added input surfaces to the palmar side of the knuckles, however, 4 participants expressed discomfort when trying to reach that part of the hand with the thumb. Participant 1 stated the position was difficult to reach when attempting the motion in the discussion for Participant 0's media player design, which features inputs on the palmar side knuckle of the index and ring fingers. Participants 0, 2, and 3 all implemented interactions on the knuckles and expressed discomfort in their own original implementations, so their placements were for low frequency use inputs or in specific parts that they could reach relatively more



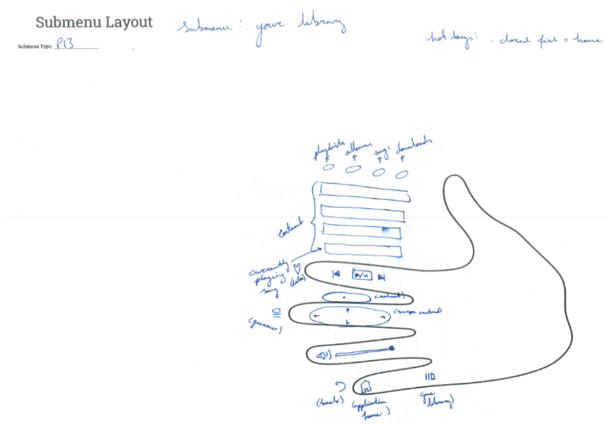
(a) This is the home menu design of participant 7, it includes original components and actions that we did not give the participants originally. Notably, the joystick widget on the lateral side of the index proximal phalanx serves to adjust the orientation of the detached display. The app ring in the middle proximal phalanx is original to this participant.



(b) This design was made by participant 11 for the maps application. This design uses two joysticks for translation and rotation in the map, with a zoom bar on the same finger. This puts all map navigation widgets in one finger. The participant also added an original Streetview button to their design.



(c) This is a submenu designed by participant 8 to search for directions in the maps application. It uses a text entry system where the phalanges contain radial interfaces that allow for the selection of characters by holding down and sliding in the direction of the desired character. The search box is found in a detached display on top of the hand.



(d) This submenu design was drawn by participant 13 and depicts a music library for the media player. The list of songs and tabs are displayed above the hand, and the user can use the joystick on the lateral side of the middle finger to select a song to play or change lists, and swipe on the touchpad to control playback.

Figure 8: Four examples of participant designs. Two of main layouts and two of submenu layouts. The designs were hand drawn on a large sheet of paper.

comfortably on the knuckles. For example, Participant 2 stated they were able to press on the palmar knuckles of the ring and pinky finger, but not for the middle and index fingers.

4.10 Submenu Designs

The participants each provided a submenu design for each of their main designs. These designs were open-ended and allowed the participants to create any menu function they thought would best suit the HPUI application. For the 4 applications, the participants gave distinct designs that matched the design language of their respective main layouts.

Media Player. Starting with the media player application, the participants mostly designed their own queue interfaces, as they adapted the provided example into their own style. Of the 15 participants, 8 of them designed queue interfaces, which were variations of the example submenu provided to them. Of the remaining 7, there was a playlist view seen in 8d, an album view, a save-to-playlist interface, a library view and a focus mode.

Social Media. For the Social Media application, 8 of the submenus were for variations on the provided share screen, 1 for saved posts, 1 for posting menu with a keyboard implementation, 4 direct messaging lists (1 containing a keyboard interface), and 1 submenu that provided an alternate layout for viewing posts.

Maps. The maps application had 8 directions submenus with 1 containing a keyboard (again variations of the example), 3 general search interfaces (1 with a keyboard, seen in 8c), 1 saved locations list, 1 location information display, and 1 go (quick directions from current location) menu.

Home. Finally, the Home menu had the most variations on the given example with 14 Settings submenus, with only 1 participant creating a different submenu representing an application search interface. The participants mostly used discrete buttons and microgestures as the primary mode of interaction with these submenus, with only one participant adding a small continuous display spanning the middle, ring, and pinky fingers. The participant noted that their continuous display would be non-deformable, citing a dislike for the deformation.

