Understanding Gesture and Microgesture Inputs for Augmented Reality Maps

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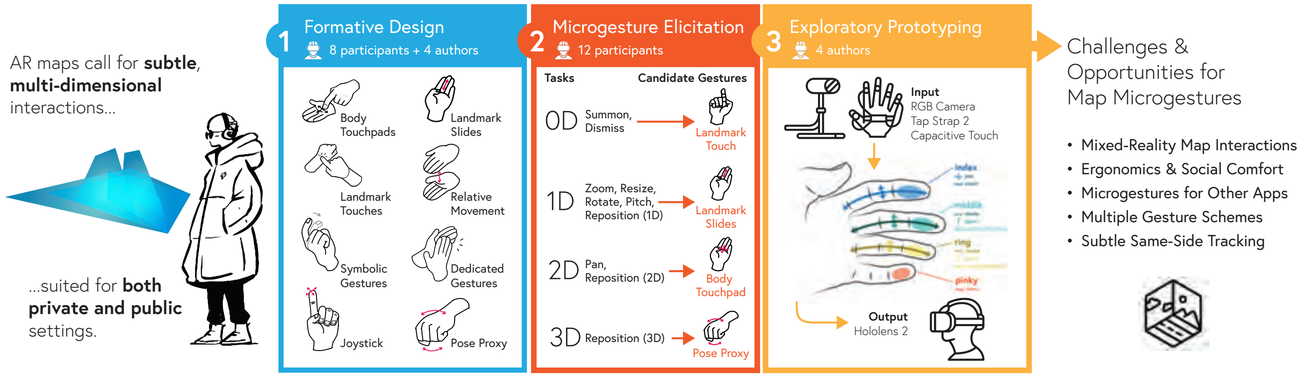

Figure 1: Via (1) a formative design exercise, (2) a microgesture elicitation study, and (3) a prototype design exploration, we examine the potential for subtle microgesture control of AR maps — highlighting challenges and opportunities for future work.

ABSTRACT

We explore the potential for subtle on-hand gesture and microgesture interactions for map navigation with augmented reality (AR) devices. We describe a design exercise and follow-up elicitation study in which we identified on-hand gestures for cartographic interaction primitives. Microgestures and on-hand interactions are a promising space for AR map navigation as they offers always-available, tactile, and memorable spaces for interaction. Our findings show a clear set of microgesture interaction patterns that are well suited for supporting map navigation and manipulation. In particular, we highlight how the properties of various microgestures align with particular cartographic interaction tasks. We also describe our experience creating an exploratory proof-of-concept AR map prototype which helped us identify new opportunities and practical challenges for microgesture control. Finally, we discuss how future AR map systems could benefit from on-hand and microgesture input schemes.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in interaction design**; *Systems and tools for interaction design*; **User studies**; **Gestural input**; **Mixed / augmented reality**; • **Applied computing** → *Cartography*.

KEYWORDS

augmented reality, on-hand interaction, maps, microgestures, design, elicitation

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1 INTRODUCTION

The human body and skin have the potential to support diverse interactive applications. These include the design of on-body interactions and gestures for improving accessibility [53], for physiotherapy learning using body-based projections [22], increasing immersion in virtual reality (VR) using self re-targeted haptics [21], and microgesture input with busy hands [70]. However, these approaches have yet to be explored for map interactions in AR.

Map navigation and interaction in AR settings has received widespread attention as AR has become widely accessible through mobile devices and commercial head-worn displays. Early work by Westhead et al. [86] introduced the benefits of using 3D maps and models and argued that the primary benefit of 3D maps is the ease with which 3D spatial information can be interpreted by a lay user — adding a 'z' dimension allows for significantly easier perception of depth and height. This extra dimension also allows for maps that represent more than just the upper surface of an area, potentially showing the underground geology or inner building topology. More recent work by Dickmann et al. [18] provides a practical introductory primer for cartographers on future applications of AR for cartography.

Researchers have applied AR maps in a variety of use cases. For instance, Höllerer et al. [36] explored how AR maps and models can be used to better understand complex interior 3D spaces quickly, Gazcón et al. [25] examined how AR maps and overlays can support geology fieldwork, Veas et al. [79] investigated how AR maps can better support site understanding in large outdoor spaces, and Ghaemi et al. [27] explored how situated links can directly connect immersive maps to their environment. Work in the HCI community has explored superimposing AR maps onto physical replicas of geographical areas [52, 69]. Other recent work has focused on improving digital map navigation in AR with mid-air hand gestures, using a horizontal intangible map display [68].

However, these state-of-the art map navigation techniques each have key shortcomings. First, annotating points of interest (POIs) in real space can only allow for egocentric exploration [2]. Second, while using physical models can allow for richer interactions, they require the user to carry the physical replicas, restricting mobile interactions. Third, mid-air gestures, while enabling mobile interactions on AR maps, do not deliver haptic feedback, can be socially unacceptable [77] and can cause fatigue when used for extended durations [9, 31, 33].

To address these limitations, we conducted a set of design explorations that examine opportunities for gesture and microgesture interactions with AR maps. Using the human body for interaction has several benefits: (a) skin provides always-available real estate for interaction [30, 75], (b) our inherent proprioceptive capabilities can be leveraged to enable eyes-free interaction [5, 6], (c) interaction on the skin also provides tactile feedback without the need for additional hardware for rendering haptics, increasing immersion in mixed reality environments [21], (d) human skin supports a wide range of tactile input modalities that is absent in commercial AR/VR controllers and mobile devices [84], and (e) body landmarks (such as flexure lines and birthmarks) offer natural visual and tactile cues that can be leveraged for interaction [5, 85].

While prior elicitation studies have investigated single-handed microgestures [10, 13, 71, 84], they have mostly focused on the kinds of discrete, abstract actions associated with music player controls (volume up/down, mute, pause/rewind/next track), menu navigation (open/close menu, select), or file manipulation (select/deselect, delete, open). While these studies have helped identify generalizable microgestures that can span diverse applications, they have tended to focus on discrete symbolic gestures, and it is unclear how their gesture sets might translate to application scenarios like interacting with 3D maps — which often involve multiple continuous and highly-integrated spatial interactions (panning, zooming, repositioning, etc.). In contrast, we hypothesize that more continuous, multidimensional, and integrated gesture sets that leverage proprioception and on-body touch might be better suited to maps, as well as a wide variety of other situated and spatial applications.

Our work examines the design of gesture and microgesture interactions through the lens of map navigation on AR devices. First, we describe a design exercise in which we explored different on-body interactions. Results from this exercise helped us identify single-handed and bi-manual gestural interaction techniques that work well for maps. Building on these results, we transitioned from body-based interactions to microgesture interactions and conducted an elicitation study to identify viable sets of single-handed microgestures for interacting with maps. Combining these exercises, we find a clear set of on-hand interaction patterns that are well-suited for supporting map navigation and manipulation tasks on AR devices. To further examine the practicality and limits of these microgesture interactions for AR maps, we conducted a prototype design exploration in which we created a set of working prototypes that combine camera- and motion-based sensing to support a range of possible inputs. These prototypes helped us understand the practical constraints of the designs suggested in our prior explorations and inform our final discussion. Finally, we discuss challenges for implementing these kinds of interactions as well as opportunities for their future use across a wider range of applications.

