

Exploring the Design Space of Input Modalities for Working in Mixed Reality on Long-haul Flights

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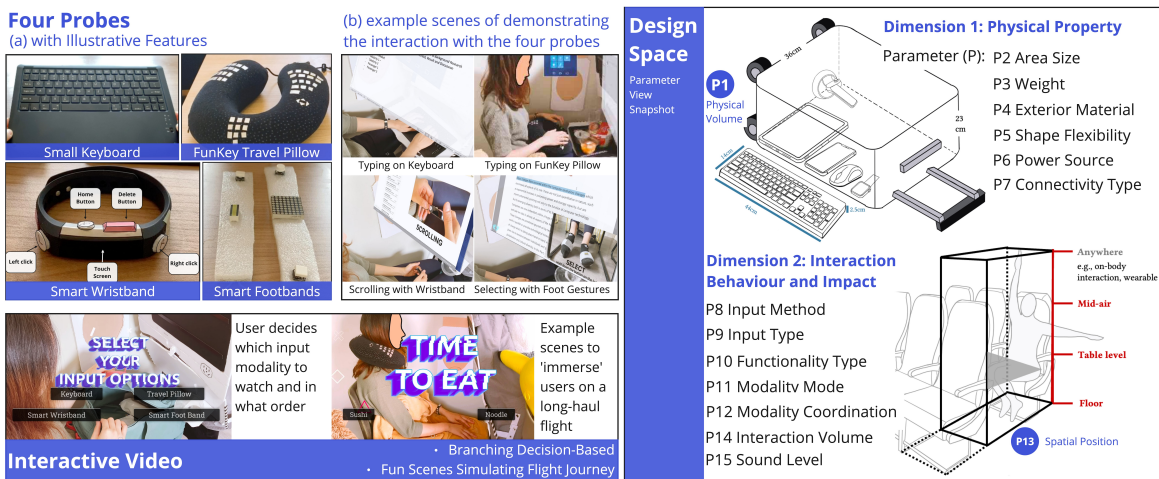


Figure 1: We developed an interactive video depicting four design probes, derived user requirements, and then mapped out the design space of input modalities for working in Mixed Reality on long-haul flights.

ABSTRACT

Flexible working, including in resource-constrained settings such as long-haul flights, poses considerable challenges. While research in mixed reality (MR) offers the potential for enhancing experiences of working on airplanes (WoA), what input modalities and interactions might be suitable for such workspaces is under-explored. To address this gap, we created four design probes and demonstrated their interactions within MR for WoA using a branching decision-based interactive video. 24 participants engaged in the think-aloud study with the video where they selected which probe to watch based on personal preference and order. The follow-up interview further solidified their general preferences for intuitive

and friction-free inputs, revealed strong concerns about reliability, discreetness, and portability, and showed high enthusiasm for interactive video. Based on these findings, we contribute a context-driven design space of input modalities for WoA in MR, extending the understanding of design opportunities for inputs with MR in confined spaces.

CCS CONCEPTS

• Human-centered computing; • Human-computer interaction (HCI); • Interaction paradigms;

KEYWORDS

Design Space Exploration, In-flight Work, Input Modalities for Mixed-Reality Headset, Interactive Video, MR Office Work

ACM Reference Format:

Wen Mo, Martin Dechant, Nicolai Marquardt, Amid Ayobi, Aneesha Singh, and Catherine Holloway. 2024. Exploring the Design Space of Input Modalities for Working in Mixed Reality on Long-haul Flights. In *Designing Interactive Systems Conference (DIS '24), July 01–05, 2024, IT University of Copenhagen, Denmark*. ACM, New York, NY, USA, 19 pages. <https://doi.org/10.1145/3643834.3661560>



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DIS '24, July 01–05, 2024, IT University of Copenhagen, Denmark
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ACM ISBN 979-8-4007-0583-0/24/07
<https://doi.org/10.1145/3643834.3661560>

1 INTRODUCTION

From the looming threat of the sudden-reclining front seat [84] to cramped space and overly intimate neighbors, people have battled considerable challenges when working on long-haul flights in economy class [12]. A recent research line in Human-Computer Interaction (HCI) has embraced the potential of Extended Reality (XR) Head-mounted Displays (HMDs) to enhance the digital work experience on transportation, capitalizing on the privacy and limitless virtual screens the devices offer [16, 53, 59]. Industry developments, such as the debut of Apple Vision Pro, highlighting the ‘travel mode’ features for plane rides [62], underscore the growing interest in this area. However, working in HMD, i.e., *VR office Work* [16] also involves using input modalities, such as a keyboard or mid-air hand gestures to perform tasks. The spatial constraint of an economy class seat on long-haul flights might limit the interaction space of an input and the prolonged use could also lead to Gorilla arm issues or an accidental clash with adjacent neighbors [49].

While the ongoing research has predominately focused on the usability of different input modalities, a recent study started evaluating the social acceptability and comfort of interaction techniques from body-worn to environment-based inputs in confined spaces [48]. However, working on airplanes (WoA) potentially complicates such interaction space with specific requirements such as supporting productivity. Moreover, taking a long-haul flight involves logistic hurdles including considering the packing space, and arranging things during inflight services. Therefore, there is a gap in diving deep into the context of air travel or similarly resource-constraint spaces to understand the user requirements and design considerations of XR input modalities that support knowledge work.

To bridge this gap, this paper extends the prior work of using XR on transportation by exploring the design space of input modalities for working in Mixed Reality (MR) on long-haul flights. Past research proposed using MR [16, 19, 46] could balance immersion and situational awareness needed in mobile contexts. This paper aimed to answer the following research questions: 1) How does the situated context of long-haul flights influence users’ requirements of input modalities? And 2) What are the design opportunities for input modalities in XR to support WoA?

Through a user-centered research process, we conducted the think-aloud studies with follow-up semi-structured interviews with 24 participants. For the think-aloud study, we designed four low-fidelity probes as proof-of-concept inputs and illustrated their interaction in MR for WoA in an interactive video. In addition, to actively engage participants and put them into context, the video was designed as a branching decision-based video, enacting various scenes on a long-haul flight while allowing participants to select which probes to watch and in what order.

Grounded in the participants’ feedback, we identified five key user requirements, falling into the categories of functionality, travel logistics, comfort, and confined space constraints. Participants’ comments revealed that functionality was valued more than space-saving. Furthermore, all participants expressed positive comments on how the interactive video encouraged them to think deeper into their choice and how engaging it was to remind them of the context of air travel.

Leveraging those insights and past literature, we distilled fifteen distinct parameters categorized into two dimensions: *D1 Physical Properties* of the input modality and *D2 Interaction Behavior and Impact*. Together, they constructed our design space of input modalities for WoA in MR that serves as critical criteria and example vocabulary, one in the User-requirement view and one in the Parameter View. They are meant to help systematically assess whether the input modalities meet the user requirements. We reflect on participants’ choices and discuss the design opportunities of input modalities for future passenger-MR interaction. This paper presents three key contributions:

- An exploration of user requirements of input modalities for WoA in MR that are informed by incorporating innovative design probes in an interactive video and applicable to other resource-constraint settings.
- A context-driven design space characterizing physical and interaction parameters of input modalities can help guide future HCI research into designing interaction in MR beyond air travel.
- A study design using probe-fused and branching decision-based interactive video as an engaging video prototype method for HCI research.

2 RELATED WORK

Exploring the design space of input modalities for WoA in MR requires understanding the uses of HMDs for passenger experiences as well as the variety of input modalities that have been explored within HMDs for knowledge work.

2.1 The exploration of Augmented Reality, Mixed Reality, and Virtual Reality for Passenger Experience

There has been increasing research interest in using XR technology to enhance passenger experiences for entertainment [22, 29] and more [48]. For example, Chittaro et al. [10] have shown that VR can make safety briefings more engaging and effective. Williamson et al. [79] surveyed the social acceptability towards using VR on a flight which showed passengers’ interest in hybrid AR/VR spaces to support separation from others and to improve the viewing experience. Overall, they found VR entertainment can offer passengers a mental escape from the confines of an aircraft.

In addition, the XR technology has also been examined to support productivity [16, 33, 53] in transportation. Grubert et al. [16] proposed ‘VR Office Work’ highlighting the advantages of VR HMDs for improving working conditions when physical workstations or setups might not be ergonomic or ideal. These immersive HMDs also offer users wide and multiple display real estate, keep users’ usual workstation setup coherent during travel or commutes, provide users with privacy, and push the boundaries of what people can do in the physical world. Despite these benefits, challenges remain. For example, current technology constraints can impact users’ familiarity and trust in virtual displays. To mitigate that, Pavanatto et al. [45] explored the potential for hybrid use of physical and Augmented Reality (AR) monitors. Furthermore, McGill et al. [46] discovered that functional issues such as physical safety

and shortcomings of the existing interaction paradigms do not adequately consider the physical constraints and social contexts.

Taking this into account, Schmelter and Hildebrand [66] attempted to measure the interaction space of VR in different seating scenarios on public transport and reported that using hand tracking as input was a better option than the VR controller as controllers could potentially cause conflicts with other passengers. Furthermore, when Medeiros et al [48] used composite videos to survey the social acceptance and comfort with AR-oriented interaction techniques (body-, device-, and environment-based) on public transport, they found advantages of discreet/subtle interaction over mid-air gesture interaction as their respondents consider mid-air interaction highly visible and might invade personal space which expressed discomfort towards it. To support discretion, Tseng et al [76] mapped small-scale finger motions onto virtual arms and hands which aimed to reduce physical motion and fatigue while enhancing safety and fewer collisions compared to traditional hand tracking in confined spaces.

However, the selection of input modalities varies for different modes of transportation and activities. There is limited work analyzing how air travel affects user needs in designing inputs for WoA in MR, especially barriers to working and social context.

2.2 Exploration of Input Methods with Head-Mounted Display for Knowledge Work

Research has extensively explored different techniques to improve the XR inputs of voice, eye-tracking [57], controller, and gestures [11]. Gestures have been studied for over three decades [18], including hands [37], fingers [9], and heads [50] for pointing, manipulation, and text entry [15, 17, 68, 70]. Many studies have also explored combining gestural interaction with the gaze [30, 56] to help reduce fatigue [25, 52]. However, the precision of such interaction for office work has limitations, as the lack of tactile feedback leads to uncertainty about executing commands [64]. To compensate, recent studies have proposed many novel input methods such as on-body interactions [72], including hand-face input [38], cheeks [81], palms [20], and proprioceptive feedback [43, 71, 82]. Other approaches have explored wearables [4, 14, 31], touchscreen tablets [7, 74], direct and indirect foot-tap [31, 36, 37], and tangible inputs [6]. Nevertheless, those novel approaches are challenged by the level of task comprehension and the fatigue they might cause when conducting knowledge work for long hours. This leads many researchers to resort to the traditional input devices of mouse and keyboard, considering their high precision, comfort, and familiarity with users for office work [17, 35, 68, 83].

In addition, while focusing on novel input techniques, this corpus of research has largely ignored the social and environmental factors that might influence the interaction techniques. Very few papers have explored input interactions in constrained spaces, which have their unique requirements [49]. This paper aims to address this gap by exploring the design space of input modalities for passenger-MR interaction in the context of WoA through a human-centered research and design process.

3 STUDY DESIGN

The goal of this study is to understand user requirements of input modalities for WoA in MR by examining the conceptual use of the four design probes via an interactive video. This similar approach has been adopted in past literature where rich insights from users were gained first and then employed to pave the way to build design space [26, 28, 74, 78]. This section presents the detailed study procedure and findings, including the design process of both the probes and the interactive video.

