# From Shielding to Avoidance: Passenger Augmented Reality and the Layout of Virtual Displays for Productivity in Shared Transit

Daniel Medeiros, Mark McGill, Alexander Ng, Robert McDermid, Nadia Pantidi, Julie Williamson, Stephen Brewster

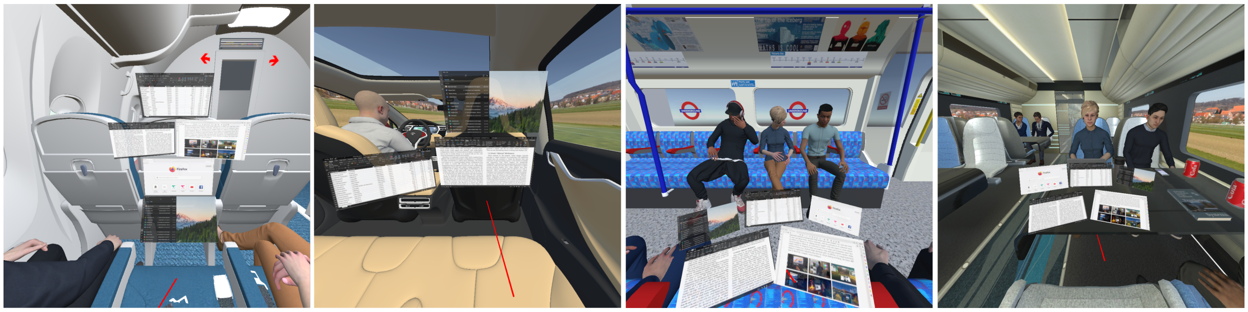

Fig. 1: Participant generated examples of AR workspace layouts across four transport environments: airplane, car, subway and train.

**Abstract**— Passengers spend considerable periods of time in shared transit spaces, relying on smartphones and laptops for work. However, these displays are limited in size and ergonomics compared to typical multi-monitor setups used in the office, impairing productivity. Augmented Reality (AR) headsets could provide large, flexible virtual workspaces during travel, enabling passengers to work more efficiently. This paper investigates the factors affecting how passengers choose to layout virtual displays in car, train, subway and plane environments, studying the affordances of each mode of transport and the presence of others. Results from our experiment showed: significant usage of the physical environment to align displays; strong social effects meant avoiding placing displays over other passengers or their belongings; and use of displays for shielding oneself from others. Our findings show the unique challenges posed by the mode of transport and presence of others on the use of AR for mobile productivity in the future.
.

**Index Terms**—Augmented Reality, Productivity, Virtual Workspaces, Mixed Reality, Extended Reality, Passengers, Transport, Transit, Airplanes, Cars, Trains, Subway, Mobility

## 1 Introduction

Travel plays a significant part in our daily lives. Public transport is how we navigate the world, from local commutes in taxis and subways, to travel over greater distances and durations in trains and planes. Passengers travelled over 873 billion kilometres in the UK in 2019 [57], whilst in the EU there were 416 billion passenger kilometres using railways [17] with over 1 billion people travelling by air in the same period [16]. New modes of transport such as autonomous ride-share services [38] are also reshaping and redefining how and when we travel. Consequently, the need to support passengers to fill their travel time usefully and productively continues to be a key economic and societal challenge. There has been an increasing reliance on personal mobile devices in these contexts - laptops, tablets and smartphones - to fill travel time. Personal devices enable passengers to move away from ergonomically uncomfortable in-vehicle screens and seat-back displays [44]. However, personal devices can be limited in size and the capacity to position them ergonomically, which can cause neck fatigue. Privacy is rarely assured, with displays frequently visible to others and subject to glare and reflections.

• *Daniel Medeiros, Mark McGill, Alexander Ng, Robert McDermid, Julie Williamson and Stephen Brewster are with University of Glasgow, UK . E-mail: {daniel.piresdesamedeiros,mark.mcgill,alexander.ng,julie.williamson, stephen.brewster}@glasgow.ac.uk.*
• *Nadia Pantidi is with Victoria University of Wellington. E-mail: nadia.pantidi@vuw.ac.nz.*

*Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of Publication xx xxx. 201x; date of current version xx xxx. 201x. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org. Digital Object Identifier: xx.xxxx/TVCG.201x.xxxxxxx*

Augmented Reality (AR) headsets can overcome many of the problems associated with personal devices. Virtual displays (typically referring to virtual containers for positioning 2/3D application content [43]) can be sized, oriented and positioned flexibly, based on user needs and comfort. Virtual displays allow the creation of a private virtual space [33] or virtual office [48], shielding passengers from undesirable behaviours and auditory or visual noise. They can overcome the problems of personal devices as they can adapt based on the travel environment visibility [43,44,47] and passengers' social connectedness to, and awareness of, other travellers [2].