2 RELATED WORK

While our work is among the first to consider on-hand interactions for AR map control, it builds upon on related work in on-body interactions and the design of AR map systems. In addition, we draw methodology and language from earlier work describing the design space of input devices.

2.1 On-Body Interaction

The human body provides a large real estate for interaction and the HCI community has explored the use of the body as an interaction medium [30, 37]. Understanding on-body interaction is an active research topic in HCI. Several empirical studies [31, 81] focused on the body-centric interaction space have identified user strategies for creating on-body gestures [55] and revealed that on-skin input increases users' sense of agency [6]. Moreover, previous research has investigated mapping strategies for input elements on the skin, such as using salient features on the palm [17, 29, 82], targets placed on the forearm [45], visual and tactile anatomical landmarks [5, 85], as well as mappings between on-skin and off-skin displays [7]. Prior work has also demonstrated that the body's sense of proprioception can be utilized for interaction [14, 75]. More recently, elicitation studies have shown the utility of body-based gestures and microgestures for performing a wide range of interactions [10, 13, 71]. Finally, previous research has also studied the social acceptability of gestural input performed on the body [54, 60], on epidermal interfaces [91] or directly on skin [84], and evaluated appropriate body locations for on-body computing [90–92].

As a subset of on-body interactions, the HCI community has also looked closely at microgestures, which support subtle [23], mobility-friendly [88], and socially-acceptable [62] interactions. Microgestures have been deployed in diverse application contexts such as text-entry [88], athletic activity [8], and for supporting always-available interaction while manipulating everyday objects [70].

While all this prior work has demonstrated that on-body interaction can be a highly promising and viable medium for socially-acceptable interaction in many contexts, we are the first to investigate the design of body-based interaction techniques (and on-hand techniques specifically) for map interaction in AR environments. Map navigation tasks are fundamentally different from the generic application scenarios, like controlling a music player or accepting or rejecting calls, explored in prior work. Interactions with maps typically involve several operations and are tied to the fundamentals of cartography. Compared to having a few controls (like pause/play/forward/rewind) in a music player, interacting with maps requires a larger, easy-to-perform and easy-to-remember gesture set. Given this gap, we consider a dedicated set of proprioceptive body-based interactions designed specifically for map navigation tasks.

2.2 Embodied Interaction with Maps

While work in cartography has broadly focused on potential new applications for AR in map-like contexts, the HCI community has tended to explore new technologies and interactions techniques. For example, touch interactions with three dimensional maps have been explored in virtual reality (VR) environments — with an emphasis on selection techniques like those catalogued by Argelaguet and Andujar [2]. Prior work has also explored a range of tangible and gestural interaction approaches.

2.2.1 *Tangible Interactions.*

A variety of research efforts have used augmented physical artifacts to explore tangible interactions with maps. Illuminating Clay [59] projects landscape models onto a clay landscape that can be manually manipulated. Relief [42], explores the potential benefits of tangibility for understanding landscape data. More recent work superimposed AR content onto physical replicas of geographical regions for various applications such as field trips, reservoir modelling, land navigation, and geography education [34, 43, 52, 56]. These approaches have shown to be highly effective where practical [44]. However, these systems rely on static installations and physical models to create rich tangible experiences. They also suffer from limited portability and are not typically conducive for everyday map use.

2.2.2 *Gestural Interactions.*

The use of gestural interactions has also become increasingly common in a variety of map applications. Rauschert et al. studied hand gestures for pointing, indicating, and outlining areas for a geospatial emergency management system [61]. Follow-on work has coupled mid-air gestures and upper body gestures with maps and virtual globes on 2D screens [1, 49, 65, 74]. Similarly, mid-air hand gestures combined with head gestures have been explored in the context of AR and VR displays [28, 66, 67]. Other researchers have studied hand gestures combined with upper body gestures (like Lee and Sohn’s “flying superman gesture” for navigation in 3D maps) [41]. More recently, Austin et al. [4] and LaViola et al. [40] have discussed how hand and foot gestures can be used to interact with immersive maps, while Newbury et al. explored the use of embodied interaction for immersive maps [50]. Unsurprisingly, various studies have confirmed that navigation of maps with gestures in the air for longer periods is fatiguing for maps viewed on 2D displays [76] and VR headsets [28, 41].

Broadly, most of the prior literature on gestural map interactions has been dominated by mid-air gestures and interactions with physical props, both of which tend to be physically fatiguing and socially uncomfortable (particularly in public spaces). In contrast, on-body gestures and microgestures have the potential to be subtle, less fatiguing, and — because they leverage human proprioception — easier to learn and perform.

3 FORMATIVE DESIGN ACTIVITY

To help establish a baseline understanding of the kinds of on-hand gestures and microgestures users might infer for AR maps, we conducted an initial design activity in which we asked participants to brainstorm new sets of gestures for common map tasks. Designers who took part in the activity included 8 members of our research lab, as well as the four authors (12 total — 4 female, 8 male).

3.1 Map Tasks and On-Body Locations

We chose to focus our exploration around a small set of standard map manipulation tasks common in web-based and mobile mapping applications. These included basic object manipulation operations (*summon*, *dismiss*, *resize*, *rotate*, *pitch* and *reposition*), as well as a set of map-specific operations drawn from Roth’s taxonomy of cartographic interaction primitives [64] (including *pan*, *zoom*, *annotate*, *filter*, *overlay*, *resymbolize*, and *search*).

Immersive AR maps are likely to be used in public and social settings where large-scale gestures and on-body interactions may be physically or socially challenging. With this in mind, we encouraged participants to focus on gestures that used only their hands and forearms, which prior work has suggested are often the most suitable locations for on-body input [5, 20, 84]. We asked participants to imagine both *same-side* interactions (using only one hand) and *opposite-side* interactions (in which one hand could touch or interact with the opposite hand/arm). We also asked participants to limit any touches to either the forearm (which provides a large area for interaction and has been used extensively in prior work) or the hand itself (which provides rich tactile landmarks such as knuckles, flexure lines, and veins [51] and also allows for single-handed interaction through microgestures [5, 29, 71]).

3.2 Procedure

To help participants more clearly envision the target map manipulation tasks, we developed a custom map application for the Microsoft HoloLens using Unity with the Mapbox API, and used it to

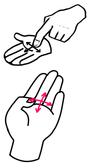
Figure 2: An example screenshot of the video demonstrations for each task (here showing a "rotate" interaction).

record short demo videos (Figure 2) demonstrating each of the map manipulation and interaction tasks. Each video showed a virtual map roughly 50cm across, positioned 80cm in front of the viewer and illustrated a change in the map's spatial location or content, but included no indication of the interaction that triggered it. To help combat legacy bias [48] (and in line with prior work [71]) we also presented participants' with sketches of various gestural interaction techniques proposed in prior research [29, 84, 85]. These sketches help participants consider a wide range of possible interactions types by "prompt[ing] users to think more generally about what gestures could be used to accomplish a given task, as well as correct[ing] any misconceptions about the capabilities of new technologies" [48].