3.1 Interactive Video as Research Method

The initial round of studies was designed and conducted amid the COVID-19 outbreak in 2020. Due to the pandemic and the logistical constraints of conducting an in-person experiment, especially on an actual long-haul flight [21, 48], we used the branching decision-based interactive video as the medium to demonstrate the conceptual use of the inputs. In HCI, using video prototyping to survey feedback is a well-established research method [60]. It is frequently used early in the design process to demonstrate the use of context to elicit user thoughts for design potential [3, 23, 44] without time, cost, and technological constraints. The interactive features were designed to encourage participants to compare the probes and provide a more engaging experience. **The detailed design and prototyping features of the video are described in 3.5.**

3.2 The Thought Process for Probes Selection

Our overall thought process for selecting and designing the probes followed three steps. First, informed by past research and our previous study [51] where we found that passengers' challenges for WoA go beyond spatial limitations. There were also feelings of being observed, interruptions and distractions, well-being issues, and logical hurdles across the entire journey. For example, the limited packing and storage space could affect the number of carry-ons, and the limited inflight seating space [1] could affect the passenger-MR interaction space considering the proximity to neighbors. Moreover, the voice might not be ideal for WoA due to privacy concerns. Secondly, given that the primary goal is to conduct digital work, we decided that each probe needs to emulate essential computer inputs – specifically, a keyboard for text entry and a mouse for navigation tasks like scrolling and selecting. Thirdly, the purpose of the design probes is to provoke user thoughts. Thus, under each functionality, there should be one being the familiar option while the other being provocative. This approach was aimed to ensure that while each probe presents its unique benefits, collectively they address the array of identified challenges.

Lastly, hand gestures and eye-tracking are common built-in features in the current commercial MR headsets (i.e., HoloLens). To explore how and whether participants would consider using alternative or multiple inputs, we included hand gestures to complement the probes' interaction in MR.

Based on this thought process, we categorized the variety of input modalities as examples in the context of air travel (Table 1) and selected four physical probes - the small keyboard and the travel pillow for the functionality of the keyboard, and the wristband and the Footbands as wearable pointing devices like a mouse.

Table 1: Examples of potential inputs to select for design probes in the context of air travel.

Examples	Non-digital Carry-on			Common Digital Device (passengers might bring onto planes)					HMD Input			Environment				
	Hand-bag	Travel Pillow	Clothes	Smart-watch	Lap-top	Tablet	Smart-phone	Key-board	Con-troller	On-body	Hand	Feet	Head	Eye	Seat-back Screen	Tray Table
Virtual (Not a carry-on)										✓	✓	✓	✓	✓	✓	✓
Wearable (easy to carry)	✓	✓	✓	✓						✓	✓	✓	✓			
Gesture											✓	✓	✓			

3.3 Probe Design and Materials

Considering the exploratory stage, we decided to construct a low-fidelity prototype as proof of concept. To balance the right level of fidelity, we added illustrative features, such as non-functional buttons. The goal of these was to suggest design possibilities to users, not the actual functions.

The main goal of the videos of the interaction probes was to visualize how users may interact with them during tasks. Further, we used these videos to visualize common tasks during the flight (e.g., working on text or presentations). Through these videos of the interaction techniques in the different tasks, we aimed to inspire participants to reflect on each probe's strengths and potential limitations during the flight. Per modality, we selected the most commonly used interaction techniques for exploration together with our participants. Each probe was mapped to a different task based on its primary function and interaction types (i.e., keyboard for text entry, pointing device for scrolling, or both). This is to assess participants' feedback on each probe's potential to perform different functions. For example, The FunKey Travel Pillow facilitated writing on PowerPoint slides, intending to assess participants' feedback on inputs with dual abilities based on the requirement for being travel-friendly, while using the Smart to read and write emails, was to gauge participants' thoughts on the precision and ease of use with small, wearable devices.

In summary, each input modality corresponds to one task as follows:

- The Small Keyboard – writing in Word document
- The FunKey Travel Pillow – writing slides in PowerPoint
- The Smart Wristband – reading and writing emails
- The Smart Footbands – scrolling through pictures and reading PDF document

3.3.1 Small Keyboard. For the basic keyboard, we chose a 75% QWERTY wireless keyboard with 83 keys. Its common steel and metal construction led to our magnetic mounting system on the front seat's back. This design aims to allow users to attach the keyboard to the screen, optimizing tray table usage, enhancing portability, and offering additional storage. Given the space constraints in cabins, this design seeks to leverage cabin features to support WoA in

MR. In our video prototype, participants had two storage options: magnetic mounting or the front seat pocket. (Figure 2).

3.3.2 'FunKey' Travel Pillow. We selected a curved travel pillow (Figure 3) as the provocative option for the text-entry keyboard type, operating as both a pillow and a wireless keyboard. Compared to the keyboard, the travel pillow keyboard is a common carry-on, repurposing it as a keyboard to enhance its portability. The soft exterior material is intended to improve wrist comfort when typing while keeping the sound level low. The pillow's unique shape mirrors the Microsoft Sculpt Ergonomic keyboard Field [65]. It consists of one ordinary black travel pillow. The illustrative features include cut-out squares representing keys and a side button to pair with the MR headset. The keys have a standard QWERTY keyboard layout, a number pad, and battery level indicators.

3.3.3 Smart Wristband. We designed a smart wristband as a lightweight and wireless pointing device. The prototype of the probe was built upon Fitbit Alta. Although it is an unusual input for MR, it is a popular wearable on the market. Being usually worn on users' wrists makes it more portable and can provide discreet interaction. To demonstrate potential future designs, we defined its screen as a touchpad for touch-based input methods. For illustrative features, we added a few buttons made of foam boards and wooden coffee stirrers, including a home and a delete button, and four extra buttons to present as user-defined shortcuts or as four directional arrows to navigate a virtual keyboard for typing (Figure 4). Speicher et al. [70] discovered that hand-held devices with at least one button performed the best while completing text entries on a virtual keyboard. In the video prototype, the user took off the wristband and held it with both hands to control it to read and write emails, including the commands of scrolling, selecting, and typing (Table 2).

3.3.4 Smart Footbands. Compared to the Smart Wristband, a pair of Smart Footbands is unique among commercial wearables, serving as the "provocative" mouse. Because of its ability to use the floor space, it has the potential to be highly private and will not disturb others, and thus probes users to evaluate its usability for hands-free interaction.

Studies in foot interaction have explored multiple approaches for prototyping, such as embedding sensors in the shoes or soles



Figure 2: From left to right: the design probe of the small keyboard, the magnetic mount, and the decision point to choose between "Store in the front pocket" and "Mount on the Screen"



Figure 3: From left to right: prototype of the FunKey Travel Pillow, one illustrative feature of the start button, and another one of the battery indicator

Table 2: The demonstrated commands for using the wristband in Outlook

Command	Gestures
Pair with headset	Press Home button
Scroll page	Swipe on the touchpad
Select Email	Click right-click button
Reply	Click the button of the user-defined shortcut
Type	Use four buttons as four directional arrows to navigate on the virtual keyboard.

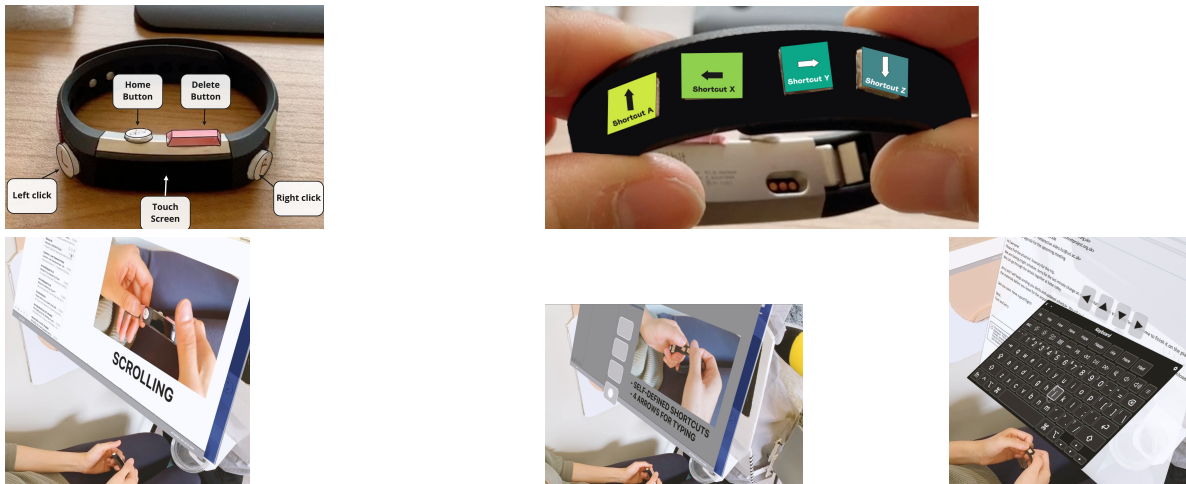
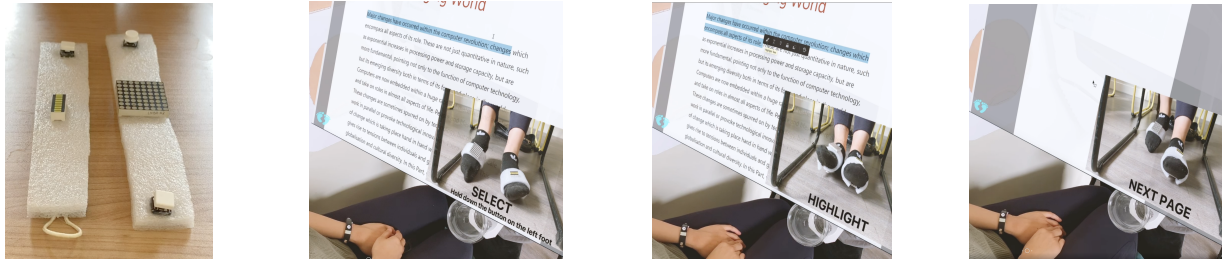


Figure 4: First row from left to right: Prototype of Smart Wristband; Illustrative Features of four buttons; Second row from left to right: Use wristband to scroll emails; Select shortcuts; Type emails with the wristband

Table 3: The demonstrated foot gestures for reading

Command	Gestures
Pair with headset	Heels down. Raise toes in both foot and click them together
Next Page	Drag right foot (dominated foot) from the front to the back of the floor
Select sentence	Hold down the button on the left foot band while repeat dragging right foot to the right side
Confirm	Hold down both heels for two seconds
Zoom in	Hold down the toes of the left foot while repeat dragging right foot to the right side
Close	Draw a full circle with both feet in counterclockwise direction.

**Figure 5: From left to right: Prototype of the Footbands, Gesture Select, Highlight, and Next Page**

[45, 65, 67]. To make it more versatile, we created a pair of Smart Footbands that could be hooked over either on shoes or socks.

The Footbands are created from packaging foam, small push buttons, and hair bands. One LED matrix and one LED bar on each foot were added to represent digital screens that could show battery level or cursor location. The left and right-click buttons are located on the two sides of the bottom of the foot. To select the feet gestures inspired by the gestures Velloso et al. (2015) [77] explored, we paired the common computing work commands with different gestures, primarily used for scrolling, clicking, and dragging (Table 3). Figure 5 presents three examples.

3.4 Virtual Hand Gestures

We presented two hand gestures: select files and move the location of virtual screens in 3D space. Interactions were presented sequentially, ensuring clarity, and allowing participants to assess how they might complement each other.

3.5 Prototype Interactive Video

To provide a compelling and relatable flight experience, we prototyped the interactive video simulating a long-haul flight experience, encompassing scenarios like tray table adjustments during meals. The video allows participants to select input modalities, with viewing duration varying between 13 to 20 minutes for the following scenarios: 1) Introduction to the study's scope and aims, 2) Select avatar to initiate the study, 3) Overview of four input modalities, 4) Pre-take-off activities from boarding, wait to take off and takeoff, 5) Work-related modalities for WoA in MR from first two decision points to selecting meals and 3rd decision point, 6) Landing.

We included some fun elements that helped participants familiarize the interactive feature (Figure 6 first row). Each decision

point leads to a different viewing branch which impacts what input to watch first.

Using each input starts with pairing the MR headset and selecting the designated task on the home menu (Figure 6 second row). The virtual AR screens are visual effects created in Adobe Premiere Pro and After Effects.