Travel environments bring unique affordances that might influence how AR virtual displays can be used, as space is often constrained and shared with other travellers in close proximity (e.g. economy plane seating). Prior research has focused predominantly on plane environments, for example demonstrating social acceptability challenges around Mixed Reality (MR) headset adoption [61], or difficulties around how virtual workspaces can fit into the constrained space of the plane [47]. However, there remain gaps in knowledge around the impact the varying travel environment, and the consequent social presence of other passengers, has on how we might utilize virtual displays and workspaces.

We address these gaps in knowledge in the use of mobile workspaces in transit by replicating real environments of different travel environments (cars, planes, trains and subways) in VR with simulated avatar passengers. VR has seen increasing use in the simulation of AR experiences for passengers [54], for example in airplane contexts [47] and for in-car windshield display design [22,28], with notable benefits in supporting controlled and safe evaluation of the passenger user experience [54]. In this work, we conducted a user study (N=20) that enabled users to create virtual workspaces by placing varying numbers of displays

(1, 3 and 5) to better understand how the physical affordances of the different passenger contexts (cars, trains, planes and subway) impact the placement of these displays in simulated AR.

The contributions of this work are threefold: 1) We show empirical evidence regarding how the transport environment, and the social presence of others, influences the creation of virtual workspace layouts; 2) Backed by qualitative evidence, we reflect on the strategies participants used and the rationales that directed the creation of these layouts, in particular demonstrating both social shielding and avoidance behaviours using AR; 3) We derive design considerations that can inform future research into AR passenger context-aware virtual workspace layouts, in particular balancing differing needs for social awareness against productivity and comfort.

## 2 Related Work

As people are spending significant amounts of time travelling, solutions are needed to make this more enjoyable and productive. In this section, we present previous work on passenger experiences, VR and AR, and the social acceptability of technology use.

### 2.1 Personal Space and Social Discomfort

The passenger transit experience can be divided into two categories: *private transport*, with cars accounting for 84 percent of passenger Kilometres in the UK in 2019/20 [57]; and *public transport*, with 4.5 billion bus journeys, 1.7 billion rail journeys, and 0.3 billion light rail and tram journeys in the UK in 2019/20. Shared public transit is typically designed to satisfy the dual aims of efficiency and comfort. The tension between these results in seating layouts that "force people into an intimate distance with strangers, causing social discomfort" [59]. This is due to a lack of physical barriers between fellow travellers and, crucially, "a lack of personal space or perceived privacy" which "elevates the traveller's stress level" [1] and increases discomfort - with *space invaders* [33] a particular concern, even leading to physical confrontations[1]. Care must be taken that the introduction of new technology does not make these situations worse.

The social discomfort caused by new technology can be eased through positive social interactions [59], as well as respecting other's personal space [19]. However, the most direct resolution is through defensive measures such as "involvement shields" intended to cover behaviours that signal improper situational involvement [23, 31]. These involvement shields have become increasingly virtual in nature. For example, personal headphones and in-flight audio and entertainment have been referred to as a *techno-cocoon* [24]. This enables users to isolate in bubbles [10, 29] that shield them from other passengers. Ahmadpour *et al*. [2] classified passenger attitudes in terms of adjusting, avoiding, approaching and shielding, linked to "passengers' concerns for control, privacy, social connectedness and/or social tolerance". As the social tolerance classification suggests, this demand for isolation is not universal as some passengers may prefer to travel in their personal cocoons (in countries like the United States), others prefer a more social experience while travelling (e.g. Asia) [24]. This paper focuses on how travellers choose to lay out AR displays to create effective workspaces. One of the key factors may be to shield themselves from other passengers using the displays, potentially impacting display usability.

### 2.2 Multi-Display Workspaces

The benefits [4] and drawbacks [30] of multi-display environments [20] have been extensively discussed. Users show a preference for such configurations, as they enable "multi-window and rich information tasks, enhanc(ing) users' awareness of peripheral applications, and offer(ing) a more immersive experience [6]. Multi-display workspaces allow us to access more information [11], facilitate peripheral awareness of information [26] and increase productivity by enabling more efficient multitasking [8].