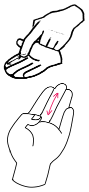
During the activity, each designer viewed the short videos in sequence and used a think-aloud procedure to ideate and propose both same-side and opposite-side gestures for each, drawing either from the existing gesture sets or proposing new ones. We also collected designers' reflections about the ease, comfort, and social appropriateness of each gesture. In addition, designers provided Likert scale rankings (ranging from *very uncomfortable* to *very comfortable*) indicating how comfortable they might be using the gestures in various social settings (*at home*, *in public*, *in an elevator*, or *on a train*). We had alternating designers start with either all same-side gestures, or all opposite gestures, then rewatch the videos and ideate gestures for the other condition. A member of the research team observed and took notes during each session, and also video-recorded the activity for further analysis. Individual designers typically took 45-90 minutes to complete the activity.

3.3 Interaction Paradigms

Throughout the design activity we observed a set of recurring interaction patterns. To evaluate these, the first two authors manually coded the entire set of proposed gestures in a style similar to Card et al.'s morphological analysis [11] — identifying both the body part(s) used and interaction type(s). If the two coders disagreed on a coding we had a third author code the proposed gesture. The resulting set of interactions highlight a variety of different possible approaches to map manipulation, each with their own ergonomic, social, and sensing trade-offs.



Body Touchpads (total 39 — 30 opposite-side, 9 same-side) This approach uses a part of the body as a 2D interaction surface, similar to a computer touchpad. This was the most commonly-used gesture, likely owing to designers' prior experience with touch screens and pads. Participants used it extensively in the opposite-side condition, moving a finger on their dominant hand over a section of their opposite arm or hand. In this context it was used primarily for panning, zooming, rotating, and resizing — generally with the same gestures one would use to control a map on their phone screen — and designers used different numbers of fingers to disambiguate the various actions. In the same-side condition designers would generally use the inside of their fingers as a touch surface and perform the gestures with their thumb. In this context it was primarily used for panning, again like a phone screen. In the same-side condition designers would often perform a dedicated or symbolic gesture to "activate" the touch pad before using it.

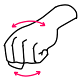


Landmark Slides (total 33 — opposite-side 16, same-side 17). This approach slides a finger or hand along the length of a body landmark [75] or between two body landmarks. This was the second most commonly used gesture. In both conditions participants used these as slider controls for the map. In the opposite-side condition participants used slides to pitch, reposition, resize, rotate, and zoom. We also saw slides used to summon or dismiss the map by sliding towards or away from the viewer. In the same-side condition we saw slides used for resizing, rotating, pitching, panning, and zooming, with the direction of the slide determining the direction of rotation/pan/scaling. In the same-side condition a landmark slide was often proceeded by a touch on a specific spot on the hand to activate the slider.

Symbolic Gestures (total 27 — opposite-side 12, same-side 16) These interactions relied on gestures that symbolically represent the action. In the opposite-side condition designers used this exclusively to summon and dismiss the map — most commonly with an open book/close book gesture similar to that described by Bostan et al. [10]. In the same-side condition, participants also primarily used symbolic gestures to summon and dismiss the map (most often with "beckon" or "shoo" gestures). However, several designers also used symbolic gestures to reposition and resize the map to preset locations or scales.

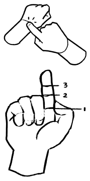
Dedicated Gestures (total 18 — opposite-side 3, same-side 15) These interactions used distinct gestures with no symbolic connection to the task. Unlike symbolic gestures, participants mostly reported choosing them for ease of use or convenience. In both the opposite-side and same-side conditions, participants used these primarily to summon, dismiss, and reposition the map. Example gestures included bloom gestures or single-handed finger snaps to summon/ dismiss the map and two-handed claps to recenter the map. In the same-side condition, we also saw some participants create dedicated gestures to pitch, resize, reposition, and search — however there was very little overlap between different participants' gesture sets.

Pose Proxy (total 17 — opposite-side 8, same-side 9)



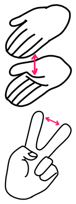
This approach involved manipulating the map by miming its movement using a hand or finger. This was most commonly performed as a quasi mode, whereby the designer would make a particular gesture with their hand, and while holding that gesture any hand movement would be translated 1 to 1 to the map. For instance, by pitching their wrist forwards the map would pitch at the same angle. In both conditions this pattern was used exclusively for pitch and rotate actions.

Landmark Touches (total 15 — opposite-side 10, same-side 5)



These interactions used distinct areas of the body as virtual buttons — a technique explored in detail in prior work by Steimle et al. [75]. In the opposite-side condition designers most commonly performed this by touching a body landmark (such as their wrist or elbow) on their non-dominant arm with their dominant hand. In the same-side condition designers most commonly performed this by touching a body landmark (fingertips, finger joints) on their hand with their thumb. In both conditions this pattern was most commonly used to summon or dismiss the map. However, by using several landmarks it was also used to resize and zoom the map — for instance, resizing the map to preset sizes for each finger joint. Landmark touches were also frequently used in combination with other gestures (total 11 — opposite-side 3, same-side 8), often to activate another mode of interaction (9 times). We also saw a few participants use landmark touches to reposition the map, performing a symbolic gesture to initiate a reposition, then using a landmark touch to specify the new placement.

Relative Expansion and Relative Movement



(total 9 — opposite-side 6, same-side 3) These interactions used the movement of two body parts relative to one another. In relative expansion two body parts are moved towards or away from each other — in relative movement one body part is moved in reference to another. For instance, moving one palm towards the other static palm is relative movement. Moving two fingers apart in a "open scissors" gesture or moving a finger and thumb apart is relative expansion. Both of these gestures were used primarily for rotation, resizing, and zooming. In the opposite-side condition the most common gesture was moving one's palms towards or away from each other to specify size, either for zooming or resizing. Another particularly interesting opposite-side example used rotating one hand around another like winding a winch to rotate the map. In the same-side condition the most common gestures were expanding and contracting thumb-to-forefinger pinches.

Joystick (total 4 — opposite-side 2, same-side 2)
This approach involved using either a hand or finger as a virtual joystick. This was an uncommon, but distinct pattern and was performed the same in both opposite-side and same-side conditions. It was performed by pointing either a finger, or the entire hand, straight up, a form of quasi mode, and pointing in the direction of interest. It was most commonly used to pan the map. Pose Proxy and Joystick present on body examples of position based and rate based gestures like those described by Satriadi et al. [68].

3.3.1 Other Interaction Approaches. While designers had little trouble proposing a variety of gestural approaches for basic object- and map-manipulation tasks like zooming, rotating, and summoning the map, they struggled to identify good candidates for more abstract cartographic operations like annotate, search, or resymbolize. For these, almost all designers who completed the activity imagined using an on-body gesture to open a menu or search bar to perform the task in a way that did not rely on gestures, then returning to more gestural approaches to interact with the map.

Although not captured in their final suggestions, designers also mentioned the potential for more imaginative interaction schemes, including interactions based on shadow puppetry, that used hands as game controllers, and relied on skin deformation or stretching. This suggests that while the set we identify represents a useful baseline set of patterns for the design of on-body map schemes, they are not exhaustive.