5 GUIDELINES

Here we present the guidelines for designing applications for HPUI. As described in Section 3, we had initially developed a set of guidelines. The guidelines here are the refined version based on the results in Section 4.5. In the following, where applicable, we first describe the motivation of the guideline and then ground it on the results from our design study. All but *G7* were in our initial guidelines. *G3* and *G5* were modified after analysing the results from the study.

G1 *Keep the adapted HPUI layout consistent with mobile and other MR UI standards for consistency.* Maintaining consistency of UI layouts allows the user to transfer their knowledge of other systems to interact with HPUI. This reduces the time needed for familiarization and the learning curve for advanced interactions.
The most emulated designs of the media player and social media HPUI examples were those that most closely matched the layout of the mobile applications they are based around. In total, 80% of the participants explicitly mentioned emulating a component from a smartphone in their designs. However, most participant designs did not attempt to emulate a mobile display but laid out the interaction elements in similar relative positions to those on existing interfaces of these applications. Participants cited familiarity as an important factor informing their design choice. Most participants did not have MR experience, so fewer participant designs took cues from those platforms. However, there were still some overlaps with MR menus in the home menu designs, as the home menu was not presented as an application that participants were already familiar with.

G2 *Most frequently used thumb-to-finger interactions must be placed where it is most comfortable to reach for a majority of users.* Previous work on thumb-to-finger interactions has shown that the perceived comfort of interacting with the fingers is not uniform across the surface of the fingers [17, 20, 27]. They show the index finger and middle finger to be more comfortable than other fingers, with the pinky finger being less comfortable [20, 27, 29]. They further show the proximal phalanx of a finger is less comfortable than the distal phalanx. The radial side of the fingers also have been used to further expand the interactive regions on the fingers [29, 45], though they were found to be less comfortable than the targets on the volar side of the fingers [29]. It should be noted that the comfort ratings collected in this body of work are primarily with tapping tasks. Depending on the task or if a gesture such as a swipe is being performed, these may not directly translate. For example, Tsai et. al [46] and Faleel et al. [20] observe the proximal phalanx to be more comfortable in some scenarios.
The heatmap data we gathered from the designs that participants created point towards the ratification of this guideline. The majority of participants consistently placed the main interaction elements for an application in the index and middle fingers of the hand, often relegating non-essential interactions to the ring and pinky fingers, citing that those last two fingers were less comfortable for frequent use. Furthermore 87% of the participants explicitly cited comfort as a reason for specific placements in their designs. Therefore, this guideline is reflective of the data that the 15 participants provided. An interesting observation we make is the preference for proximal phalanges of the index finger and middle finger over the distal phalanx of the ring finger. This contradicts the previous findings with thumb-to-finger interactions where the middle fingers' proximal phalanx is rated lower than the distal phalanx of the ring finger [20, 27]. While this is still in line with the guideline itself, it could imply that there are more factors influencing comfort and preference than the bio-mechanical properties of thumb-to-finger interactions.

G3 *For content where legibility is of significance, they should be placed as static surfaces where possible. Continuously deformable interfaces should be used sparingly.* Continuous deformable display surfaces allow for a larger interactable surface [20]. While the deformable interface attempts to resolve the limited thumb reach, it would reduce the legibility of the content [40, 48]. The deformable interface can be used on a single finger, for example, for a widget such as a volume control [50].
We had assumed the deformable display can be used sparingly for content that needed to be easily legible or that had content that was important to see in its original form such as images or text. The applications presented were designed with this in mind. But, its implementations shown to participants were negatively received for the applications that contained. The media application and home menu applications in particular saw little use of continuous displays in their designs. 33% of participants cited the deformation to be a hindrance or aesthetically displeasing when navigating the content. Although the number of participants giving negative feedback on the deformations is low, the participants only used continuous deformable displays in their main designs 6 times across all of them. The map application did see more success, but overall the intense deformation of the

surface was undesirable for participants. Even for the map application, some participants had placed the map view in the around-the-hand space and interacted with it indirectly with microgesture widgets. The feedback given by the participants is a symptom of the continuous display surface's main goal, to deform with the hand of the user, so they can reach inputs on the display they otherwise could not.