When rendered by AR headsets, virtual displays have the potential to "break the physical rules and constraints of physical display spaces" to the benefit of usability and ergonomics [43]. These displays are dynamically configurable, unconstrained in terms of layout, orientation, depth and scale, able to either supplement or replace existing physical displays [53]. These features have been previously exploited by McGill *et al*. [43], where horizontal three/five display virtual workspaces were dynamically actuated based on head movements to improve the ergonomics of interacting with peripheral displays. Ens *et al*. referred to such virtual displays as "Ethereal Planes", suggesting a breadth of exo- and ego-centric layouts [12]. For the latter, research has envisioned content being placed around the user in a variety of configurations vertically [13], horizontally, two-plus-two [36], or oriented toward the user as in the "personal cockpit" [13, 15].

For passengers, virtual workspaces offer a chance to move away from the constraints of mobile devices such as tablets, smartphones and laptops, to appropriate or occlude the space around them for display [43, 48]. Support for passenger use of AR headsets is growing, with research tackling the key barriers like motion sickness and maintaining alignment [44]. As a result, we can expect that consumer AR and VR headsets will function correctly in autonomous cars, planes, trains and other modes of transport. A common usage of AR is the use (or simulation) of windshield displays for displaying augmented information about the physical environment, both inside and outside automated vehicles [28, 54, 56]. Whilst VR will allow for passengers to entirely escape their physical environment [34], AR is of particular interest for the mobile productivity use case. Recent research explored the simulated use of AR in a plane setting [47] and found that the social context of the environment appeared to influence preferences between horizontal and vertical display layouts, and could be an important factor to consider when designing virtual workspaces for use in shared transport. Therefore, we investigated social context as a key factor in the study reported in this paper and tested display layouts across four common modes of transport.

### 2.3 Passenger Augmented Reality: A Cause of or Solution to Social Discomfort?

AR gives passengers a new level of control over their environment, giving the ability to encroach on others' personal space and erect virtual private shields [23, 31] which occlude the sights and sounds of others. Where the affordances of physical shields like displays or headphones are highly visible to bystanders, these new virtual barriers are invisible. However, passenger AR also introduces the risk of inadvertently unacceptable encounters [27], for example seeming to stare at another passenger or gesture towards them when virtual content collides with physical surroundings. Staring can be a "complex, nuanced, and meaning-laden social interaction... which is sometimes a random, idiosyncratic confrontation and at other times a highly structured social ritual" [21]. This could significantly impact the acceptance of AR in public transport, and interactivity and awareness have been shown to impact acceptance of VR in such contexts [5, 60]. Consider also that in public transport we have a perception of personal space that can extend around our seat to the seatback directly in front or the arm rest. If we render wide horizontal workspaces, these could infringe upon the perceived personal space of others [18, 33, 52], introducing significant social acceptability concerns [61].

A key question for this paper is how the shared social space changes the usage of AR. Do passengers adapt their usage to take into account the presence of others and their perceived personal space, and the social acceptability of their own actions? Or is AR used to change the perception of physical space, erecting virtual barriers to others, prioritising personal comfort and usability over the invasion of others' personal space. It is unknown how these physical elements help in creating feasible display layouts, while avoiding violations of social norms and privacy [25, 35]. Our focus in this paper is on how travellers choose to lay out AR displays to create effective workspaces. One of the key factors may be to shield themselves from other passengers using the displays, which potentially impacts display usability.

[1] www.sfgate.com/travel/article/sfo-flight-passengers-fight-delays-police-16248923.php

## 3 Study: Exploring AR Workspace Layouts in Simulated Passenger Environments

Our study investigated the layout of AR displays by passengers in different forms of shared transport. We looked at how participants would configure different numbers of displays, how the physical surroundings affected layout choices, and the social effects of other passengers in their environment. Understanding these considerations is crucial to designing effective virtual workspaces for passengers. We formalise our aims in the following two research questions:

**RQ1 - Mode of Transport:** Does the Mode of Transport and proximity of other passengers significantly alter virtual display layouts? If so, what aspects of the environment influenced the layouts, and how?

**RQ2 - Number of Displays:** To what extent does the Number of Displays impact the user's capability to create, and preferences for using, a virtual display layout?

### 3.1 Virtual Transit Environments and Avatars

To simulate the experience of travelling in different Modes of Transport, we used four high-fidelity interior models: an airplane, a car, a train and a subway train, rendered in VR using an Oculus Quest 2 headset. They had different seating layouts and physical affordances so that we could examine their effects on display layouts. The use of VR as a testbed for AR is a common form of creating a more controlled environment, particularly for public settings [40–42, 58]. There was no perceived motion to avoid any issues of simulator/cyber-sickness. We also did not include any sounds in the different modes of transport.