In addition, we noticed that many of the simple gestures our designers chose are similar to those documented in previous microgesture elicitation research. For instance, using a landmark slide to zoom the map is semantically similar to the swipe gesture identified by Chan et al. [13] for controlling the volume of a media player. However, gestures such as Joystick or Pose Proxy, chosen to perform 3D manipulation tasks, highlight how map systems require a broader set of interaction gestures than many previously studied systems. We discuss some of these details in section 4.5 with additional context from our formal elicitation study.

3.4 Social Comfort

Inspired by prior work [35] we asked designers to rank how comfortable they would be using these gestures in various public spaces on a 5-point Likert scale where 1 indicated "would not use" and 5 indicated "very comfortable using". When asked how comfortable they would be using the gestures in various public spaces (Figure 3) designers reported moderate comfort across all conditions (Mean=3.9), but also rated the same-side gestures (Mean=4.3) as more socially comfortable then the opposite-side gestures (Mean=3.5). In addition, they noted almost no concern whatsoever using any of the gestures in a private spaces (Mean=5.0, same-side=5.0, opposite-side=4.9).

Designers noted that the primary factor influencing how comfortable they would be using each gesture was based on how large or obvious the gesture was — with opposite-side gestures generally being more conspicuous than same-side ones. This disparity increased when designers considered public spaces such as elevators and trains which might be crowded or where gestures might be socially awkward. These findings are consistent with prior work by Hsieh et al. [35], although we note that they are likely culture-dependant [60]. Because this design activity was performed within a western university with human-computer interactions designers and researchers who are comfortable with new technology, these comfort levels are likely higher than one might see in other real-world contexts.

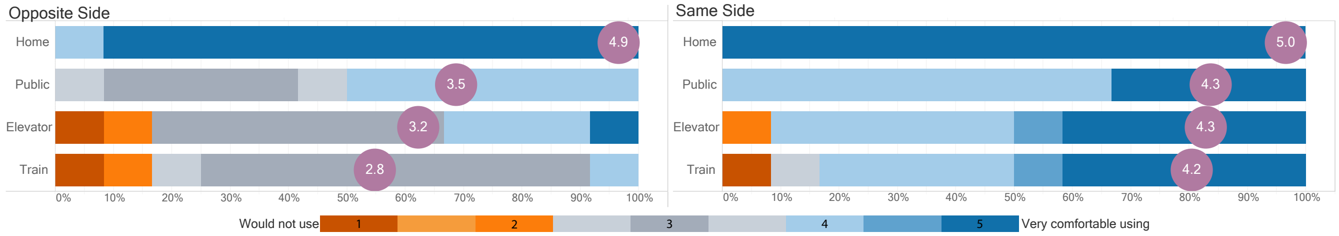


Figure 3: Designers' social comfort ratings for their opposite-side gestures (left) and same-side gestures (right) in various social settings. Circles show mean comfort scores across all participants.

However, while designers rated same-side gestures as more socially comfortable, they also consistently observed that they were more challenging to design. This stemmed in part from uncertainty about how to construct internally-consistent gesture sets, as well as concerns that some one-handed gestures might be too small to perform reliably or to track using current sensing systems. Designers also expressed concern that they might inadvertently create gestures that could be misinterpreted as inappropriate or rude expressions in sign languages. This strong preference for subtle one-handed gestures that could work well in public settings with less risk of misinterpretation motivated the next two phases of our research — in which we focused on systematically eliciting and prototyping new sets of same-side microgestures for AR map tasks.

4 MICROGESTURE ELICITATION

Given the positive reception to same-side gestures in our design activity and the designers' enthusiasm for subtle interactions compatible with public use (Figure 3) we decided to perform a more narrow elicitation study to identify viable sets of same-side microgestures. Unlike the earlier design activity, we structured this experiment as a formal elicitation study and focused specifically on identifying gestures for a narrower set of everyday map manipulation tasks.

4.1 Procedure

We recruited 12 total participants (5 female, 7 male) through a combination of internal mailing lists and word of mouth. We asked participants to perform many of the same tasks as the designers in the design activity. However, we removed the annotate, filter, overlay, resymbolize, and search tasks as designers found them to be better solved by techniques other than gestures — such as gaze tracking, or menus. The final list of tasks was: *summon*, *dismiss*, *resize*, *rotate*, *pitch*, *pan*, *zoom*, and *reposition*. Prior to the elicitation we showed participants demo videos of an AR map running on a HoloLens. We then showed participants a short 10s video of each map interaction before asking for a gesture to perform it. We kept each video looping in the background as the participants performed and discussed their gestures.

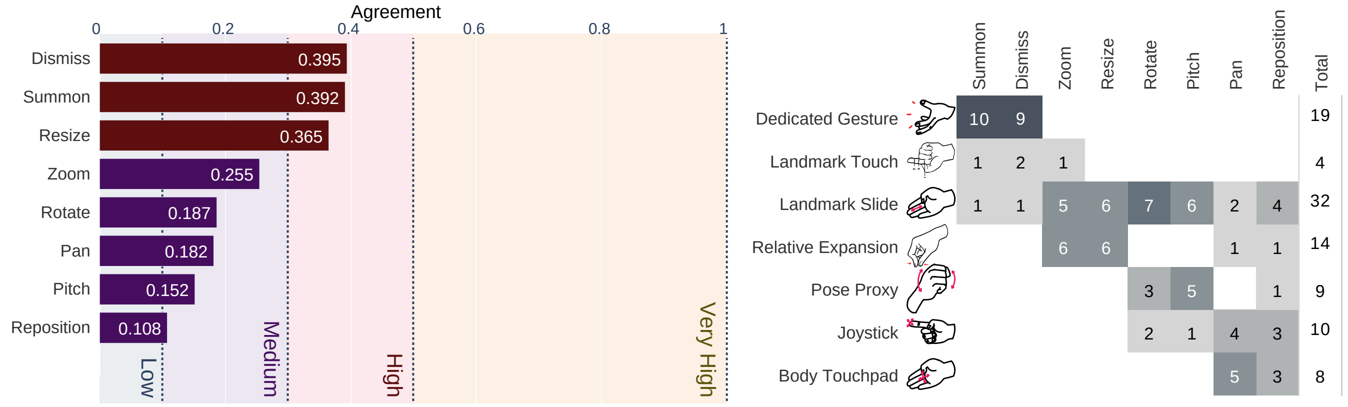
During each gesture elicitation we asked for a gesture, as well as Likert scale ratings for how good the participant felt that gesture was at solving the problem, and how comfortable they would be using that gesture in public. If either the goodness or social comfort score was rated as a 2 or lower on a 5 point Likert scale then we revisited the gesture with the participant after completing the entire set and prompted them to try to develop and rate a replacement. Consequently a gesture will only have a score of 2 or lower in our analysis if the second iteration also rated poorly.