G4 *Limit the number of discrete elements to the landmarks on the fingers.* When placing interactive elements on the fingers, they need to be positioned in such a manner that they reduce the error [27, 29] due to the inaccuracies of interacting with fingers [6, 7, 44]. Given the similarities with touch interfaces such as smartphones, it is possible that an element placed on the fingers could be much smaller [11]. But using such an interface could limit the use of proprioception for novice-to-expert transition [13].

During the design sessions, participants mostly placed only one target on a given segment of a finger. Some did not follow this rule completely but rarely were there more than four discrete elements on each finger. From the main designs, 93% of the layouts used the phalanges and hand segments as references for placing elements. Thumb-to-finger interaction affords a degree of precision that prevents most input errors that one might commit on a mobile device. However, proper spacing of elements and a variety of gestures makes the interface more robust against user error.

G5 *Prefer HPUI (i.e., displaying interactive elements). For microgestures, use clearly marked gesture widgets (e.g., joystick (see Section 4.1)). If using gestures or voice, clearly denote them with appropriate labels and tooltips.* In addition to the advantage of direct input afforded by HPUI, using it also affords better discoverability. Though gestures and voice could be used, their weak discoverability reduces the overall usability of an interface [16, 38]. The use of graphical elements would also afford better novice to expert transition [13] as a user does not have to memorize a gesture but gradually develop muscle memory to quickly perform a gesture sequence that involves thumb-to-finger interactions.

This is also reflected in our results. All the participants developed designs that displayed the relevant interactions clearly on or around the hand. However, some participants deviated from the simple display and included interactions that were not immediately visible. Such designs involved hidden selection options, displays on the dorsal side of the hand as well as gestures that are not immediately evident to the user. These made up only about 7% of the designs. These designs required the participant to explain and illustrate how to interact with such elements and add an extra layer of complexity to the acquisition of their interfaces. However, the designs are not worth discounting as some, such as the slide and release input on the tips of the fingers, are promising evolutions of HPUI interaction.

While the preliminary guidelines we developed discouraged the use of gestures and voice, here we modify it to include valuable edge cases that a developer may implement to suit specific use cases. Any additional interactions that may not be able easily found should be introduced to the user via some form of documentation or, preferably, with tooltips. With HPUI being a virtual interface, unlike touch devices, it is trivial to have hover states. This modification is corroborated by traditional usability heuristics. [30].

The participants made use of the microgesture surfaces we provided them in the examples for the majority of their designs. Even though there were examples provided to participants that allowed for microgestures without any accompanying visual element on any part of the surface to act as a scroll. Participants overwhelmingly preferred the more discrete method of placing these interactions. Additionally, any selection surfaces, such as carousels of discrete buttons that could be swiped through were clearly marked as specific interactions. The most demanding gesture we provided in examples, that being the home menu selection, was implemented by most participants due to how accessible it was. Although it does not represent any specific action, having the home icon at the base of the palm informed participants that they could actuate it by closing their hands or even just curling a finger into the palm, making the interaction intuitive. Having a dedicated position for a microgesture affords better control without needing to look directly at the control surface, enhancing the use of proprioception and removing a potential added layer of complexity to on-hand display interactions.

G6 *If gestures are to be used, use socially appropriate microgestures.* Because HPUI is meant to be used in multiple different environments, much like a smartphone, it is important to take into account how the user is perceived and the actions they would perform in a public environment. Certain gestures should be avoided for these interfaces, such as large motions that could conflict with crowded environments [10, 21]. The results further corroborate this. None of the participants created any designs that could be considered socially unacceptable except for one. This design is the aforementioned "gun" interface. This design involved making a pistol gesture with the hand and mimicking a shooting motion to select an element. We asked the participant whether they could see this interface being used in a public environment, and they concluded that this design would not be socially acceptable. When asked if they would still implement it, the participant stated that it could still be used in private environments as it was still engaging. For private contexts, interfaces such as those may be entertaining for users, and developers may add such interactions as options.