Each Mode of Transport was selected because it posed unique social challenges regarding how the AR user was exposed to others. Consequently, they each were populated with avatars representing bystander members of the public - recreating the experience of solo travelling. For the *car* (Figure 2-A), the user sat in the rear right seat while a single avatar sat in the front left driver's seat, the equivalent of a taxi ride. In the *train* (Figure 2-B), a typical two-by-two table seating arrangement was used where the user sat in the left seat facing forward while avatars sat in the other three seats. Two additional avatars were used to fill peripheral seats to create a more realistic train carriage scene. In the virtual *subway* (Figure 2-C), passengers sat opposite each other with seven other avatars distributed within the scene to create a busy transit scenario: an avatar sat on each side of the user, three avatars were placed directly across, and the remaining two standing avatars were placed around the carriage. In the *airplane* (Figure 2-D), the user sat in the middle of a row of three seats with two avatars, one sitting either side, a common situation when travelling in economy class.

The virtual avatars were selected from the Adobe Mixamo library, which includes human-like characters and animations. The animations represented different activities (e.g., typing on a laptop, talking to each other, moving their hands) to make them appear more life-like and recreate real-world social situations, increasing their perceived social presence [49]. Our avatars did not convey any awareness/attention cues (e.g. staring at the passenger user) as they only increase social presence when there is a need for collaboration between users and agents [50], which is not our case. Whilst we could envision a variety of avatar behaviours which might impact social discomfort, our focus was on the impact of co-presence alone and not the impact of potentially socially disruptive behaviours by other passengers. Controlling avatar social behaviour was particularly important given the breadth of personality traits/behaviours a social agent could mimic, mixed in with potential cultural effects/interpretations, e.g. if one culture is more private, less likely to establish eye contact, more/less likely to stare, etc.

### 3.2 Experimental Design and Methodology

Twenty participants (13 females and 7 males, mean age = 25.4 years, SD = 8) were recruited and were paid £20 for their time. Most of the participants had previous experience with VR headsets (13 participants out of 20), but most had no experience with AR (13 participants). Most reported using some type of device (tablet/laptop/mobile phone) for work (16 participants) and for entertainment purposes (19 participants) while in transit.

The study used a within subjects design, with participants experiencing all conditions. There were two independent variables: *Mode of Transport* (Airplane, Subway, Car, Train) and *Number of Displays* (1, 3, 5 displays), resulting in twelve conditions in total. The *Mode of Transport* and *Number of Displays* were counterbalanced using a Balanced Latin Square Design to reduce any learning effects. All *Number of Displays* conditions were completed for a particular *Mode of Transport* before moving onto the next transport type. The experiment took approximately 90 minutes to complete. We ensured the participants took a rest between conditions to minimise any possible VR-induced sickness.

After completing all the conditions in a Mode of Transport, the participants filled in a post-transport questionnaire on a tablet. In addition to the questionnaire, we conducted a semi-structured interview to capture participants' perceptions about the display configurations they experienced and to get suggestions on how the environment influenced the layouts they had just created. The experiment was approved by the ethics committee of our University. It was conducted in a large room during the COVID-19 pandemic with appropriate precautions taken. We greeted the participant, presented them with an information sheet describing the experiment and a consent form, where they gave their consent for the activity and interview logs used. After that, they filled in a short questionnaire to collect demographic information and previous experience of VR and AR. They were seated on a fixed chair and given the Quest headset. Once comfortable, participants performed a training session to familiarise themselves with the controls for manipulating the virtual displays. For the main experiment, a *Mode of Transport* was shown and the participant was presented with one, three or five displays. They were asked to position/resize/tilt the display(s) to their preference to create a layout suitable for productivity. Once the participant was satisfied with their choice, the layout was saved. After that, participants were asked to fill in a post-condition questionnaire about the condition they had just experienced.

### 3.3 Experimental Task

We evaluated layouts with one, three and five displays to see how participants would choose to lay them out. This range would force users to think about the size and location of displays carefully while allowing people to recreate a complete workspace environment. Each display showed a static screenshot of common desktop applications used for productivity tasks. A screenshot of a sample Word document was shown for the one display condition; For three displays, a spreadsheet and email client were added; For the five displays condition, a Web browser and a PDF viewer were added.

Users manipulated the displays into the layouts they wanted using the right-hand Oculus controller to: (1) position the displays on the x- and y- axes, (2) control the depth, moving the displays closer or further away and potentially beyond any seats, objects and avatars in front), (3) scale to make the displays smaller or larger but keeping the 16:9 aspect ratio, and (4) tilt the displays up/down, and left/right.