Finally, after completing all elicitation tasks, we asked participants about their overall social comfort with the gesture set, and which tasks they thought were best- and worst-suited to microgestures. We also collected more general reflections about microgestures for map use. This entire process was video recorded over Zoom and a transcript was automatically generated based on the video. The study took between 20 to 30 minutes to complete. This study was approved by our institution's research ethics board.

4.2 Coding and Analysis

We coded gestures in several ways. First, the researcher administering the study recorded plain English descriptions of gestures as participants performed them. That researcher then coded each gesture as a glyph using Chaffangeon Caillet's et al.'s μGlyph notation [12], documenting the actuator, referent, movement, and context components of the gesture used by the participant. Finally, we categorized each gesture using the interaction paradigm classes from our earlier design activity (Section 3.3). If a gesture had an activation gesture (such as tapping a finger to activate zoom mode) we only analyzed the gesture used for the task (in this case, the zoom) — however, the complete interactions are recorded in our supplementary material.

Drawing from every μGlyph component we observed during the study, Author 1 manually coded how similar each μGlyph component was to those generated by other participants for the same task. For instance, Participant 12 performed pitch by sliding their thumb along their finger tips, which has a μGlyph of t↔••(i,r,m,p•t) and Participant 10 performed pitch by sliding their thumb along the front side of their fingers which has a μGlyph of t↔••(i,m,r,p•f). These had the same actuator component (t [thumb]), movement component (↔ [slide along]), and context component (•• [start and end in contact with receiver]) so each of those component pairs was coded as "identical". Because these two gestures had slightly different receivers (i,r,m,p•t [the tips of the index, ring, middle, and pinky fingers]) and (i,m,r,p•f [the front of the index, ring, middle, and pinky fingers]), in the code book we marked this pair of receiver components as "closely related" because their role in the gesture was very similar (a surface that was slid along). We considered gestures to be in agreement if every component was closely related or identical within the glyph. A Google Colab notebook containing the full analysis is available in our supplementary material.



	Summon	Dismiss	Zoom	Resize	Rotate	Pitch	Pan	Reposition	Total
Dedicated Gesture	10	9							19
Landmark Touch	1	2	1						4
Landmark Slide	1	1	5	6	7	6	2	4	32
Relative Expansion			6	6			1	1	14
Pose Proxy					3	5		1	9
Joystick					2	1	4	3	10
Body Touchpad							5	3	8

Figure 4: (Left) Microgesture agreement rates between participants for each task. Dotted lines show agreement thresholds [78]. Conditions below 0.1 show low agreement, between 0.1 and 0.3 show medium agreement, between 0.3 and 0.5 show high agreement, and above 0.5 show very high agreement. (Right) Participant microgesture paradigms by task.

4.3 Agreement and Grouping

We calculated gesture agreement based on recommendations by Vatavu and Wobbrock [78], using bootstrapped ARe with agreement thresholds based on their recommendations. (An agreement score greater than 0.5 shows very high agreement, greater then 0.3 shows high agreement and greater than 0.1 shows low agreement.) The overall agreement score was 0.25 across all the tasks, which can be qualified as medium agreement. This range of agreement is comparable to the previous work involving hands as primary input [13, 71, 84].

We saw high agreement for summon, dismiss, and resize; medium agreement in pan, zoom, pitch and rotate; and medium-low agreement for reposition (Figure 4 left). When considering individual μGlyph components we saw very high agreement for most tasks with some components showing total agreement within a task. For instance, every resize gesture was actuated with the thumb.

4.3.1 High Agreement Gestures. We observed high agreement for summon, dismiss, and resize tasks. Of those tasks, both summon and dismiss were performed almost exclusively using a **dedicated gesture**, a blooming gesture for summon, and a closing fist gesture for dismiss. Resize had 2 dominant strategies. The first strategy was **relative expansion** where participant would perform a pinching gesture between the thumb and a finger or fingers. The second strategy used was a **landmark slide** which participants performed by sliding their thumb along the length of a finger.

4.3.2 Medium Agreement Gestures. We observed medium agreement for pan, zoom, pitch and rotate tasks. For pan, zoom, and pitch each we noted 2 dominant strategies, along with several unrelated strategies or gestures only used once. For pan tasks, the common strategies were **body touchpad** where the participant used the surface of hand or fingers as a touch pad and **joystick** where the participant treated either their finger, or entire hand, as the arm of a joystick. Zoom was performed very similarly to resize, with the two main strategies being **relative expansion** and **landmark slide**. However, while participants performed resize almost exclusively with those two, we saw a number of one-off strategies for zooming. For example, one participant used a **landmark touch** strategy by tapping the tips of 2 fingers as zoom in and zoom out buttons. Pitch was mostly performed using **pose proxy** or **landmark slide.** For pose proxy, The participant would start the gesture by entering a specific pose and then pivot either their wrist or fingers proportionally to how much they wanted to pitch the map. For landmark slide, the participant would use a part of their hand (such as a finger) as a slider to set the map's pitch. We observed 3 strategies used for rotate, **pose proxy**, **landmark slide**, and **joystick**. Pose proxy and landmark slide where used in much the same way as for pitch. However, rotation also saw a joystick strategy where the participant would spin a finger in the air. This is similar to a pose proxy, however a single rotation of a finger corresponded to much less than one rotation of the map.

4.3.3 Low Agreement Gestures. Finally, we saw low agreement on the reposition task. Participants noted difficulty creating an appropriate gesture for reposition and tried a wide variety of strategies including **landmark slide, relative movement/expansion, pose proxy, and joystick**. However, there was little consistency even between participants who chose the same strategy.

4.4 Social Comfort

As in our earlier design activity, we asked participants how comfortable they would be with using these on-body interactions in various public spaces. Overall participants rated their comfort with using their gestures sets as high in public spaces (Figure 5 bottom right). This matches our prior results, where same-side or microgestures were seen as generally socially acceptable and comfortable. However, when asked about comfort in spaces with restrictive social norms, such as on the elevator or the train, some participants noted that they would be less comfortable. In particular, the participant that rated their gesture set as a 1 in an elevator with strangers said that given the short time spent in an elevator they would rather wait until they got off. These ratings of comfort are lower then we observed in our design activity, likely owing to the more diverse