G7 *The user should have full control over the size and positioning of HPUI displays around the hand.* This guideline was included after analyzing the results of the design sessions. 3 participants explicitly stated they wanted customization in their layouts, in total 4 participants included some form of interaction for repositioning elements. Modularity and customization were discussed often throughout the design sessions. Participants each found which display angles or input positions they found most comfortable, and which ones they would modify to best fit their ergonomics. One participant designed a system for repositioning the over-hand display by using a secondary microgesture joystick on the index finger. Furthermore, some participants created alternate designs that they envisioned to be toggleable for different preferences. Prioritizing fine-tuning for comfort and ergonomics should be paramount in any application, including on HPUI, as an excellent layout for one user may be uncomfortable for another.

6 DISCUSSION

The qualitative and quantitative results collected from the study illustrate the design decisions of the participants. The designs they created were not based on any of the guidelines we established, as they were unaware of them. Yet many of these designs fit within the patterns of these guidelines, both ratifying them and informing us on how these guidelines can be further refined with additional experimentation, which has been discussed in Section 5.

It is worth noting that the input space of HPUI is similar to that of the microgestures. But, the addition of the output space alters how microgestures might be applicable to HPUI. The visual components can act as a guide to gestures which they can learn gradually over time. For example, to use a gesture where the users have to drag their thumb along the index finger, with HPUI we could have a widget on the index finger the user can interact with. This is also direct input similar to the interactions on smartphones. Despite this, as described in Section 3, HPUI cannot be treated the same as smartphones. The guidelines we propose are intended to address this gap.

The above is also a reason for using a design study (Section 4), which is more exploitative than an approach like elicitation studies [51]. In future work, we would have to further evaluate and validate our results with more qualitative approaches to better understand and utilize this design space.

6.1 Applications

With these guidelines defined in Section 5, we can evaluate application layouts more effectively. If we were to now return to the layouts for the example designs we generated at the beginning of the study (Figure 1), we can evaluate them and determine which were the best designs for each application.

6.1.1 Media Player Evaluation. Beginning our evaluations with the three main media player layouts, all three layouts adequately fulfill most of our identified guidelines barring the 7th. G7 is not fulfilled for any of these designs because there is no clear way to alter the position and orientation of UI elements to best match user preference. As the guideline was borne of user feedback, it was not taken into account when designing the original examples. The same can be said of the submenu layout, with the addition that this layout may not fulfill G3 with the current implementation of the deformable surfaces on the fingers, as they can deform the song titles in the queue.

6.1.2 Social Media Applications Evaluation. The first two social media examples follow the same guidelines as the main media player layouts. They especially fulfill G5 as the navigation inputs are delineated by widgets. The third layout Breaks guidelines as the text and images of the post all deform in a continuous display, making the caption difficult to read and the image distorted. This also applies to the submenu, as the list of contacts to message is also on a deformable continuous display and their names can be distorted. Apart from that, these designs all fulfill the other guidelines barring G7.

6.1.3 Maps Applications Evaluation. The map layouts all follow most guidelines. Once again, the third layout may violate G5 due to the continuous deformable display, but the ability to zoom in on parts of the map may help offset the distortion of the image and map text. The submenu design also runs into the problem of text deformation, but due to the large text-boxes and short inputs, these deformations are far more legible than those from the social media app. Once again, the lack of customization makes these layouts fail the criteria of G7

6.1.4 Home Applications Evaluation. Two of The home layouts follow all the guidelines, the first and second layouts fulfill G7 by containing a transform button for moving displays open in the home. Furthermore, the third design is an acceptable use of a continuous deformable display because the apps can still be discerned from and selected no matter the degree of distortion in the display.

6.2 Limitations and Future Work

6.2.1 Study Limitations. Our study would have benefited from a larger sample size and a more diverse age range in its participants. Furthermore, many designs provided by the participants were alterations of the examples that they were given. The length of the study was also affected by the limitations of our tracking solution, relegating us to only be able to prime one participant at a time.

6.2.2 Testing functional HPUI. The designs demonstrated to participants in this study were static implementations meant to only give an idea of the layouts and deformation of the interfaces on the hand. The next step would be to test functional applications within HPUI to determine how users interact with them more practically. This could be implemented by leveraging API for the relevant applications within the Unity engine. In the case of the applications utilized in this study, we could use the Spotify API for the media player, the Instagram Graph API to view social media posts, and the OpenStreetMap API to test a functional map interface. They could all be selected via a purpose-built home menu interface in-engine. Testing functional applications will give insight into how the development of HPUI can be standardized with its own rules around functionality to supplement the guidelines generated in this paper.