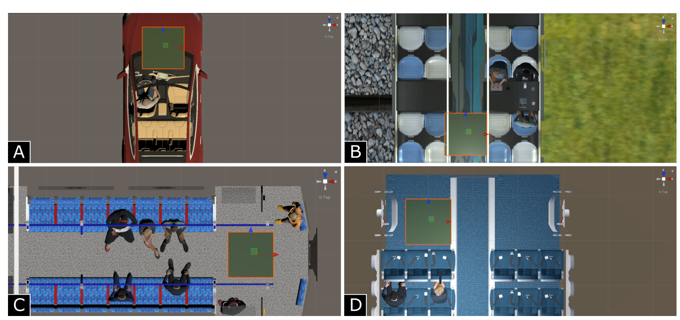


Fig. 2: Top-down view for the Modes of Transport. We included a reference cube with 1m side for scale reference. (A) Car (B) Train (C) Subway (D) Plane. The dimensions of each environment were broadly representative of real-world transit experiences.

Participants did not interact with the content in the displays as the focus was on display layout creation.In all tested conditions, the displays were initially positioned 0.8 meters in front of the participant's head position. The initial display positions were kept the same for all Modes of Transport to avoid bias in creating layouts between scenes. The displays were stacked in front of each other according to the display's rendered task (main task and secondary tasks).

The experiment ran on an Oculus Quest 2 headset connected to a desktop PC via Oculus Link. This setup guaranteed that the scene was rendered in maximum resolution and ran at maximum frame rate. Each display had slight transparency (*alpha* = 230, 90%) so that the participant could see the surroundings behind the display to simulate AR as current headsets are not 100% occlusive).

## 3.4 Data Collection

Our dependent variables covered a range of quantitative and qualitative data to fully investigate our research questions.

### 3.4.1 Quantitative Data

Participants responded to 9-point Likert-type questions both after each condition and after each Mode of Transport.These questionnaires were used to collect feedback on attitudes toward the creation of the layouts, the influence of others, and comfort. This feedback was then used to understand how these factors affect content placement with different transport types (RQ1) and varying Numbers of Displays (RQ2). For the post-condition questionnaires, there were five questions: **Satisfaction**: How satisfied were you with your final display layout? (1-Not satisfied, 9-Very satisfied); **Task Difficulty**: How difficult was it to create your final display layout? (1-Very easy, 9-Very Difficult); **Influence of Avatars**: How did the presence of the avatars impact your decisions when creating the layout? (1-No Impact, 9-High Impact); **Visual Comfort**: Please rate the visual comfort of the layout you created (1-Very low, 9-Very High); **Likelihood of use**: How likely would you be to use the layout you designed in this travel environment in the real world? (1-Very Unlikely, 9-Very Likely).

After each Mode of Transport, we asked users to rank their preferred layout in terms of the Number of Displays. They were also asked to rank their likelihood of using the displays created in a real-world situation. Participants were then shown a screenshot of the scene with a grid overlaid.on the tablet. They were asked to mark where they would position content (green - positive) and where they would not (red - negative). This was to gain further insight about locations in the scene which were acceptable or not for content placement (RQ1).

We captured quantitative data in the form of logs for each display for every layout created by participants. *Content positioning* data included the position of each display, depth and orientation relative to the participant, which was used to understand if people oriented screens according to their view or dependent on the physical surfaces present in the environment. These data were then used to generate summary statistics. We also calculated the perceived size of the displays, based on size and distance from the participant, describing the extent to which the display consumed the horizontal field of view of the headset.

After completing each set of layouts in a Mode of Transport, participants filled in a supplementary questionnaire with two additional questions. The first asked them to rate their preferred layout in terms of the No. of Displays, while the second they rated how likely they would use the layouts created in real life.

### 3.4.2 Qualitative Data

After completing all the experimental conditions, we conducted short semi-structured interviews to capture participants' perceptions of the display configurations they created within each Mode of Transport. The interview questions also prompted participants about the influence of other passengers and physical constraints in the virtual environment in their layouts, by addressing specific aspects for each Mode of Transport in turn (e.g. the confined space of the car, people sitting face-to-face, and a table between passengers in the case of the train), for more granular detail. The semi-structured interviews were audio-recorded and then transcribed for purposes of analysis. Interview data were analysed using Thematic Analysis [7]. In line with Braun and Clarke's approach, the analysis involved familiarisation with the dataset through careful reading and re-reading of the data, line-by-line coding, generating initial codes, sorting, and constructing and reviewing sub-themes and themes. The resulting themes from the analysis were reviewed in a data session with three other members of the research team until consensus was reached that they accurately represented the patterns of meaning which occurred across participants during the interviews.