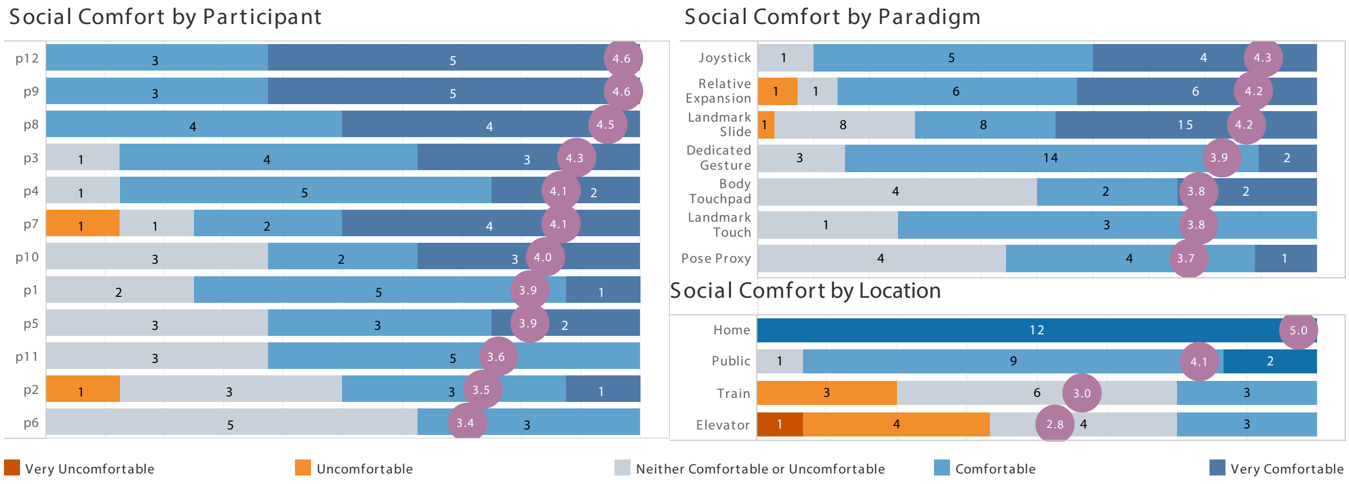


Figure 5: Participants' social comfort ratings. All ratings used a 5-point Likert scale. Circles show mean comfort scores across all participants. (Left) Social comfort distributions for each participant. (Top Right) Social comfort totals for each task paradigm across all participants. (Bottom Right) Participants' social comfort scores for their final gesture sets in various social settings.

set of participants — comfort with new technology is unsurprisingly higher amongst members of a HCI lab than the general public. However, P11 noted "I also think that the kind of public comfort with all of this will shift over time as culture around microgestures shifts, and if it becomes more usual" and P9 commented "As more people get used to it, I think it'll be normal to use in public and not awkward." suggesting that, if adopted, these types of on-body interactions will become more acceptable over time.

Overall comfort with each gesture varied considerably between participants (Figure 5) however, participants were very rarely uncomfortable with the idea of using any particular gesture in public. Where participants commented on social comfort it was normally about concerns that their gesture may be interpreted by others incorrectly, such as misinterpreting it as sign language (and therefore showing a false desire to communicate). In addition, several participants reworked gestures that they decided could be misconstrued as either pointing or culturally rude.

4.5 Consensus Gestures and Task Dimensions

Overall, participants struggled more with multi-dimensional inputs than with low-dimensional ones. Reposition was generally considered the most difficult task — requiring participants to simultaneously vary 3 spatial dimensions (x,y,z). This suggests it may be better suited to an in-air gesture instead of a microgesture. Participants likewise noted difficulty creating a pan gesture, which required controlling 2 dimensions. However, shared experience with laptop touch pads and multitouch gestures for mobile devices helped inform many participants' final gestures. Participants were split on which task was easiest with microgestures, with 5 choosing summon/dismiss and 4 choosing zoom. Those that chose summon and dismiss noted that the task itself was very simple and easy to create a good gesture for — with those who chose zoom noting that it was familiar from touch devices and that it involved a simple linear scale.

In keeping with those findings, we noticed a clear trend in the number of dimensions of the task and gestures participants selected for them (Figure 4 right). Furthermore, participants consistently reported that tasks where they needed to control several dimensions simultaneous were harder to design gestures for. Most participants assigned simple 0D tasks like summon and dismiss dedicated gestures (or, more rarely, a landmark touch). Participants generally considered zoom, resize, rotate, and pitch to be 1D tasks and used landmark slides, relative expansion, or pose proxy. Pan is a 2D task and was frequently solved with body touchpad, joystick, or 2 combined landmark slides (1 for each dimension). Although repositioning is a 3D task, many participants found it difficult to compose microgestures for simultaneously varying three dimensions and instead treated it as either a 1D or 2D task (typically by ignoring distance from the viewer while repositioning) or would combine multiple simpler gestures together to solve it (such as using 3 distinct landmark slides to reposition the map in x, y, and z). Further, two participants suggested using a microgesture from a second hand to help control the 3D tasks: P3 suggested that they could "use [their] second hand to control the y-axis" and P8 commented "I wish I had a second hand, when I was doing all this" during the reposition task.

5 PROTOTYPE DESIGN EXPLORATION

Gesture elicitation studies in HCI typically involve designing a consensus gesture set and then providing a set of design guidelines [10, 13, 71, 84]. In this work, we added an additional design exploration step in which we developed prototypes that examined the implications for real-world deployment of these gestures. Implementing microgesture recognition presents several technical challenges including: (1) handling **occlusion** when hands and fingers can hide one another while gestures are being performed; (2) supporting **precise tracking** of fine-grained movements; and (3) detecting inputs irrespective of hand and body **orientation**. Our

Dimensions	Task	Potential Gestures
0D	summon, dismiss	dedicated gesture, **landmark touch**
1D	zoom, resize, rotate, pitch, reposition (1D)	**landmark slide**, relative expansion, pose proxy
2D	pan, reposition (2D)	**body touchpad**, joystick
3D	reposition (3D)	**pose proxy***

Table 1: Candidate gestures for each task based on participant agreement, ordered by the number of dimensions varied in the task. Bolded gestures are those we used in our exploratory prototype. *There was no consensus gesture for 3D repositioning.

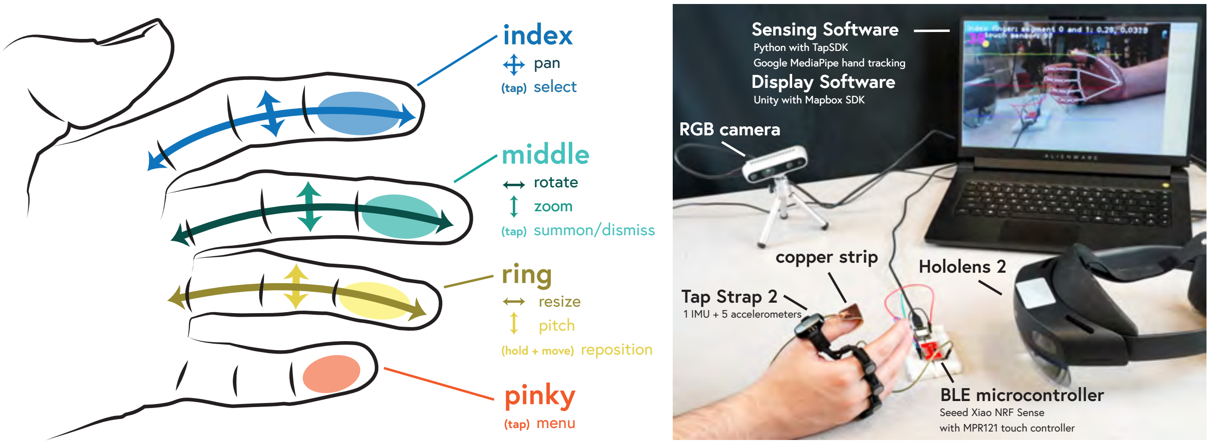


Figure 6: The gesture set (left) and hardware setup (right) for our proof-of-concept prototype.

goal was to better characterize the challenges and limitations associated with implementing a functional version of these kinds of microgesture using current hardware and software approaches. Our proof-of-concept acted as a prompt for further critical reflection on our elicitation findings and motivated much of our discussion in section 6.