Participants had three chances to select from four input modalities during a single viewing. After choosing an input modality, it was excluded from subsequent options. If no selection was made, the video defaulted to the leftmost option (Figure 7). Before disembarking, participants could revisit a previous branching point to view the missed probe or continue to land. This approach aims to encourage participants to make selections and understand whether the selection order indicates any preferences.

Additionally, from our previous study, we learned passengers often choose lightweight tasks when the tray table needs to be stowed away such as during taxing or mealtime. To reflect that, each modality is filmed under two conditions— mealtime and not mealtime (Table 4). Under which condition the modality is presented is based on the order of participants' choice.

The mock environment includes a triple-seat row in the economy class and the setup of a typical back of a front seat to simulate the use of the tray table, the seat-back screen, the cup holder, and the front pocket. The interactive elements and the final video are generated on an online interactive content creation tool, eko studio [58]. The final video is published on eko's video-sharing website [59].

3.6 Participants

24 participants, comprising nine males and 15 females, volunteered for the evaluation study. Their ages spanned 18 to 60, broken



Figure 6: First row from left to right: Select Avatar, pre-taking off activities, watching to take off or not, sushi or noodle; Second row from left to right: Pairing MR headset with an input, Select App on Home Menu, Select file, Multiple Screens.




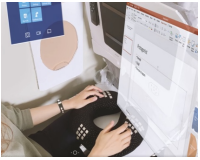





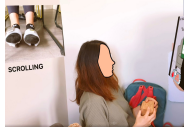
Figure 7: First row - examples of branching decision tree; Second row – From left to right: first decision point with four options, second decision point after selecting the Smart Wristband, fourth decision point, continue to land or go back to mealtime.

down as follows: seven aged 18-25, eight aged 26-30, six aged 31-35, two aged 36-40, and one aged 51-60. While one participant regularly traveled in business or first class, the remainder flew economy. Ethnically, half identified as white, 10 as Asian, and two as mixed-race. The majority resided in the UK during the study, with exceptions being one each in Norway, South Korea, and the US. Eight had working experience with VR and MR, 15 had casually used VR headsets, and one was entirely unfamiliar with XR. Recruitment was primarily via direct emails and social media sites like Twitter and LinkedIn. This research has ethical approval from [anonymized institution] to conduct these studies.

3.7 Procedure

We first shared an online participant information sheet, consent form, and demographic survey with each participant and received the signed versions ahead of the studies. The study started with capturing participants' consent for being recorded and they were then informed of the study procedure, which began with a think-aloud study and followed with a semi-structured interview. As part of the think-aloud study, participants were instructed to share their screens and thoughts with the researcher while watching the video. Notes were gathered on participants' selections and thoughts. In the follow-up interviews, we asked questions in four key areas: (1)

Table 4: Presents the design of the four probes under two conditions.

Condition	Keyboard	FunKey Travel Pillow	Smart Wristband	Smart Footbands
Non-mealtime				
Mealtime				

feedback on WoA in MR and their opinions on MR versus VR for WoA; (2) thoughts about the pros and cons of each design probe, and why they are chosen in that order; (3) thoughts on other inputs; (4) experience with the interactive video.

The time spent watching videos varied between 12.82 minutes to 21.1 minutes depending on participants' selection (AVG = 16.35 minutes). The average duration was 21.88 minutes for the follow-up interview. All sessions were audio recorded and transcribed immediately.

3.8 Data Analysis

We used the reflective Thematic Analysis [8] to analyze our interview data across two stages. In stage one, the first author transcribed each interview and counted the selection orders of each probe. Regarding the coding of the transcriptions, our approach was mainly top-down but we also used an initial bottom-up approach to explore and familiarize ourselves with the data. Thus, we first open-coded our data, and then using a top-down approach, we organized the identified codes into the primary four areas outlined in the interview protocol using an affinity diagram. For instance, coding users' comments of "soft material", "ergonomic shapes" and "not an extra carry-on" as the *Advantages of FunKey pillow and mapping these codes to the area of thoughts about the pros and cons of each design probe.*

In stage two, the initial codes were further refined and collaboratively discussed by all authors through a series of meetings. Through this process, the codes were translated into five key user requirements for WoA. For example, "lack of precision", "need tactile feedback", and "require typing functions" signals the importance of the input to be reliable, intuitive, and precise. "looking weird", "discreet in use" and "quiet" imply users' need to keep a low profile. "Easy to charge", "wireless", and "not an extra carry-on" and users' preference for the wearable nature of the wristbands illustrates that the input needs to be portable. To align them more closely with the context, subsequent discussions with all authors and iterative analysis led to the evolution and regrouping of these requirements into four aspects: Travel Logistics, Functionality, Comfort, and Confined-Space constraints. These aspects were instrumental in guiding the development of parameters and dimensions of our design space. From there, combining insights from our data analysis

and past literature, we, a team of HCI designers, researchers, and XR developers, engaged in multiple rounds of internal analysis and discussions to define and select dimensions and parameters of the design space for exploration with users.

3.9 Results

This section presents the selection result of the four input modalities and the insights of the above four topics. In doing so, we then describe how they evolved into critical user requirements.

3.9.1 Selection Order. The travel pillow keyboard and the small keyboard were the two most popular probes for participants to watch in the first branching point, while the wristband was favored in the second decision point (N=9), and the Footbands in the third (N=13) (Table 5). Additionally, 11 participants revisited the previous decision point to catch the missed input modality. As for reasoning, participants chose input modalities based on their level of interest and familiarity. Most participants found the small keyboard the most familiar and therefore, seven participants skipped its demonstration. At the same time, three participants skipped the FunKey travel pillow as they would never pack one on a long-haul flight.

3.9.2 Attitudes towards WoA in MR. All participants were optimistic about using MR headsets for computer work on planes. They valued the space-saving, multi-screen capabilities, and privacy protection that wearing an MR headset provided. Additionally, the ergonomic advantages of MR headsets were evident, particularly in addressing challenges like low tray table heights. In short, participants envisioned a future where MR facilitates flexible working from anywhere.

However, a variety of concerns were raised by participants. First, participants felt self-conscious, attracting stares from other passengers. They also raised concerns about inadvertently infringing on others' spaces, aligning with the past findings [79]. Paradoxically, an MR headset that is too blended in as a glass might render work undetectable to others, eliminating the visible cue of being "busy." Following that, most participants expressed reservations about the headsets' portability and size, questioning their weight, durability, and convenience for travel. Recurring logistical topics include battery time, charging method, too much friction to put it on, and ease of setup. One participant who has worked in VR for

Table 5: Participant Feedback Summary

Input Modality	Selected watching order	Preferred Input	Reported Advantages	Reported Concerns
Small Keyboard	1st: 8 2nd: 5 3rd: 0 4th: 4 Not selected: 7	12	<ul style="list-style-type: none"> • Most Familiar • High productivity, precise and tactile feedback • Socially acceptable 	<ul style="list-style-type: none"> • Extra carry-on • Need to charge • Takes up tray table space and is not portable • Not ergonomic to type due to the tray table height
FunKey Travel Pillow	1st: 9 2nd: 7 3rd: 4 4th: 1 Not selected: 3	7	<ul style="list-style-type: none"> • Similar to a keyboard • Ergonomic shape and wrist support • Soft material - potentially to quieten typing sound level • Portable as a wearable - not an extra carry-on for some people while others are open to try 	<ul style="list-style-type: none"> • Whether it is durable enough to serve two purposes • Unfamiliar with Split layout design • It might appear weird typing on a pillow • Accidentally hit buttons • Not hygienic
Smart Wristband	1st: 3 2nd: 9 3rd: 7 4th: 3 Not selected: 2	3	<ul style="list-style-type: none"> • Small and portable as a wearable • Discreet when in use • Perfect for lightweight work • Provide tactile feedback 	<ul style="list-style-type: none"> • Difficult to type, can write something short but not a report • Fingers might be tired after typing with it for long
Smart Footbands	1st: 4 2nd: 3 3rd: 13 4th: 3 Not selected: 1	2	<ul style="list-style-type: none"> • Free up users' hands- multitask • Free up tray table space • A nice change and feet exercise for long-haul flights • Discreet when in use on the floor • Perfect for inflight gaming 	<ul style="list-style-type: none"> • The learning curve is steep and Prone to make mistakes. • Too much friction to wear • Can become tiring quickly • Need a lot of floor space • Not hygienic

over 7 years noted the issue of make-up smudging due to headset use. Lastly, both novices and professional XR users questioned the technology's viability. While novices wondered about eye strain, screen proximity, and motion sickness, professionals delved into specifics such as camera resolution and tracking stability during flight.

3.9.3 MR Versus VR for WoA. Recent studies have highlighted the benefits of Mixed Reality (MR) in maintaining the balance between immersion and inflight awareness which is critical for air passengers [39, 46, 47]. This is reflected in participants' strong preference for MR over virtual reality (VR) for WoA. They appreciate that MR combines the environment and virtual computer, allowing for immersion without sacrificing situational awareness such as flight announcement, inflight service, and most importantly, their neighbors. Although VR might take passengers into a potentially more immersive environment, participants were concerned about being too immersed – losing awareness of what is happening on the flights, having headaches, and getting disoriented after prolonged use. Specifically, for work-related tasks, they were concerned about the ability to see and use the keyboard in VR.

3.9.4 Feedback on Design Probes. Table 5 presents the summary of participants' selection results and feedback on each input modality. 12 participants chose the small keyboards as their preferred input modality due to their familiarity with it. However, its relatively

larger size raised concerns about being an extra carry-on, occupying most of the tray table, and not ergonomic for typing due to the 'awkward' tray table height. Some proposed a foldable "Origami" design to improve its portability. The magnetic mount option received mixed feedback from 17 participants. 10 appreciated its space efficiency, cleanliness, and role as a visual cue, reducing the chances of misplacing the keyboard. Yet, some had reservations about it blocking the seatback screen and stability during turbulence.

The travel pillow keyboard was the second-favorite choice (N=7). Participants considered its shape to be ergonomic, material good for quiet typing sound, and overall dual-purpose as wearable such as can simply wear it when the table is occupied. However, they expressed concerns over its durability, unfamiliar split layout, comfort in typing, and public acceptance concerns. Two participants raised potential hygiene issues when placing it near the face or accidentally hitting the wrong buttons. There were also questions about its value for those not regularly using travel pillows.

The smart wristband (N=3) and Footbands (N=2) were less popular but valued for their discretion. The wristband, familiar to many, was noted for portability and suitability for simple tasks like scrolling on the touchpad without mid-air movements. Its tactile feedback improved reliability, but participants worried it required too much effort when typing, exhausting fingers.

The Footbands were seen as innovative but with a steep learning curve. It also requires too much friction to wear in a cramped seat and the hassles it brings when standing up or getting out of the

seat. Participants mentioned there is not enough floor space for its interaction and are concerned about its reliability and how tiring it would become. Some are also worried about hygiene problems such as smell or touching one's feet or shoes during mealtime. However, many participants mentioned that it can have free hands which is good for multitasks and could be a fun feature for inflight gaming or a method to stretch feet. One participant specifically mentioned the potential to use it concurrently with hands like drumming to improve productivity. Its potential in the accessibility domain was noted by four participants.

3.9.5 Other Inputs. Beyond the design probes, participants discussed a few alternative input options. Hand gestures were recognized as intuitive and apt for simple tasks, with the added benefit of not being an additional carry-on. Yet, participants are concerned about the attention they might draw [48], the spatial requirements, and potential interference with neighboring passengers. Additionally, the absence of tactile feedback and extended mid-air interactions raised ergonomic questions. Doubts mirrored those of foot interactions, primarily surrounding the reliability and precision of gesture tracking. Similar reservations extended to eye-gaze inputs; many were unfamiliar with its mechanics, voicing concerns about potential eye strain or unintended command execution. Other suggestions included clothes-based wearable inputs, like a travel jacket, and an acoustic dome around the headset to ensure privacy for voice commands. Other ideas include transforming a pen into a controller or wearing gloves to provide tactile sensation. However, a consensus emerged favoring carrying a minimal number of devices on flights.