6.2.3 Heuristic evaluation of HPUI designed around guidelines. To further develop the design guidelines for HPUI, a future usability study will be conducted to perform an A-B comparison of functional HPUI developed with and without the guidelines in mind. Aggregating participant evaluations will inform on the practical effectiveness of the developed guidelines and will ratify them into a set of concrete rules.

7 CONCLUSION

The design landscape for mixed reality interfaces is still mostly unexplored. HPUI can broaden the horizons of this space by laying the groundwork for novel interactions without handheld controllers. Previous works determined the feasibility and technology behind putting interaction spaces on and around the hand but did not examine how designers would approach them. The findings in this paper not only provide a look into how designers approach this novel interaction space but also present a blueprint for HPUI development design guidelines that can be iterated upon for further implementation. These results will be used to inform new empirical investigations in the HPUI design space, evolving and verifying how HPUI can be best implemented for all contexts.

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A COMPONENT DISPLAYS

The following figures are the charts we showed participants while they were designing their interfaces. They were not limited strictly to using these components, but they had to include their functionality.

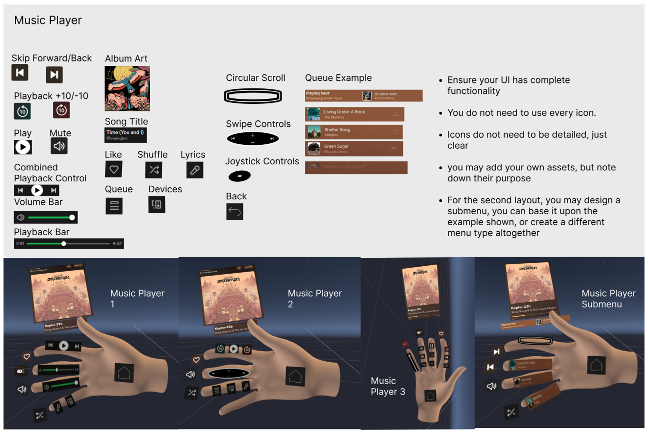

Figure 9: Chart showed to participants when they were developing the media player application and its submenu.

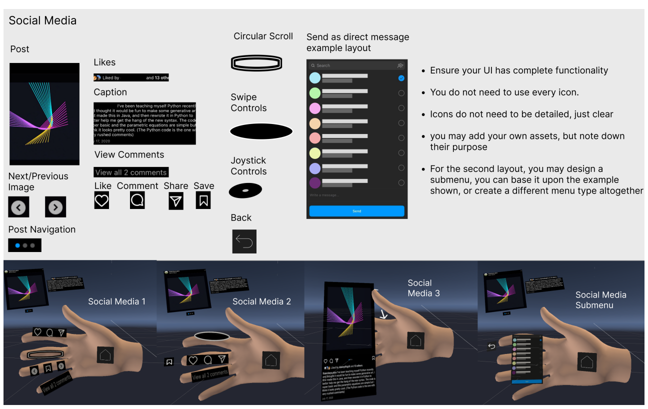

Figure 10: Chart showed to participants when they were developing the social media application and its submenu.

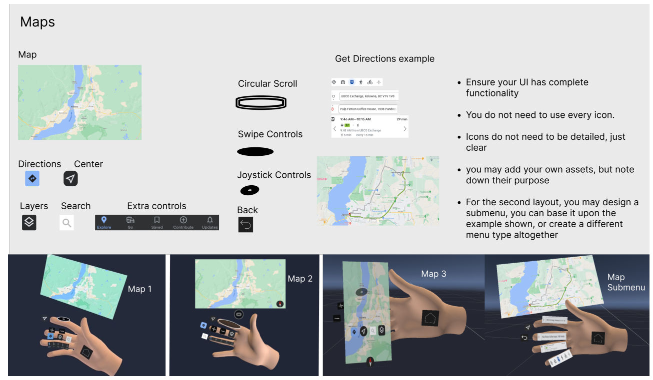

Figure 11: Chart showed to participants when they were developing the map application and its submenu.

Figure 12: Chart showed to participants when they were developing the home menu application and its submenu.