The results from our elicitation study highlight that some specific microgesture types — and thumb-to-finger **landmark slides** in particular — appear to be well suited to a wide range of different map interactions, while remaining quite subtle. With this in mind, we developed a proof-of-concept prototype (Figure 6) that implements a unified single-handed microgesture set built around slides and taps. We believe that this early technical exploration will inspire future work that focuses on the technical implementation of microgestures for AR.

5.1 Hardware and Software

For microgesture recognition, we developed a hybrid sensing scheme that incorporates multiple sensing technologies including optical hand tracking[1] running at 40fps via an RGB camera, a finger-worn IMU wearable that contains a thumb-mounted IMU and accelerometers on each of the fingers (Tap Strap[2]), and a capacitive touch sensor (implemented using a copper sticker on the thumb and interfaced with a MPR121 touch controller connected with a BLE microcontroller[3]). Individually, each of these sensing schemes has inherent trade-offs. Optical tracking can provide precise finger movement information [73], but it cannot detect subtle touch-up and touch-down events that correspond to taps or the beginning and end of slides [83]. In contrast, a finger-worn IMU strap can sense distinct taps, but cannot recognize where the tap has occurred (for example, middle finger vs. thumb). Capacitive touch sensors, meanwhile, are unable to detect motion but can provide precise touch events.

5.1.1 *Gesture Detection.*

To implement our gestural interaction techniques, we needed to reliably detect taps and directional events on all the fingers. We characterize taps by spikes in the accelerometer values reported by the Tap Strap. Due to finger individuation [39], there is a possibility of neighbouring fingers performing accidental taps. To avoid this, we use the hand tracker data as an additional filtering mechanism to recognize a tap event for the finger closest to the thumb. For continuous gestural interaction techniques (like panning), we use finger motion and intersection data from the hand tracker and touch information from the capacitive sensor integrated via a state machine. Slide onsets are triggered when the touch sensor in the thumb makes contact with a finger. The hand tracker then determines which finger the slide occurs on. Finally, the angular velocities reported by the IMU are scaled appropriately and reported as a slide value with x- and y-dimensions aligned to the target finger. This gesture detection engine runs in Python then triggers the interaction events in an AR map application built with the Mapbox and HoloLens SDKs.

5.1.2 *Gesture Set.*

Because the results from our design activity and elicitation study highlight the generalizability of landmark slides across tasks, our proof-of-concept gesture set (Table 1, Figure 6) uses

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[1] https://google.github.io/mediapipe/solutions/hands.html
[2] https://www.tapwithus.com/
[3] https://www.seeedstudio.com/Seeed-XIAO-BLE-Sense-nRF52840-p-5253.html

them for most actions. Taps, meanwhile provide simple lightweight interactions for 0D tasks like triggering menus (pinky), summoning or dismissing the map (middle finger), or making selections (index finger). We use finger slides for all 1D interactions, including rotating (middle finger-along), zooming (middle finger-across), resizing (ring finger-along), and pitching (ring finger-across) the map. We assign these gestures to fingers based on their relative frequency of use, with less frequent gestures assigned to harder-to-reach digits. We also assigned slide orientations to keep interactions aligned intuitively with the map, with zoom and pitch corresponding to vertical slides and rotate corresponding to horizontal ones in most common hand orientations. For 2D pan interactions, we treat the index finger as a body touchpad by tracking movement across and along the finger simultaneously. This combination of slides and taps takes cues from the one-handed microgestures described by Dewitz et al. [16] and the hand-proximate user interfaces described by Perella-Holfeld et al. [58]. In particular, our mapping assigns the most common interactions to more ergonomic gestures [58] and prioritizes fingertips over more difficult one-handed gestures involving the lower fingers and areas towards the palm [16].

Since these slides and taps can be executed with the hand in diverse orientations (including on the user's lap or at their side) they can be extremely subtle and are unlikely to be misinterpreted as socially awkward gestures. Considering this, we also opted to use subtle landmark taps to summon and dismiss the maps, rather than the more dramatic bloom and close gestures suggested by our participants. Our scheme relies on larger hand motions only for repositioning the entire map in 3D relative to the user, which users accomplish by holding their thumb to the tip of their ring finger and then moving the entire hand in 3D space (using accelerometers to track 3D changes in hand position). While our prototype monitors for interactions continuously, real-world implementations would likely need to include toggles or other mode switches to prevent accidental interactions with the map while performing other tasks.

5.2 Initial Experiences

We developed our prototype primarily to demonstrate the feasibility of microgesture input for maps and illustrate the potential for a simple, unified set of map interactions built around a gesture vocabulary that emphasizes only landmark slides and touches. However, our team's experiences creating, testing, and using the prototype over a two-month period also provided insight into both the technical and conceptual implications of microgesture use, which we discuss in greater detail in section 6. While anecdotal, these experiences left us with a strong sense that microgesture interactions strike a crucial balance between subtlety, expressiveness, and immediacy — and that both current and forthcoming sensing approaches have the potential to support robust microgesture input for AR maps and other applications.

6 DISCUSSION

Our experience with the design activity and proof-of-concept prototype revealed several interesting threads of discussion.

6.1 Interacting with Mixed-Reality Maps

In this paper we focus on relatively simple realizations of augmented reality maps. Our proof-of-concept map observes many of the conventions of mobile and desktop-based map systems — simply projecting them into the space in front of the viewer. However, mixed-reality (MR) presents many potential opportunities for other types of maps that take advantage of these same technologies in ways that are impractical or impossible with mobile and desktop systems — creating maps that appear to be integrated into the viewers' surroundings and blur the line between map and environment. For example, MR maps have the potential to operate at extreme scales that are impractical on conventional devices, including environmental overlays [25] and to transition from miniature to larger-than-life representations [3]. They also have the potential to support interactive links between the map and environment, an approach common in worlds-in-miniature [15] interfaces. Mixed reality maps also have the potential to employ unusual geometries [26] and representations [57]. While our currently presented scheme is targeted at simpler AR map representations, the patterns we observed and described have considerable flexibility, and our same-side gesture scheme could likely be extended to accommodate these more complicated designs.

6.2 Ergonomics and Social Comfort of Microgestures for Map Interaction

Existing work that focuses on interaction with AR maps has relied heavily on mid-air gestural interaction [38, 46, 80]. While mid-air gestural interaction can be beneficial for manipulating large-scale maps [28, 66, 67], various studies have confirmed that the use of mid-air gestures over longer periods is fatiguing [28, 33, 41, 76]. These kinds of large-scale gestures are also more likely to be deemed distracting, awkward, or otherwise socially unacceptable [47, 63]. Because they are subtle and can be executed in a variety of body positions with relatively little arm movement, we believe that on-body microgestures have the potential to considerably improve the ergonomics of these interactions, while also being less socially disruptive. Participant feedback from our study (Figure 5) emphasized this sense of comfort, with the simple one- and two-finger microgestures receiving particularly high social-acceptability ratings (joystick $\mu = 4.3/5$, relative expansion $\mu = 4.2/5$, landmark slide $\mu = 4.2/5$) and participants also reporting high levels of social comfort with their overall microgesture sets ($\mu = 4.1/5$), even in public settings. When prototyping, we prioritized creating a complete set of gestures that we believe maximizes ergonomics and social comfort.