3.9.6 Interactive Video. All participants found the overall experience with the interactive video very engaging and entertaining. Ten participants chose to have the take-off experience as the flight storyline helped place them into context. Six participants reported that the different scenarios reminded them of the detailed experiences on a flight, and it is easier for them to visualize various situations, which would not be as effective if only presenting the four input modalities alone.

'You show the part that's the planes taking off. You kind of like, really feel the vibration and. . . the sound, and like you're opening a window and stuff. . . I think it was really good that you put that in at the beginning because, like, they got me into thinking that I was inside the plane and inside that experience'

Participants also found that making selections subconsciously influences them to pay much more attention while watching. It proves to be a highly effective way to encourage participants to think critically about each input option which helps to unearth in-depth aspects of the design space, as one noted: 'You're weighing up the options already in your head. Because you're like, oh, which one should I pick? And even if you don't care which one you pick, because it's a test. You're still learning by looking critically at each thing, which could spark ideas about why you like something and why you don't like something. So, I think that element of the videos is beneficial for getting people into the mindset of choosing.'

3.10 Research Question One: Identifying User Requirements

To answer the first research question, it is evident that the situated context of long-haul flights significantly influences how users perceive and choose input modalities for WoA in MR. The limited personal space in the air cabin and inflight activities led participants to lean toward portable probe options like travel pillow keyboards and wristbands. The proximity to neighbors highlighted the concerns about obstructive interaction. Participants' requests for durable and reliable input and minimal carry-ons highlighted the unique challenges of air travel. Grounded in participants' feedback, we derived five critical User Requirements (URs) of input modalities for WoA in MR in the categories of functionality, travel logistics (UR2), comfort (UR3), and confined-space constraints (UR4 &5)

3.10.1 UR1: Reliable, Intuitive, and Precise. The requirement for functionality, meaning how reliable and precise the function one input supports and how intuitive and easy it is to use was a prominent theme, echoing Davis' Technology Acceptance Model (TAM) [13]. When tasks demanded extensive typing, keyboards remained the primary choice, despite it might be another carry-on or relatively large. Although the travel pillow seemed promising, participants were worried about their durability. In addition, while studies have investigated employing the existing air cabin space, such as projecting a virtual keyboard proportionally to the surface area [49], the tactile and mechanic feedback and direct input still make a physical keyboard more reliable and desirable to our participants, making them believe it can seamlessly integrate into MR.

Similarly, despite gestures being not an extra carry-on, participants all have doubts about their precision. Even when participants only consider doing some light work or just watching a movie in MR, they prefer the direct input and tactile feedback from small wearables over either hand or foot gestures. The same sentiment is also reflected when participants frequently questioned the reliability of the MR technology.

For WoA in MR to gain mainstream acceptance or for people to be willing to invest in such a working style, especially in contexts like long-haul flights, both MR and the design of the inputs need to be perceived as reliable, intuitive, and precise [13, 75], not only (a) individually but also (6) in collaboration such as multimodal interaction. The participant's comment on drumming is a good example of multimodal concurrent interaction. It is essential to ensure it is intuitive and easy to coordinate multiple inputs together to enhance productivity.

3.10.2 UR2: Portable. Although the performance and usability aspects of input are paramount, considering the context of WoA, when travel logistics of both the packing and the table space are limited, portability does matter. Participants' interests in the travel pillow, unanimous preference for minimal carry-ons, and concerns about charging and arranging items when they need to move from their seats, highlight that the input should be (a) small and light for packing, taking little storage room in air cabin and luggage, (b) convenient (i.e., wireless) to carry, move, and put away across all flight stages and under different inflight scenarios such as during turbulence, mealtime, etc., and (c) easy to manage charging globally, especially oversea airlines might have different sockets.

3.10.3 UR3: Comfortable in Use. ‘Uncomfortable’ and ‘tiring’ are the other two repeatedly mentioned vocabularies participants used when evaluating the design probes as well as WoA in MR. These sentiments about comfort were tied to ergonomic challenges from the uncomfortable typing postures due to inconvenient table height, to the tiring prolonged movements of arms, fingers, and feet. This emphasizes the importance of designing ergonomic and comfortable use of the input including its physical attributes and the interaction in MR.

Moreover, when designing multimodal interaction for WoA in MR, the collaboration aspect also applies. This involves ensuring the comfortable coordination between multiple inputs as well as facilitating smooth transitions between different inputs, minimizing potential conflicts or disruptions in user interactions, especially when these inputs are used sequentially or concurrently.

3.10.4 UR4: Minimal interaction footprint. Derived from participants’ concerns about encroaching on neighbor’s space via mid-air movements, and constraints of limited floor space, the third requirement is also related to mitigating the confined-space constraints but focusing more on the aspect of interaction space across all flight stages. The requirement here is to occupy as little table space (for static inputs) and seat room (for dynamic inputs like gesture movements) as possible, minimizing the interaction footprint.

3.10.5 UR5: Keep a Low Profile: Discreet and Quiet. Another recurring theme due to the confined space constraints was passengers’ desire for discretion in public transportation. Participants’ primary concerns about working in MR or using hand gestures both stem from their fear of attracting attention or bothering other passengers. The positive reception of the pillow keyboard for its quiet sound level and the appeal of wearable inputs whether it’s a commonly worn device or its interaction place/position is invisible, also underscores the importance of input modalities that keep a low profile in terms of both visibility [48] and audibility.

4 DEVELOPING THE DESIGN SPACE

To answer the second research question, we aim to develop a design space that is descriptive, evaluative, and generative [5]. Our design space is intended to be a tool to help systematically evaluate input modalities and interaction to guide design opportunities for WoA in the MR.

Integrating the insights derived from the study with past literature, we mapped the user requirements based on their categories to the entire journey of flight. From there, through extensive discussions and iteration among the authors, we identified two design space dimensions including **D1 Physical Properties** and **D2 Interaction Behavior and Impact**, both complementing each other. Each dimension is defined by distinct parameters, the values selected based on the literature [27, 74, 83] and study analysis. **D1** primarily determines the portability and space-efficiency of the input modalities, and **D2** is mainly attributed to comfort, functionality, and confined space constraints. **D2** also emphasizes the interaction space of WoA, considering the interaction between or among multiple inputs. Together, we designed two views of these dimensions, and their corresponding parameters, offering a dual perspective.

Following up the visualization, we introduce each parameter in detail, discussing how they relate to user requirements, posing questions, and lastly describing how to use them. They are meant for practitioners and academics in HCI to ponder the limitations and potentials when designing interaction techniques or creating a novel input modality for WoA in MR.

4.1 Design Space Views

Figure 8 presents the **User Requirement View** of the design space, demonstrating the relationship among categories, URs, and parameters across all flight stages. It maps each requirement to the stage of the flight, which dimension this UR is correlated to, and what parameters are involved.

Parameter View of the design space (Figure 9) provides an overview of where different input sits in the spectrum of each parameter. We used common input modalities as examples. However, each input modality has various models on the market and ranges in size, weight, and dimensions due to different materials. Our selection of choices is meant for directional use, not for exact comparison.

4.2 D1: Physical Properties

The first dimension encompasses seven parameters that explore how the physical properties of an input modality impact the interaction in a mobile situation and how the situated environment could affect passengers’ choice of input modality.

D1-P1. Physical Volume describes the 3D dimensions of input modalities considering their **Length, Width, and Height**. We compare the volume of some common modalities against the most accepted international carry-on size (56cm * 36cm * 23 cm) [73]. Because an input modality is a potential carry-on and some come in pairs, such as controllers, how can designers utilize the items passengers usually bring onboard, adapt airline supplies as input methods, or take advantage of the existing cabin space?

D1-P2. Area Size refers to the full size of the 2D surface an input modality occupies. Using the tray table as the benchmark, we divided it into **Small** (less than 25% Tray), **Medium** (between 25% to half), and **Large** (more than half). How can an input modality take up minimum tray table space without sacrificing functionality? Are multiple small inputs and the combination of their interaction better than one large device?

D1-P3. Weight is measured in **grams**, represented by comparing common inputs, such as mice, smartwatches, off-the-shelf controllers, and keyboards. An input modality can be small in physical volume but heavy, which might not be easy to move around or ideal as a carry-on item.

D1-P4. Exterior Material refers to the tactile feel of an input modality’s surface. There are many categories of materials, from metal and wood to fabric, plastic, and more. Considering that hardware is composed of multiple types of materials, it is difficult to map one modality to one material. Therefore, we focus on the exterior material and categorize it at the level of **Hard Material** or **Soft Material**, which directly impacts how an input modality can be stored, as Hard Material is less compressible, while Soft Material might be more comfortable and warmer to touch.

User Requirements across Flight Stages					Design Space Components		
Category	Packing	Taxing - Takeoff	Inflight (considering various scenarios: meal time, turbulence, neighbours getting up and etc.)	Landing - Taxing	Disembarking	Dimension (D)	Parameter
Travel Logistics	Portable - (a) light and small to be stored					D1: Physical Property	P1. Physical Volume P3. Weight P4. Exterior Material P5. Shape Flexibility
	Portable - (b) convenient to carry, move and put away					D1: Physical Property	P1. Physical Volume P3. Weight P4. Exterior Material P5. Shape Flexibility P7. Connectivity Type
	Portable - (c) easy to manage charging globally					D1: Physical Property	P6. Power Source P7. Connectivity Type
Functionality	Reliable, Intuitive, and Precise - (a) easy to perform needed tasks					D2: Interaction Behaviour and Impact	P8. Input Method P9. Input Type P10. Functionality Type
	Reliable, Intuitive, and Precise - (b) easy to coordinate					D2: Interaction Behaviour and Impact	P8. Input Method P9. Input Type P10. Functionality Type P11. Modality Modes P12. Modality Coordination
Comfort	Comfortable in use- (a) ergonomic interaction					D1: Physical Property D2: Interaction Behaviour and Impact	P4. Exterior Material P9. Input Type P10. Functionality Type P14. Interaction Volume
	Comfortable in use- (b) ergonomic coordination					D2: Interaction Behaviour and Impact	P9. Input Type P10. Functionality Type P11. Modality Modes P12. Modality Coordination P14. Interaction Volume
Confined-Space Constraints	Minimal interaction footprint - occupy minimum table space and/or seat room					D1: Physical Property	P1. Physical Volume P2. Area Size P4. Exterior Material P5. Shape Flexibility
	Keep a low profile - Quiet					D1: Physical Property D2: Interaction Behaviour and Impact	P4. Exterior Material P8. Input Method P15. Sound Level
	Keep a low profile - Discreet					D1: Physical Property D2: Interaction Behaviour and Impact	P1. Physical Volume P2. Area Size P8. Input Method P11. Modality Modes P12. Modality Coordination P13. Spatial Position P14. Interaction Volume

Figure 8: The user requirement view

D1-P5. *Shape Flexibility* considers whether an input modality can shift shape, divided into **Static**, **Foldable**, **Collapsible**, and **Stackable**. A full-sized input modality might be large for travel - can it thus be made of small components, stacked together, or foldable for easy carry? How can an input device flexible in shape retain durability and reliability?

D1-P6. *Power Source* refers to how the input modality is charged and divided into **Wired**, **Rechargeable**, and **Disposable Batteries** and **Battery-free**. Recent research interest in battery-free technology for electronics [32, 80] provides the potential for future input modalities to rely less on conventional methods of charging and be more adaptable worldwide, which would require less preparation and fewer items to bring. However, what resources can be used to harvest the energy to avoid power failure during air travel and how it would interfere with interaction remains unknown.

D1-P7. *Connectivity Type* describes how the input is connected to the MR headset, divided into **Wired** and **Wireless Technology** (i.e., Bluetooth). The more wires required for charging or connecting,

the more clutter it can cause in an economy-class seat, making it more difficult to move when needed.