# 4 Results

## 4.1 Quantitative Results

In the following subsections, we present the analysis of the results from the questionnaires and log files conducted using the R statistical analysis package.

### 4.1.1 Post-Condition - Attitudes Towards Created Layouts

Figure 3 summarises the responses to the five attitude questions asked after each condition. An Aligned Rank Transform (ART) [62] was used to transform the data for each question and a two-factor repeated-measures ANOVA was then performed with *Mode of Transport* (for RQ1) and *Number of Displays* (for RQ2) as factors. All plots show 95% confidence intervals (green error bars) [9].

Regarding ***Satisfaction*** with the layout created, we found significant results for both the Mode of Transport ($F_{3,57}$=4.162 p=0.01) (RQ1) and Number of Displays ($F_{2,38}$=23.096 p<0.001) (RQ2).We found also that users were significantly more satisfied with layouts created in the Car as compared to the Subway (p=0.023) (RQ1) (none of the other comparisons were significantly different). Users were significantly

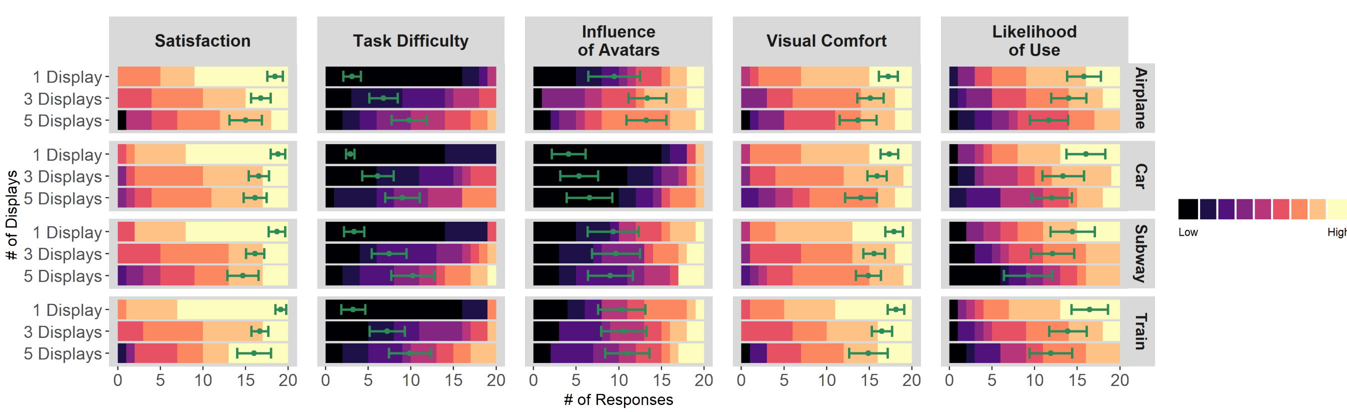


Fig. 3: Summary of the post-condition questionnaire responses. The stacked bars show the count of responses. The green bars show the 95% confidence interval of the responses on a scale of 0 to 9. Lighter colours indicate higher/stronger responses.

more satisfied with the layouts created using 1 display than with both 3 ($p<0.001$) and 5 displays ($p<0.001$) (RQ2). There were no significant interaction effects.

There was a significant effect of ***Task Difficulty*** for Number of Displays ($F_{2,38}$=55.08, $p<0.001$) (RQ2): layouts with one display were easier to create than 3 ($p<0.001$) and 5 displays ($p<0.001$), with 5 displays being more difficult than 3 (p=0.001). There was no effect for Mode of Transport.

The ***Influence of Avatars*** showed a significant effect for Mode of Transport ($F_{3,57}$=30.27, $p<0.0001$) (RQ1). We also found a significantly lower influence of the presence of the avatars in the Car when compared to the Airplane ($p<0.001$), Subway ($p<0.001$) and Train ($p<0.001$) settings (no other pairs were significantly different). We found interaction effects between mode of transport and number of displays (layouts).

For ***Visual Comfort***, we found a significant effect for Number of Displays ($F_{2,38}$=20.67, $p<0.001$) (RQ2), with the 1 display layout rated as the most visually comfortable when compared to the other two (3 display: $p<0.001$ and 5 display:$p<0.001$). There was no effect for Mode of Transport and no interaction effects.