6.3 Microgestures for Other Applications

Map are an extremely commonplace application type, but rely on a surprisingly complex set of interactions — particularly in comparison to most other mobile and wearable applications, which tend to be built around 1D or 2D canvases with just a small set of swiping or scrolling interactions. For instance, on phones, tablets, and laptops, maps are one of the few genres of apps that extensively use multitouch gestures like pinches and two-finger swipes on top of existing 2D touches, slides, and taps. While the focus of this paper is to examine on-body interactions in the context

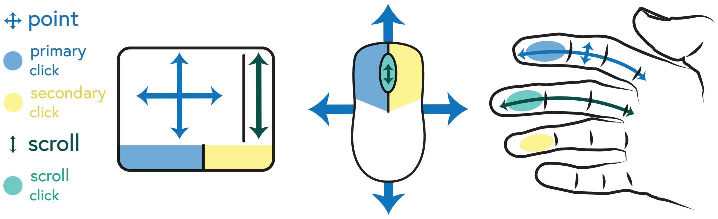

Figure 7: Body touchpads, slides, and taps can support close morphological approximations of devices like trackpads and mice.

of AR maps, we anticipate that the gesture patterns and gesture sets that we identify in this work (especially subtle 0D, 1D, and 2D microgestures) also have the expressive power to control many other types of applications across a variety of display types, including applications requiring 3D manipulation. For example, the combination of a 2D body touchpad, a 1D landmark slide, and three landmark touches all mapped to adjacent fingers is a very close morpohological approximation (per Card et al.'s framework [11]) of a laptop trackpad or 3-button mouse with scroll wheel (Figure 7). A subset of our proof-of-concept gesture set could easily be used in place of mouse- or trackpad-based input across most desktop, tablet, and mobile applications (including ones which rely on multitouch support for actions like scrolling or zooming). Given sufficiently precise tracking, these kinds of microgestures could let users interact with desktop and mobile displays from a distance and/or without repositioning their arms, considerably reducing the physical effort and ergonomic constraints imposed by mice, trackpads, and touch screens.

Because microgestures are amenable to use in public spaces and expressive enough for complex interactions, they may also be good candidates for interactions with wall- and environment-scale interfaces, adding precision and flexibility to the kinds of body-centric interactions imagined by researchers like Shoemaker et al. [72]. For example, the kinds of simple 0D, 1D, and 2D microgestures we demonstrate could be readily combined with either gaze- or hand-based deictic pointing to support interactions with televisions, wall-sized displays, or ubiquitous computing environments.

6.4 Multiple Gesture Schemes

During our elicitation, we noticed a distinct split in how participants envisioned each gesture. In one group most tasks were completed using a combination of landmark slides (and the composite body touchpad). In the other group, most tasks were completed using a combination of relative expansions, joystick, and pose proxy. In the interests of maximizing subtlety and supporting use in public settings, our proof-of-concept implementation took inspiration primarily from the first group. However, gesture sets that use ungrounded gestures like relative expansions and pose proxy have the potential to be valuable as well — supporting larger and more expressive 1D, 2D, and 3D motions. By virtue of their larger size, more limited dependence on touch, and decreased risk of self-occlusion, these gestures may also be easier to track using simple camera-based tracking systems. The distinct separation between these two different gesture approaches along with the huge space of possible gesture and microgesture interactions also suggests that the two may be compatible, and future systems could potentially implement both of these schemes (and maybe others) simultaneously. Such an approach could allow viewers to use subtle microgesture schemes in public spaces or while performing other tasks, then pivot to larger ungrounded gestures in private spaces or when actively focusing on the map. This distinct split between gesture sets also suggests good pairings for performing several interactions simultaneously. For example, zooming could be performed with a landmark slide, a gesture from the first group, while panning is performed using joystick, a gesture from the second group. As Wu et al. [87] note, offering multiple gesture sets could also help improve the discoverability of gestures (helping address the "vocabulary problem" common in many computing systems [24]) while also supporting individuals with different mobility needs and preferences.

6.5 Challenges for Subtle Same-Side Tracking

Based on our experience implementing our prototype we believe that there is still a number of improvements to current sensing technology that are necessary in order for these subtle same-side control schemes to move into widespread public use. Currently, the biggest hurdle is accurate hand tracking outside of the main device's field of view (FOV). Moderately accurate hand tracking is already possible using the cameras mounted on AR headsets like the HoloLens 2 or Apple Vision Pro — but tracking the viewer's hands outside of their immediate FOV is much more challenging. We chose a hybrid sensing approach that combines a thumb-mounted IMU (from the Tap Strap), a touch sensor on their thumb, and an external camera to solve this issue. However, that solution requires the viewer to wear multiple cumbersome external devices. Going forward, camera systems that are designed to be wearable (like Yang et al.'s Magic Finger [89]) offer a potential lightweight solution, but would require considerable miniaturization and tuning to support everyday use. Glove-based hand tracking sensors designed for motion capture (like StretchSense [19]) could likely meet the capture fidelity required for this type of application, but may not be practical to wear in many settings. Finally, pico-radar technologies like Google's Soli [32] represent another promising approach, but are currently challenging to deploy outside of small (often stationary) capture areas.

7 CONCLUSION

As mixed reality and spatial computing hardware continues to improve, maps seem poised to be one of the most valuable and widely-used classes of AR applications (as is currently the case on smartphones). Our work points towards a future with rich interactive AR map experiences, and highlights the potential for map interactions that are subtle, simple, and expressive enough to work in a wide variety of different public and private contexts. Moreover, by addressing the more complicated space of gestures needed to support maps, we expect this work may also help point the way towards microgesture inputs for a wider range of AR tools.

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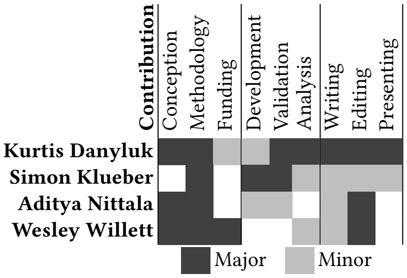
To support a more detailed attribution of authors roles, the table below highlights major and minor contributions by each author to this research project and to the production of this publication. We use a variation of the CRediT (Contributor Roles Taxonomy — https://credit.niso.org/) which we have modified to capture roles and contribution types common in HCI and Visualization research.



Contribution	Conception	Methodology	Funding	Development	Validation	Analysis	Writing	Editing	Presenting
Kurtis Danyluk	■	■	▒	▒	■	■	■	■	■
Simon Klueber		■		■	■	▒	▒	▒	▒
Aditya Nittala	■	■		▒	▒		▒	■	
Wesley Willett	■	■	■			▒	▒	■	

■ Major ▒ Minor

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