4.3 D2: Interaction Behavior and Impact

Interaction Behavior and Impact encompasses eight parameters serving as the guideline to evaluate what interaction and how and where it takes place, which can impact productivity in the context of WoA in MR.

D2-P8. *Input Method* categorizes input modalities into **Mouse**, **Keyboard**, **Touch-based**, **Gestures**, **Voice**, **Gaze**, **Controller-based**, and **Wearable-based**. The differences between input methods can be either an advantage or a shortcoming depending on multiple aspects, including but not limited to user tasks, personal habits, the interaction design [27], and the UI design of the applications. For example, how does the interaction differ for a 2D or 3D application in MR? Working in MR is a new interaction language.

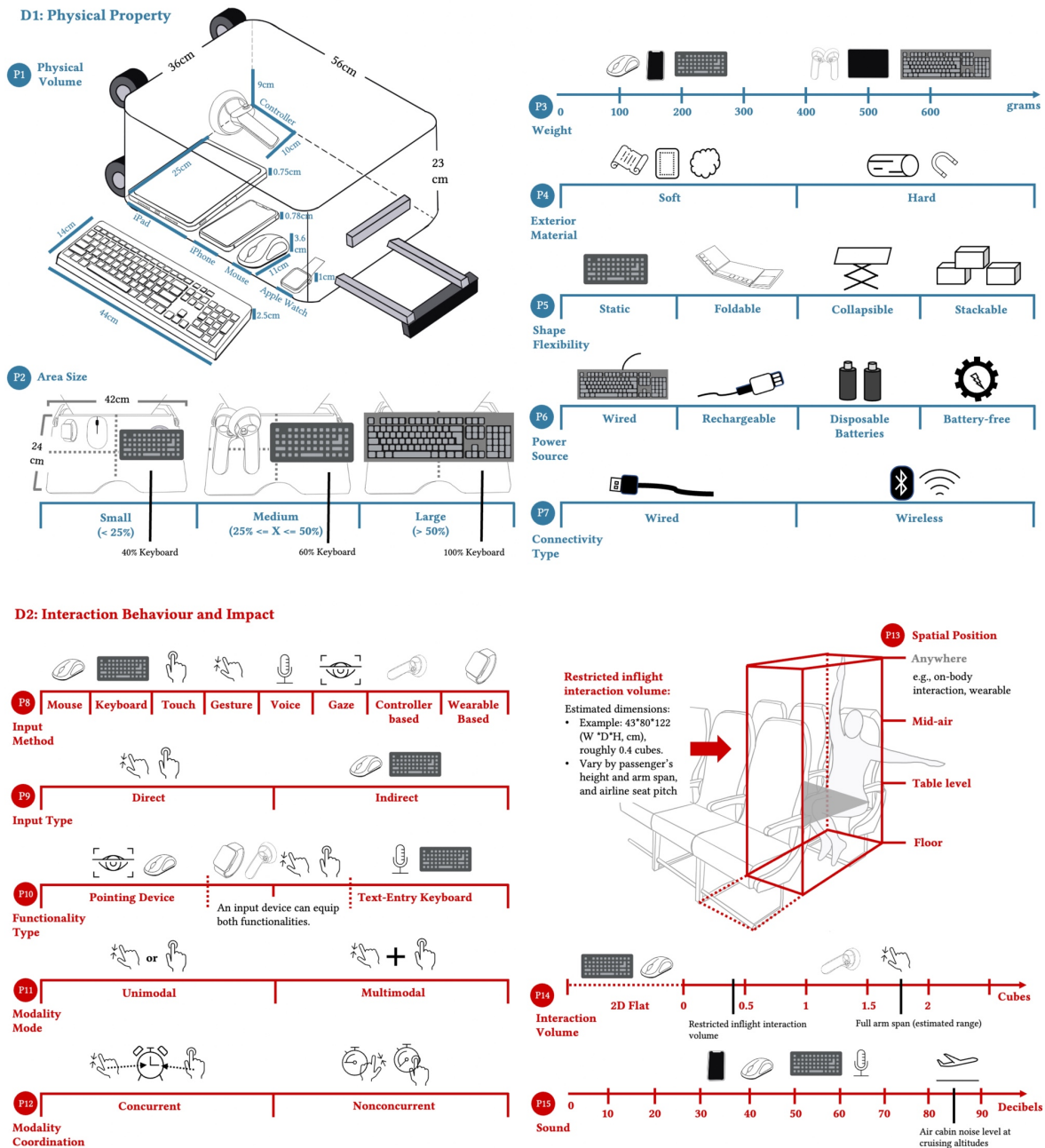


Figure 9: The parameter view

How can the design between an input method and application reduce the learning curve for people? How should designers create discrete interactions for different methods?

D2-P9. *Input Type* is classified into **Direct Input**, which shares the same surface as the output display (i.e., fingers manipulate a virtual object), and **Indirect Input**, which has a different physical position as output (i.e., mouse moves a cursor to a target location on a desk window) [27]. Direct input in MR, for example, manipulating a virtual object with hand gestures, is not more natural than indirect

input with a mouse because the direct input could obscure the vision of the object, lack the same precision as a mouse, and have no tactile feedback. Thus, the prolonged mid-air direct input can cause discomfort and strain on the arms. To what extent does each input type impact ease, familiarity, and comfort for working in MR? How does that affect the design of input modalities?

D2-P10. *Functionality Type* is divided into two main categories **Pointing Device** (i.e., mouse, pen, finger tracking) and **Text-Entry keyboard**. A pointing device can execute many events, from drag

and drop to select and click. An input modality can support both functions, but one may be easier than the other. For example, a mouse can be used for text entry via a virtual keyboard in MR, but it takes longer to type. Hand gestures enable dragging, scrolling, and typing, but repetitive movements can be fatiguing. How can design balance functionality and reduce interaction fatigue?

D2-P11. *Modality Mode* refers to the number of modalities employed in MR, divided into the values of **Unimodal** and **Multi-modal**. Can multimodal interaction (- for instance, the combination of mid-air hand gestures and keyboard) improve productivity and reduce fatigue during long-hour knowledge work? Will multimodal interaction attract more attention in air cabins than unimodal interaction? Considering confidentiality issues with voice input and the limitations of hand gestures, keyboard, and mouse, what alternative or combination of input modalities can support WoA in MR?

D2-P12. *Modality Coordination* describes how multiple modalities work together, whether **Concurrent** or **Nonconcurrent**. For instance, can mid-air hand tracking be used to rotate a virtual object while foot gestures manipulate its size at the same time? Would simultaneous interaction be more effective but harder and less comfortable than nonconcurrent? What tasks benefit from multimodal interaction working at the same time? What input modalities are most suitable for working simultaneously without straining the hands, arms, or legs?

D2-P13. *Spatial Position* refers to the location of the interaction, categorized into **Floor**, **Table-level**, **Mid-air**, and **Anywhere**. For example, a mouse and keyboard are most likely placed on a table, while hand gestures typically happen mid-air. The interaction location affects its discreetness, with mid-air gestures drawing more attention than foot gestures on the floor. However, unfamiliar input modalities can create barriers to their adoption. This parameter highlights the need for a taxonomy of interaction locations in MR for WoA.

D2-P14. *Interaction Volume* relates to the amount of space required for the interaction, quantified in the value of **Cubes**. For instance, the mouse and keyboard interaction space is likely 2D as they are mostly bound to the small tray table, whereas mid-air hand gestures require an average arm span of 1.5-2 cubic meters. The average seat width in an economy class is only around 17 inches (43cm), less than half a cubic width, and the seat pitch varies from 74 to 81 cm. The physical environment restricts the interaction volume of hand gestures due to the potential of invading a seatmate's territory. How can the design guide users to stay within their own space? Should WoA interactions use input modalities with minimal interaction volume? How does the interaction volume impact user comfort?

D2-P15. *Sound Level* is measured in **decibels (DB)** based on the sound intensity an input modality could potentially make, demonstrated using examples of standard inputs. The sound level depends on the types of tasks users would perform, the interaction techniques, and the material of the contact surface. Should the design display decibel figures when the interaction reaches a certain threshold to allow users to be more mindful of the airplane environment?

Considering we are at an exploratory stage, we decided not to include some common parameters such as performance metrics (e.g., pointing speed, error rate, accuracy) or map interaction techniques to tasks such as pinch, zoom, rotate, select, and more. We believe

they are complex topics that demand an elaborate design space. As the technology matures, more parameters can be continually added to improve the design space and meet the requirements of various settings.

4.4 How to use the design space

Our design space provides a structured approach for MR technology designers, seeking to determine the suitability of an input modality for WoA with HMDs or other space-constraint environments. They can leverage both the User-Requirement View and the Parameter View to help identify the potential strengths and weaknesses of the chosen interaction technique and how well the design aligns with the URs.

For example, in the context of air travel, hand gestures (P8) are inherently portable thanks to their lack of physical volume (P1). However, in **D2**, users might be concerned about the conflicts with the confined space constraints as it might incur a large interaction volume and draw attention (P13 & 14). Furthermore, extended periods of mid-air gesturing (P8&9) (P13) could lead to user discomfort. Additionally, the direct manipulation of virtual objects (P9&10) might risk being not precise. The virtual interaction could also increase the sound level when tapping or typing on a surface (P15).

To address these challenges and enhance the URs through leveraging other categories, designers can find alternative input modalities in Parameter View that require less interaction volume (P14), facilitate indirect input (P9) to increase precision and support more text-entry work (P10). While a keyboard is a seemingly good candidate, designers should take into account the potential issues of size (P1&2), static shape (P5), charging needs (P6), table height (P13), and typing sound (P15). It is also another carry-on increasing the risks of damage or loss during travel.

To mitigate this, one approach is to reimagine keyboard design such as transforming the material and shape to make it more portable such as integrating it into clothes: a keyboard jacket. A wearable as an indirect input (P9), is considered highly portable and discreet for interaction. However, the design must carefully consider the visibility and reachability of the wearables for effective working in the XR [24]. On-body interaction could attract unwanted attention when typing on hair, skin, or jacket, but the benefits of being portable, and precise might outweigh the disadvantages.

This example underlines that our design space is not meant to provide definitive solutions but rather to guide practitioners in systematically considering various aspects. It emphasizes the importance of prioritizing user requirements based on specific contexts and the need to understand how each design decision impacts the overall usability and practicality of the input modality.

5 DISCUSSION

Participants' concerns for each presented modality shaped our design space, setting the stage for designers and engineers to address challenges linked to WoA in MR. Through a WoA case study, we delve into the complexities of a resource-constrained environment, which covers a variety of possible factors that could impact work productivity and their relations to input modalities for MR. Designers and engineers can select the most relevant parameters to

evaluate their importance based on different contexts and design input modalities responsive to diverse scenarios.

5.1 Potential Applications in Other Contexts

The potential applications of our findings and design space extend well beyond air travel. The challenges of spatial constraints, privacy, social acceptability, and ergonomic design are ubiquitous across various transportation modes and dynamic environments, both public and private [41, 42, 55]. Our design space could serve a critical role in developing input modalities that meet diverse, essential user requirements for creating MR systems.

For instance, similar to air travel, public transportation such as trains, undergrounds, and buses often involves tight seating arrangements [63] and crowded conditions where the need for minimal interaction space of inputs when working is paramount. Using our design space, designers should consider the physical properties such as size and material of input devices (D1-P1, D1-P4) and their interaction behaviors (D2-P9 Input Type, D2-P13 Spatial Position, D2-P14 Interaction Volume) need to be minimally intrusive and do not disturb others or occupy more space than necessary.

Additionally, public transportation also requires heightened situational awareness, as passengers must remain alert to upcoming stops and transfers, echoing the requirement for the input devices to be portable (D1-P7 Connectivity Type). Our design space provides critical guidelines for developing input modalities that are easily deactivated or stowed when attention must shift suddenly.