Regarding the ***Likelihood of Use***, the analysis showed significant results for both Mode of Transport ($F_{3,36}$=4.109, p=0.007) (RQ1) and Number of Displays ($F_{2,57}$=27.18, $p<0.001$) (RQ2). Participants rated that they would be less likely to use layouts created in the Subway compared to both the Airplane (p=0.006) Car (p=0.013) and Train (p=0.019) environments (RQ1). We observed similar behaviour for Number of Displays, with the 1 display layout being the most likely to be used in real life when compared to both 3 ($p<0.001$) and 5 display Layouts ($p<0.001$) (RQ2). There were no interaction effects.

#### 4.1.2 Post-Mode of Transport Questionnaires

After each mode of Transport, Participants rated their **overall preferred layout** and how likely they would use their created layout in real-life. These layouts (RQ2) were ranked using a scale from 1 to 3, where 1 was the most and 3 the least preferred layout. The results showed that participants rated 3 displays as their most preferred (73.5%), followed by 1 display (21.25%), and then 5 displays (5.55%). When asked whether they would use the created layouts in real life, 58% of the participants reported they were likely or very likely to use the displays they created (RQ2). For Mode of Transport, results showed 75% of participants would be likely to use their Plane layouts, followed by the Train (65% ) and the Car (60%). For the Subway, participants ranked layouts more negatively (40% of negative responses) than positively (35% of positive responses).This reaffirms the impact of Mode of Transport in layout creation (RQ1)

#### 4.1.3 Content Positioning

To understand the positioning strategies adopted, we classified each of the virtual displays according to its position in the 3D environment (Figures 5. These displays were coded according to their position in relation to the user's calibrated head position on both the Vertical (Above, Below and Centre) and Horizontal (Left, Right, and Centre) axes. This gives a useful heatmap of the most common virtual display locations for each Mode of Transport. For more granular information regarding individual displays, we recorded every layout created and used these to generate summary statistics regarding display orientation, to give insight into how nearby surfaces were appropriated. There were two categories: *Flat* in space and *Oriented* toward the user (Figure 6).

*Positioning of Virtual Displays:* We observed a trend of people appropriating physical elements of the physical space in the scene to position displays against - both for vertical surfaces (e.g. seatbacks, on planes and cars) and horizontal surfaces (e.g. tables in the train). In addition, results show a tendency of participants to avoid positioning displays in front of an avatar's eyes when avatars were located opposite, as seen in the train and subway settings.Participants avoided positioning displays in their peripheral view to maintain some level of situational awareness (Figure 5). This shows that the Mode of Transport had a clear effect on the layout of displays (RQ1).

For 1 display layouts, virtual displays were commonly positioned along the vertical axis (with 15 participants positioning displays front centre).Participants adopted a similar strategy with layouts consisting of three displays, where they were primarily positioned vertically at the centre of their field of view. The strategy in the Train environment was different from the other modes of transport. Here, participants placed their displays below the centre line, anchored to the table in front of them (similar to where a laptop might be placed). This was even more pronounced in the 5 display condition (Figure 5, bottom right); users tended to place the additional virtual displays all over the environment. Two participants in both the 3 and 5 display conditions did not use one of the displays, making the display small and moving it far from sight. These behaviours indicate a significant influence of the number of displays on the layout placement (RQ2).

*Orientation of Virtual Displays:* We classified the display layouts created by the participants in accordance to their orientation. In our classification, *Flat* indicates layouts that are flat in space, *Mixed* contain both flat and displays oriented towards the user and *Oriented*, only displays oriented toward the user. Results for display orientation showed a tendency for people to angle displays towards themselves in layouts with one display. However, in the Car environment, most users oriented the displays flat in the world (RQ1), placed against the seatback in front of them. For layouts with 3 displays, there was a general tendency to use a mix of flat and oriented displays that consisted of a centrally positioned flat display and peripheral displays oriented towards the user,