Regarding private settings, the in-car MR workspace [40, 41] can also benefit from our design space. For example, applying multimodal interactions (D2-P11 Modality Mode) that blend voice, touch, and gesture controls, could enhance the virtual working experience for passengers. Additionally, future work could research integrating MR input modalities into the current in-vehicle system to ensure that the interaction remains fluid and less cognitively taxing for the user, which is crucial in environments like self-driving cars where passengers' attention may need to change swiftly between tasks [41]. This could not only deliver a more cohesive, and efficient user experience but also improve safety.

In addition to transportation, the principles of the importance of discretion and minimal space usage, are also applicable to other dynamic public scenarios like cafes and libraries. For instance, devices that are collapsible or foldable (D1-P5 Shape Flexibility) and operate quietly (D2-P15 Sound Level) would be particularly beneficial.

Furthermore, virtual workspace [16] has become increasingly relevant in today's hybrid work environments. From navigating large office spaces to working effectively from smaller home office setups, highlights the need for input devices that are portable, easy to set up (D1-P1, D1-P3, D1-P6 Power Source), and support diverse functionality (D2-P10). These design considerations identified in our design space will be crucial for ensuring productivity without the traditional constraints of fixed office environments.

All different settings entail specific challenges. Extending the requirements established for WoA to other settings can lead to significant benefits. Our design space allows designers to identify the most relevant parameters for each context. For example, discreet

interaction might be less crucial for home settings, but design input modalities that are small and portable, i.e., wearables to either declutter office desks or easy to carry to the sofa can be beneficial to many users. Moreover, an input modality designed for the rigors of air travel—security checks, turbulence, etc.—would work well in any mobile workspace.

By incorporating a broader range of contexts into the design process, researchers and designers can leverage our design space to develop input modalities that are not only contextually adaptable but also align with the essential user requirements.

5.2 Future Work with Other Stakeholders

Research has started exploring the interaction concepts of using VR for in-flight entertainment [79]. However, the passenger-centric lens is limiting. Research can examine how airline staff and flight attendants can benefit from passengers' WoA in MR and what barriers and concerns they would have. For example, discreetness is the desired user requirement. However, questions arise, such as whether it would incur safety concerns when cabin crew are unaware of what passengers are doing during flight or how to integrate alerts and broadcasting into the HMD systems for passengers. Future work of HCI can help manage these interactions by inviting these stakeholders into the design process. This applies to any other public transportation from buses and trains to taxis. Even for a shared office environment, understanding the perspectives of both direct users and bystanders [54], be they partners or colleagues, is instrumental for an optimal MR experience.

5.3 Limitations

Although this study shows overall positive results for adopting MR headsets for digital work on the plane, there are a few limitations. First, this study sets the scene for the future where Head-Mounted Displays (HMDs) are more common, much lighter, and easier to use, which does not introduce potential ergonomic issues, such as not being limited to eye strains or visually induced motion sickness [34] from the long hours of wearing. As reflected in our participants' responses these problems affect the acceptability and comfort level of using MR headsets to work. However, Soyka et al.'s [69] studies established that turbulence during air travel will not cause sickness. Pöhlmann et al also demonstrated [58] that the visual and audio cues could help alleviate motion sickness while reading. This supports the prospects of using the MR headset on the plane.

Secondly, this study's reliance on video survey methodology requires participants to use their imagination to envision how they might interact with the probes with MR in the demonstrated scenarios [36], which may not fully capture the nuances of interacting with actual probes over a long-haul flight. This can impact the ecological validity of our findings, a recognized drawback in video-based studies [61]. Despite these challenges, the video survey approach has long been employed as a valuable and reliable [2] alternative in research that could yield rich, insightful data [48]. Koelle et al. [36] argued that this approach allowed for a broader, more diverse sample, enhancing the generalizability of study results across different cultural and regional contexts. Furthermore, we employed the interactive video where we not only invited participants to engage with the video but also simulated a long-haul flight. This approach

has received positive feedback from the participants who found it very helpful in placing them into the contexts. Additionally, the use of video surveys facilitates controlled and safe conditions for studies when traditional in-person/ laboratory studies are not feasible. Looking ahead, complementing this approach with in-person testing within aircraft or similarly constrained physical environments could help validate and deepen our understanding of the physical and sensory dimensions of interacting with input modalities for WoA in MR.

Thirdly, the user needs and the design space constructed in this paper are derived from feedback from participants who have homogenous work backgrounds. Therefore, the identified challenges and the choice of the preferred input modalities are constrained by the types of work participants commonly do. Additionally, the task interaction demonstrated in the video was the direct equivalent of how work is conducted on a 2D screen and limited by one type of multimodal coordination -nonconcurrent. However, MR opens the possibilities of how the common office work could be done differently in a 3D environment. We envision passengers working on different tasks beyond the choices of 2D window-based work and might use multiple modalities simultaneously, which implies different types of interaction. Future research can engage participants from a wider variety of professional backgrounds and demonstrate more complex use cases that might provide further insights into the design space.

Last but not least, while our design space was developed through rigorous internal validation by the authors, who bring expert knowledge and experience in design, HCI, and XR development, we acknowledge that it has not yet been evaluated externally by other industry designers or HCI researchers. This limitation was due to the exploratory nature and scope of this research. To achieve broader validation and ensure the design space meets the evolving needs of the field, we suggest future work include workshops or interviews with industry practitioners to gain deeper insights into the usability and applicability of the design space.

Despite these limitations, our study also provides immense opportunities for future research to probe deep into each problem space. Given the exploratory nature of this paper, this study aimed to elicit user thoughts, establish guidelines for how to conduct digital work with HMDs, and illustrate future design directions. Therefore, we believe the stated limitations do not constrain the findings of this research.

6 CONCLUSION

The knowledge work in MR on transportation shows great promise to improve the experience of WoA for travelers who fly economy class on long-haul flights. Grounded in the user-centered study, this paper investigates the critical user requirements of input modalities for WoA in MR. After using four input options as design probes via an interactive video, participants' feedback revealed nuanced criteria for input modalities. We found that the productivity level supported by the input modality was the top concern for users, followed by the portability of the input, comfort of use, interaction space, and how private the interaction is. Our interactive video was

well-received by all participants who considered it not only engaging but also facilitating critical thinking, which offers a new way to deeply understand user interaction in simulated environments.

Informed by these results, we constructed a design space of input modalities with two views, categorizing dimensions of Physical Properties and Interaction Behavior and Impact. The goal is to provide guidelines and design directions to support the ergonomic and productive interaction experience of WoA in MR. These findings offer directions for future studies to design different input modalities and interaction techniques for WoA in MR as well as conduct information work in other resource-constrained settings.

REFERENCES

- [1] Naseem Ahmadpour, Jean-Marc Robert, and Gitte Lindgaard. 2016. Aircraft passenger comfort experience: Underlying factors and differentiation from discomfort. *Appl. Ergon.* 52, (January 2016), 301–308. <https://doi.org/10.1016/j.apergo.2015.07.029>
- [2] Fouad Alallah, Ali Neshati, Nima Shebani, Yumiko Sakamoto, Andrea Bunt, Pourang Irani, and Khalad Hasan. 2018. Crowdsourcing vs Laboratory-Style Social Acceptability Studies? Examining the Social Acceptability of Spatial User Interactions for Head-Worn Displays. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*, April 21, 2018. Association for Computing Machinery, New York, NY, USA, 1–7. <https://doi.org/10.1145/3173574.3173884>
- [3] Jeffrey Bardzell, Shaowen Bardzell, Christian Briggs, Kevin Makice, William Ryan, and Matt Weldon. 2006. Machinima prototyping: an approach to evaluation. In *Proceedings of the 4th Nordic conference on Human-computer interaction: changing roles (NordiCHI '06)*, October 14, 2006. Association for Computing Machinery, New York, NY, USA, 433–436. <https://doi.org/10.1145/1182475.1182530>
- [4] Anthony Bazelle, Hugo Pourrier-Nunez, Maxime Rignault, and Michael Chang. 2018. Simulation of different materials texture in virtual reality through haptic gloves. In *SIGGRAPH Asia 2018 Posters (SA '18)*, December 04, 2018. Association for Computing Machinery, New York, NY, USA, 1–2. <https://doi.org/10.1145/3283289.3283370>
- [5] Michel Beaudouin-Lafon. 2004. Designing interaction, not interfaces. In *Proceedings of the working conference on Advanced visual interfaces (AVI '04)*, May 25, 2004. Association for Computing Machinery, New York, NY, USA, 15–22. <https://doi.org/10.1145/989863.989865>
- [6] Lonni Besançon, Paul Issartel, Mehdi Ammi, and Tobias Isenberg. 2017. Mouse, Tactile, and Tangible Input for 3D Manipulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*, May 02, 2017. Association for Computing Machinery, New York, NY, USA, 4727–4740. <https://doi.org/10.1145/3025453.3025863>
- [7] Verena Biener, Daniel Schneider, Travis Gesslein, Alexander Otte, Bastian Kuth, Per Ola Kristensson, Eyal Ofek, Michel Pahud, and Jens Grubert. 2020. Breaking the Screen: Interaction Across Touchscreen Boundaries in Virtual Reality for Mobile Knowledge Workers. *IEEE Trans. Vis. Comput. Graph.* 26, 12 (December 2020), 3490–3502. <https://doi.org/10.1109/TVCG.2020.3023567>
- [8] Virginia Braun and Victoria Clarke. 2019. Reflecting on reflexive thematic analysis. *Qual. Res. Sport Exerc. Health* 11, 4 (August 2019), 589–597. <https://doi.org/10.1080/2159676X.2019.1628806>
- [9] Volkert Buchmann, Stephen Violich, Mark Billinghurst, and Andy Cockburn. 2004. FingARTips: gesture based direct manipulation in Augmented Reality. In *Proceedings of the 2nd international conference on Computer graphics and interactive techniques in Australasia and South East Asia (GRAPHITE '04)*, June 15, 2004. Association for Computing Machinery, New York, NY, USA, 212–221. <https://doi.org/10.1145/988834.988871>
- [10] Luca Chittaro, Cynthia L. Corbett, G. A. McLean, and Nicola Zangrando. 2018. Safety knowledge transfer through mobile virtual reality: A study of aviation life preserver donning. *Saf. Sci.* 102, (February 2018), 159–168. <https://doi.org/10.1016/j.ssci.2017.10.012>
- [11] Andrea Colaço, Ahmed Kirmani, Hye Soo Yang, Nan-Wei Gong, Chris Schmandt, and Vivek K. Goyal. 2013. Mime: compact, low power 3D gesture sensing for interaction with head mounted displays. In *Proceedings of the 26th annual ACM symposium on User interface software and technology (UIST '13)*, October 08, 2013. Association for Computing Machinery, New York, NY, USA, 227–236. <https://doi.org/10.1145/2501988.2502042>
- [12] Kara Cutruzzola. How to Actually Get Work Done on an Airplane. *The Points Guy UK*. Retrieved August 15, 2020 from <https://thepointsguy.co.uk/news/how-to-get-work-done-on-a-plane/>
- [13] Fred D. Davis. 1985. A technology acceptance model for empirically testing new end-user information systems: theory and results. Thesis. Massachusetts Institute of Technology. Retrieved September 10, 2020 from <https://dspace.mit.edu/handle/>

- 1721.1/15192
- [14] David Dobbstein, Philipp Hock, and Enrico Rukzio. 2015. Belt: An Unobtrusive Touch Input Device for Head-worn Displays. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*, April 18, 2015. Association for Computing Machinery, New York, NY, USA, 2135–2138. <https://doi.org/10.1145/2702123.2702450>
- [15] Tafadzwa Joseph Dube and Ahmed Sabbir Arif. 2019. Text Entry in Virtual Reality: A Comprehensive Review of the Literature. In *Human-Computer Interaction. Recognition and Interaction Technologies (Lecture Notes in Computer Science)*, 2019. Springer International Publishing, Cham, 419–437. https://doi.org/10.1007/978-3-030-22643-5_33
- [16] Jens Grubert, Eyal Ofek, Michel Pahud, and Per Ola Kristensson. 2018. The Office of the Future: Virtual, Portable, and Global. *IEEE Comput. Graph. Appl.* 38, 6 (November 2018), 125–133. <https://doi.org/10.1109/MCG.2018.2875609>
- [17] Jens Grubert, Lukas Witzani, Eyal Ofek, Michel Pahud, Matthias Kranz, and Per Ola Kristensson. 2018. Text Entry in Immersive Head-Mounted Display-Based Virtual Reality Using Standard Keyboards. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, March 2018. 159–166. <https://doi.org/10.1109/VR.2018.8446059>
- [18] Darren Guinness, Alvin Jude, G. Michael Poor, and Ashley Dover. 2015. Models for Rested Touchless Gestural Interaction. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction (SUI '15)*, August 08, 2015. Association for Computing Machinery, New York, NY, USA, 34–43. <https://doi.org/10.1145/2788940.2788948>
- [19] Jie Guo, Dongdong Weng, Zhenliang Zhang, Haiyan Jiang, Yue Liu, Yongtian Wang, and Henry Been-Lirn Duh. 2019. Mixed Reality Office System Based on Maslow's Hierarchy of Needs: Towards the Long-Term Immersion in Virtual Environments. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, October 2019. 224–235. <https://doi.org/10.1109/ISMAR.2019.00019>
- [20] Sean G. Gustafson, Bernhard Rabe, and Patrick M. Baudisch. 2013. Understanding palm-based imaginary interfaces: the role of visual and tactile cues when browsing. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*, 2013. ACM Press, Paris, France, 889. <https://doi.org/10.1145/2470654.2466114>
- [21] Aaron Gutiérrez, Daniel Miravet, and Antoni Domènech. 2021. COVID-19 and urban public transport services: emerging challenges and research agenda. *Cities Health* 5, sup1 (July 2021), S177–S180. <https://doi.org/10.1080/23748834.2020.1804291>
- [22] Jonas Haeling, Christian Winkler, Stephan Leenders, Daniel Keßelheim, Axel Hildebrand, and Marc Necker. 2018. In-Car 6-DoF Mixed Reality for Rear-Seat and Co-Driver Entertainment. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, March 2018. 757–758. <https://doi.org/10.1109/VR.2018.8446461>
- [23] Corey D. C. Heath, Tracey Heath, Troy McDaniel, Hemant Venkateswara, and Sethuraman Panchanathan. 2020. Using Participatory Design to Create a User Interface for Analyzing Pivotal Response Treatment Video Probes. In *Smart Multimedia (Lecture Notes in Computer Science)*, 2020. Springer International Publishing, Cham, 183–198. https://doi.org/10.1007/978-3-030-54407-2_16
- [24] Florian Heller, Kashyap Todt, and Kris Luyten. 2021. An Interactive Design Space for Wearable Displays. In *Proceedings of the 23rd International Conference on Mobile Human-Computer Interaction (MobileHCI '21)*, September 27, 2021. Association for Computing Machinery, New York, NY, USA, 1–14. <https://doi.org/10.1145/3447526.3472034>
- [25] Juan David Hincapié-Ramos, Xiang Guo, Paymahn Moghadasian, and Pourang Irani. 2014. Consumed endurance: a metric to quantify arm fatigue of mid-air interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*, April 26, 2014. Association for Computing Machinery, New York, NY, USA, 1063–1072. <https://doi.org/10.1145/2556288.2557130>
- [26] Ken Hinckley, Michel Pahud, Hrvoje Benko, Pourang Irani, François Guimbretière, Marcel Gavrilu, Xiang “Anthony” Chen, Fabrice Matulic, William Buxton, and Andrew Wilson. 2014. Sensing techniques for tablet+stylus interaction. In *Proceedings of the 27th annual ACM symposium on User interface software and technology (UIST '14)*, October 05, 2014. Association for Computing Machinery, New York, NY, USA, 605–614. <https://doi.org/10.1145/2642918.2647379>
- [27] Ken Hinckley and Daniel Wigdor. INPUT TECHNOLOGIES AND TECHNIQUES. 49.
- [28] Ken Hinckley, Koji Yatani, Michel Pahud, Nicole Coddington, Jenny Rodenhouse, Andy Wilson, Hrvoje Benko, and Bill Buxton. 2010. Pen + touch = new tools. In *Proceedings of the 23rd annual ACM symposium on User interface software and technology (UIST '10)*, October 03, 2010. Association for Computing Machinery, New York, NY, USA, 27–36. <https://doi.org/10.1145/1866029.1866036>
- [29] Philipp Hock, Sebastian Benedikter, Jan Gugenheimer, and Enrico Rukzio. 2017. CarVR: Enabling In-Car Virtual Reality Entertainment. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17)*, May 02, 2017. Association for Computing Machinery, New York, NY, USA, 4034–4044. <https://doi.org/10.1145/3025453.3025665>
- [30] Baosheng James Hou, Joshua Newn, Ludwig Sidenmark, Anam Ahmad Khan, Per Bækgaard, and Hans Gellersen. 2023. Classifying Head Movements to Separate Head-Gaze and Head Gestures as Distinct Modes of Input. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*, April 19, 2023. Association for Computing Machinery, New York, NY, USA, 1–14. <https://doi.org/10.1145/3544548.3581201>
- [31] Yi-Ta Hsieh, Antti Jylhä, Valeria Orso, Luciano Gamberini, and Giulio Jacucci. 2016. Designing a Willing-to-Use-in-Public Hand Gestural Interaction Technique for Smart Glasses. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*, May 07, 2016. Association for Computing Machinery, New York, NY, USA, 4203–4215. <https://doi.org/10.1145/2858036.2858436>
- [32] Qianyi Huang, Yan Mei, Wei Wang, and Qian Zhang. 2018. Toward Battery-Free Wearable Devices: The Synergy between Two Feet. *ACM Trans. Cyber-Phys. Syst.* 2, 3 (June 2018), 20:1-20:18. <https://doi.org/10.1145/3185503>
- [33] Christian P. Janssen, Andrew L. Kun, Stephen Brewster, Linda Ng Boyle, Duncan P. Brumby, and Lewis L. Chuang. 2019. Exploring the concept of the (future) mobile office. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings (AutomotiveUI '19)*, September 21, 2019. Association for Computing Machinery, New York, NY, USA, 465–467. <https://doi.org/10.1145/3349263.3349600>
- [34] Jason Jerald. Motion Sickness. In *The VR Book: Human-Centered Design for Virtual Reality*. Association for Computing Machinery and Morgan & Claypool. Retrieved September 9, 2020 from <https://doi.org/10.1145/2792790.2792806>
- [35] Pascal Knierim, Valentin Schwind, Anna Maria Feit, Florian Nieuwenhuizen, and Niels Henze. 2018. Physical Keyboards in Virtual Reality: Analysis of Typing Performance and Effects of Avatar Hands. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*, April 21, 2018. Association for Computing Machinery, Montreal QC, Canada, 1–9. <https://doi.org/10.1145/3173574.3173919>
- [36] Marion Koelle, Swamy Ananthanarayan, and Susanne Boll. 2020. Social Acceptability in HCI: A Survey of Methods, Measures, and Design Strategies. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*, April 21, 2020. Association for Computing Machinery, New York, NY, USA, 1–19. <https://doi.org/10.1145/3313831.3376162>
- [37] Aaron Kotranza, John Quarles, and Benjamin Lok. 2006. Mixed reality: are two hands better than one? In *Proceedings of the ACM symposium on Virtual reality software and technology (VRST '06)*, November 01, 2006. Association for Computing Machinery, Limassol, Cyprus, 31–34. <https://doi.org/10.1145/1180495.1180503>
- [38] DoYoung Lee, Youryang Lee, Yonghwan Shin, and Ian Oakley. 2018. Designing Socially Acceptable Hand-to-Face Input. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18)*, October 11, 2018. Association for Computing Machinery, New York, NY, USA, 711–723. <https://doi.org/10.1145/3242587.3242642>
- [39] Laura Lewis, Harshada Patel, Mirabelle D’Cruz, and Sue Cobb. 2017. What makes a space invader? Passenger perceptions of personal space invasion in aircraft travel. *Ergonomics* 60, 11 (November 2017), 1461–1470. <https://doi.org/10.1080/00140139.2017.1313456>
- [40] Jingyi Li, Ceenu George, Andrea Ngao, Kai Holländer, Stefan Mayer, and Andreas Butz. 2021. Rear-Seat Productivity in Virtual Reality: Investigating VR Interaction in the Confined Space of a Car. *Multimodal Technol. Interact.* 5, 4 (April 2021), 15. <https://doi.org/10.3390/mti5040015>
- [41] Jingyi Li, Alexandra Mayer, Florian Müller, Andrii Matvienko, and Andreas Butz. 2023. Location-Aware Virtual Reality for Situational Awareness On the Road. In *Proceedings of the 2023 ACM Symposium on Spatial User Interaction (SUI '23)*, October 13, 2023. Association for Computing Machinery, New York, NY, USA, 1–12. <https://doi.org/10.1145/3607822.3614530>
- [42] Jingyi Li, Luca Woik, and Andreas Butz. 2022. Designing Mobile MR Workspaces: Effects of Reality Degree and Spatial Configuration During Passenger Productivity in HMDs. *Proc. ACM Hum.-Comput. Interact.* 6, MHCI (September 2022), 181:1-181:17. <https://doi.org/10.1145/3546716>
- [43] Pedro Lopes. 2016. Proprioceptive Interaction: The User’s Muscles as Input and Output Device. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 2016. ACM Press, San Jose, California, USA, 223–228. <https://doi.org/10.1145/2851581.2859014>
- [44] Wendy E. Mackay and Anne Laure Fayard. 1999. Video brainstorming and prototyping: techniques for participatory design. In *CHI '99 Extended Abstracts on Human Factors in Computing Systems (CHI EA '99)*, May 15, 1999. Association for Computing Machinery, New York, NY, USA, 118–119. <https://doi.org/10.1145/632716.632790>
- [45] Denys J. C. Matthies, Franz Müller, Christoph Anthes, and Dieter Kranzlmüller. 2013. ShoeSoleSense: proof of concept for a wearable foot interface for virtual and real environments. In *Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology - VRST '13*, 2013. ACM Press, Singapore, 93. <https://doi.org/10.1145/2503713.2503740>
- [46] Mark McGill, Gang Li, Alex Ng, Laura Bajorunaite, Julie Williamson, Frank Pollock, and Stephen Brewster. 2022. Augmented, Virtual and Mixed Reality Passenger Experiences. In *User Experience Design in the Era of Automated Driving*, Andreas Riener, Myoungsoon Jeon and Ignacio Alvarez (eds.). Springer International Publishing, Cham, 445–475. https://doi.org/10.1007/978-3-030-77726-5_17

- [47] Mark McGill, Julie Williamson, Alexander Ng, Frank Pollick, and Stephen Brewster. 2020. Challenges in passenger use of mixed reality headsets in cars and other transportation. *Virtual Real.* 24, 4 (December 2020), 583–603. <https://doi.org/10.1007/s10055-019-00420-x>
- [48] Daniel Medeiros, Romane Dubus, Julie Williamson, Graham Wilson, Katharina Pöhlmann, and Mark McGill. 2023. Surveying the Social Comfort of Body, Device, and Environment-Based Augmented Reality Interactions in Confined Passenger Spaces Using Mixed Reality Composite Videos. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7, 3 (September 2023), 113:1–113:25. <https://doi.org/10.1145/3610923>
- [49] Daniel Medeiros, Graham Wilson, Mark McGill, and Stephen Anthony Brewster. 2023. The Benefits of Passive Haptics and Perceptual Manipulation for Extended Reality Interactions in Constrained Passenger Spaces. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*, April 19, 2023. Association for Computing Machinery, New York, NY, USA, 1–19. <https://doi.org/10.1145/3544548.3581079>
- [50] Katsumi Minakata, John Paulin Hansen, I. Scott MacKenzie, Per Bækgaard, and Vijay Rajanna. 2019. Pointing by gaze, head, and foot in a head-mounted display. In *Proceedings of the 11th ACM Symposium on Eye Tracking Research & Applications*, June 25, 2019. ACM, Denver Colorado, 1–9. <https://doi.org/10.1145/3317956.3318150>
- [51] Wen Mo, Martin Johannes Dechant, Nicolai Marquardt, Amid Ayobi, Aneesha Singh, and Catherine Holloway. 2024. Knowledge Work on Airplanes: Challenges, Workarounds, and Design Implications. In *Extended Abstracts of the 2024 CHI Conference on Human Factors in Computing Systems (CHI EA '24)*, May 11, 2024. Association for Computing Machinery, New York, NY, USA, 1–7. <https://doi.org/10.1145/3613905.3650873>
- [52] Florian Müller, Joshua McManus, Sebastian Günther, Martin Schmitz, Max Mühlhäuser, and Markus Funk. 2019. Mind the Tap: Assessing Foot-Taps for Interacting with Head-Mounted Displays. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, 2019. ACM Press, Glasgow, Scotland UK, 1–13. <https://doi.org/10.1145/3290605.3300707>
- [53] Eyal Ofek, Jens Grubert, Michel Pahud, Mark Phillips, and Per Ola Kristensson. 2020. Towards a Practical Virtual Office for Mobile Knowledge Workers. (August 2020). Retrieved August 25, 2022 from <https://www.microsoft.com/en-us/research/publication/towards-a-practical-virtual-office-for-mobile-knowledge-workers/>
- [54] Joseph O'Hagan, Julie R. Williamson, Florian Mathis, Mohamed Khamis, and Mark McGill. 2023. Re-Evaluating VR User Awareness Needs During Bystander Interactions. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*, April 19, 2023. Association for Computing Machinery, New York, NY, USA, 1–17. <https://doi.org/10.1145/3544548.3581018>
- [55] Pablo E. Paredes, Stephanie Balters, Kyle Qian, Elizabeth L. Murnane, Francisco Ordóñez, Wendy Ju, and James A. Landay. 2018. Driving with the Fishes: Towards Calming and Mindful Virtual Reality Experiences for the Car. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 4 (December 2018), 184:1–184:21. <https://doi.org/10.1145/3287062>
- [56] Ken Pfeuffer, Benedikt Mayer, Diako Mardanbegi, and Hans Gellersen. 2017. Gaze + pinch interaction in virtual reality. In *Proceedings of the 5th Symposium on Spatial User Interaction (SUI '17)*, October 16, 2017. Association for Computing Machinery, Brighton, United Kingdom, 99–108. <https://doi.org/10.1145/3131277.3132180>
- [57] Alexander Plopski, Teresa Hirzle, Nahal Norouzi, Long Qian, Gerd Bruder, and Tobias Langlotz. 2022. The Eye in Extended Reality: A Survey on Gaze Interaction and Eye Tracking in Head-worn Extended Reality. *ACM Comput. Surv.* 55, 3 (March 2022), 53:1–53:39. <https://doi.org/10.1145/3491207>
- [58] Katharina Margareta Theresa Pöhlmann, Gang Li, Mark McGill, Reuben Markoff, and Stephen Anthony Brewster. 2023. You spin me right round, baby, right round: Examining the Impact of Multi-Sensory Self-Motion Cues on Motion Sickness During a VR Reading Task. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*, April 19, 2023. Association for Computing Machinery, New York, NY, USA, 1–16. <https://doi.org/10.1145/3544548.3580966>
- [59] Ramesh Raskar, Greg Welch, Matt Cutts, Adam Lake, Lev Stesin, and Henry Fuchs. 1998. The office of the future: a unified approach to image-based modeling and spatially immersive displays. In *Proceedings of the 25th annual conference on Computer graphics and interactive techniques (SIGGRAPH '98)*, July 24, 1998. Association for Computing Machinery, New York, NY, USA, 179–188. <https://doi.org/10.1145/280814.280861>
- [60] Julie Rico and Stephen Brewster. 2010. Usable gestures for mobile interfaces: evaluating social acceptability. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*, April 10, 2010. Association for Computing Machinery, New York, NY, USA, 887–896. <https://doi.org/10.1145/1753326.1753458>
- [61] Yvonne Rogers, Kay Connelly, Lenore Tedesco, William Hazlewood, Andrew Kurtz, Robert E. Hall, Josh Huresey, and Tammy Toscos. 2007. Why it's worth the hassle: The value of in-situ studies when designing ubicomp. In J. Krumm, G. D. Abowd, A. Seneviratne and T. Strang (eds.), Springer, Berlin, 336–353. Retrieved May 5, 2024 from <https://oro.open.ac.uk/15665/>
- [62] Emma Roth. 2023. The Apple Vision Pro could come with a “travel mode” for plane rides. *The Verge*. Retrieved July 17, 2023 from <https://www.theverge.com/2023/6/22/23770217/apple-vision-pro-travel-mode-plane-rides-vr>
- [63] James Rothwell. 2024. German trains to get frosted glass cabins for two. *The Telegraph*. Retrieved May 4, 2024 from <https://www.telegraph.co.uk/world-news/2024/04/17/germany-unveils-smooth-cabins-on-inter-city-trains/>
- [64] Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori. 2015. Head-mounted display with mid-air tactile feedback. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology (VRST '15)*, November 13, 2015. Association for Computing Machinery, New York, NY, USA, 51–58. <https://doi.org/10.1145/2821592.2821593>
- [65] Maximilian Schirmer, Johannes Hartmann, Sven Bertel, and Florian Echterl. 2015. Shoe me the Way: A Shoe-Based Tactile Interface for Eyes-Free Urban Navigation. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services - MobileHCI '15*, 2015. ACM Press, Copenhagen, Denmark, 327–336. <https://doi.org/10.1145/2785830.2785832>
- [66] Thereza Schmelter and Kristian Hildebrand. 2020. Analysis of Interaction Spaces for VR in Public Transport Systems. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, March 2020. 279–280. <https://doi.org/10.1109/VRW50115.2020.00058>
- [67] Dominik Schmidt, Christoph Sterz, Yanina Yurchenko, Patrick Baudisch, Raf Ramakers, Esben W. Pedersen, Johannes Jasper, Sven Köhler, Aileen Pohl, Hannes Rantzsch, Andreas Rau, and Patrick Schmidt. 2014. Kickables: tangibles for feet. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*, 2014. ACM Press, Toronto, Ontario, Canada, 3143–3152. <https://doi.org/10.1145/2556288.2557016>
- [68] Daniel Schneider, Alexander Otte, Travis Gesslein, Philipp Gagel, Bastian Kuth, Mohamad Shahm Damlakhi, Oliver Dietz, Eyal Ofek, Michel Pahud, Per Ola Kristensson, Jörg Müller, and Jens Grubert. 2019. ReconViguration: Reconfiguring Physical Keyboards in Virtual Reality. *IEEE Trans. Vis. Comput. Graph.* 25, 11 (November 2019), 3190–3201. <https://doi.org/10.1109/TVCG.2019.2932239>
- [69] Florian Soyka, Elena Kokkinara, Markus Leyrer, Heinrich Buelthoff, Mel Slater, and Betty Mohler. 2015. Turbulent motions cannot shake VR. In *2015 IEEE Virtual Reality (VR)*, March 2015. 33–40. <https://doi.org/10.1109/VR.2015.7223321>
- [70] Marco Speicher, Anna Maria Feit, Pascal Ziegler, and Antonio Krüger. 2018. Selection-based Text Entry in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, 2018. ACM Press, Montreal QC, Canada, 1–13. <https://doi.org/10.1145/3173574.3174221>
- [71] Misha Ira, Abhinandan Jain, and Pattie Maes. 2019. Adding Proprioceptive Feedback to Virtual Reality Experiences Using Galvanic Vestibular Stimulation. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, 2019. ACM Press, Glasgow, Scotland UK, 1–14. <https://doi.org/10.1145/3290605.3300905>
- [72] Misha Ira and Chris Schmandt. 2015. MetaSpace II: Object and full-body tracking for interaction and navigation in social VR. *ArXiv151202922 Cs* (December 2015). Retrieved June 5, 2020 from <http://arxiv.org/abs/1512.02922>
- [73] Lauren Stuttaford. 2021. Airline Carry On Luggage Size Restrictions (Updated for 2022). *Air Doctor*. Retrieved September 13, 2022 from <https://www.air-dr.com/media/travel/airline-carry-on-luggage-size-restrictions-a-2021-guide>
- [74] Hemant Bhaskar Surale, Aakar Gupta, Mark Hancock, and Daniel Vogel. 2019. TableInVR: Exploring the Design Space for Using a Multi-Touch Tablet in Virtual Reality. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, 2019. ACM Press, Glasgow, Scotland UK, 1–13. <https://doi.org/10.1145/3290605.3300243>
- [75] Hamed Taherdoost. 2018. A review of technology acceptance and adoption models and theories. *Procedia Manuf.* 22, (January 2018), 960–967. <https://doi.org/10.1016/j.promfg.2018.03.137>
- [76] Wen-Jie Tseng, Samuel Huron, Eric Lecolinet, and Jan Gugenheimer. 2023. FingerMapper: Mapping Finger Motions onto Virtual Arms to Enable Safe Virtual Reality Interaction in Confined Spaces. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23)*, April 19, 2023. Association for Computing Machinery, New York, NY, USA, 1–14. <https://doi.org/10.1145/3544548.3580736>
- [77] Eduardo Velloso, Dominik Schmidt, Jason Alexander, Hans Gellersen, and Andreas Bulling. 2015. The Feet in Human-Computer Interaction: A Survey of Foot-Based Interaction. *ACM Comput. Surv.* 48, 2 (November 2015), 1–35. <https://doi.org/10.1145/2816455>
- [78] Qiaosi Wang, Ida Camacho, Shan Jing, and Ashok K. Goel. 2022. Understanding the Design Space of AI-Mediated Social Interaction in Online Learning: Challenges and Opportunities. *Proc. ACM Hum.-Comput. Interact.* 6, CSCW1 (March 2022), 1–26. <https://doi.org/10.1145/3512977>
- [79] Julie R. Williamson, Mark McGill, and Khari Outram. 2019. PlaneVR: Social Acceptability of Virtual Reality for Aeroplane Passengers. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, 2019. ACM Press, Glasgow, Scotland UK, 1–14. <https://doi.org/10.1145/3290605.3300310>
- [80] Jasper de Winkel, Vito Kortbeek, Josiah Hester, and Przemysław Pawelczak. 2020. Battery-Free Game Boy. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 3 (September 2020), 111:1–111:34. <https://doi.org/10.1145/3411839>

- [81] Koki Yamashita, Takashi Kikuchi, Katsutoshi Masai, Maki Sugimoto, Bruce H. Thomas, and Yuta Sugiura. 2017. CheekInput: turning your cheek into an input surface by embedded optical sensors on a head-mounted display. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology (VRST '17)*, November 08, 2017. Association for Computing Machinery, New York, NY, USA, 1–8. <https://doi.org/10.1145/3139131.3139146>
- [82] Ja Eun Yu and Gerard J. Kim. 2015. Resolving view difference between eye and camera for proprioceptive pointing and selection in augmented reality applications. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology - VRST '15*, 2015. ACM Press, Beijing, China, 198–198. <https://doi.org/10.1145/2821592.2821648>
- [83] Qian Zhou, George Fitzmaurice, and Fraser Anderson. 2022. In-Depth Mouse: Integrating Desktop Mouse into Virtual Reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems (CHI '22)*, April 29, 2022. Association for Computing Machinery, New York, NY, USA, 1–17. <https://doi.org/10.1145/3491102.3501884>
- [84] Plane Passenger's MacBook Screen Destroyed After Person In Front Reclines. Retrieved August 15, 2020 from <https://www.unilad.co.uk/technology/plane-passengers-macbook-screen-destroyed-after-person-in-front-reclines/>