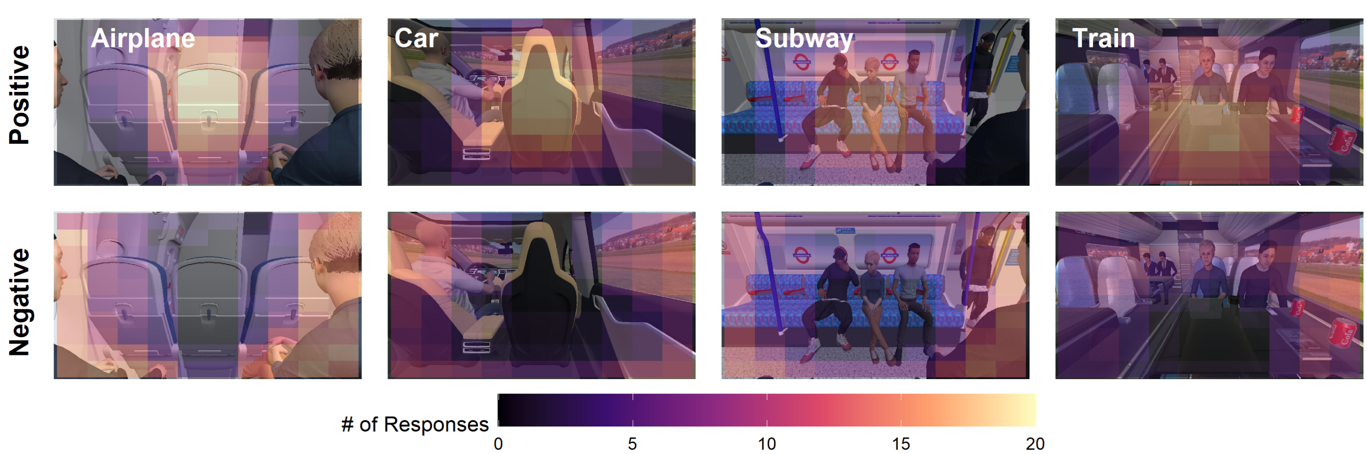


Fig. 4: Heatmaps obtained from from the content positioning grids, split by Mode of Transport, positive responses (where users would place content – top) and negative responses (where users would not place content – bottom). Lighter colours indicate more responses.

| Environment | # of Displays | Mean Depth (m) | MD Std.Dev | Mean Diagonal Size (m) | MDS Std.Dev | Mean Perceived Size (°) | MPS Std.Dev | MPS of Largest Display (°) | MPSLD Std.Dev |
|---|---|---|---|---|---|---|---|---|---|
| Airplane | 1 | 0.60 | 0.14 | 0.64 | 0.23 | 49.54 | 11.14 | 49.54 | 11.14 |
| Car | 1 | 0.52 | 0.07 | 0.56 | 0.12 | 50.29 | 9.82 | 50.29 | 9.82 |
| Subway | 1 | 0.66 | 0.32 | 0.62 | 0.20 | 48.33 | 14.75 | 48.33 | 14.75 |
| Train | 1 | 0.74 | 0.36 | 0.68 | 0.23 | 47.74 | 16.57 | 47.74 | 16.57 |
| Airplane | 3 | 0.60 | 0.15 | 0.50 | 0.17 | 40.16 | 10.76 | 46.76 | 12.61 |
| Car | 3 | 0.57 | 0.09 | 0.48 | 0.12 | 40.48 | 11.20 | 48.08 | 11.22 |
| Subway | 3 | 0.61 | 0.20 | 0.49 | 0.13 | 40.63 | 14.15 | 46.76 | 15.46 |
| Train | 3 | 0.71 | 0.20 | 0.54 | 0.21 | 37.30 | 10.80 | 42.54 | 10.41 |
| Airplane | 5 | 0.59 | 0.10 | 0.44 | 0.13 | 35.69 | 10.07 | 45.88 | 11.02 |
| Car | 5 | 0.59 | 0.12 | 0.41 | 0.13 | 34.27 | 10.16 | 43.60 | 12.12 |
| Subway | 5 | 0.66 | 0.42 | 0.46 | 0.17 | 38.01 | 13.35 | 47.94 | 16.10 |
| Train | 5 | 0.75 | 0.35 | 0.49 | 0.20 | 34.24 | 13.91 | 44.18 | 19.70 |

Table 1: Summary of virtual display depth and size based on log files, with lighter colours representing larger numbers. Mean Perceived Size (MPS) refers to the horizontal size in degrees of the display, taking into account actual width and depth relative to the participant. We calculated the perceived size of each display in °as the angular diameter, using $\alpha = 2\tan^{-1}(horizontalsize/(2*distancetodisplay))$

similar to office setups. An exception to this can be seen in the Train. Here, half of the participants created Oriented-only displays, where the central display was positioned above the table and angled towards the user. These results indicate a tendency of users to anchor displays to the table and not place them directly at eye level, as indicated by Figure 5. For the 5 Display conditions, participants created a more varied set of layouts due to the limited space, but with a focus on the table as an anchor (Figure 6).

*Display Size:* We calculated summary statistics for every display across layouts - the diagonal size (in meters); the depth of the display relative to the user (in meters); and the resultant perceived size (in °), as can be seen in Table 1. Results show that participants used a narrow range of displays sizes when creating a layout. A common approach shows a centrally positioned display, bigger than the rest. This strategy

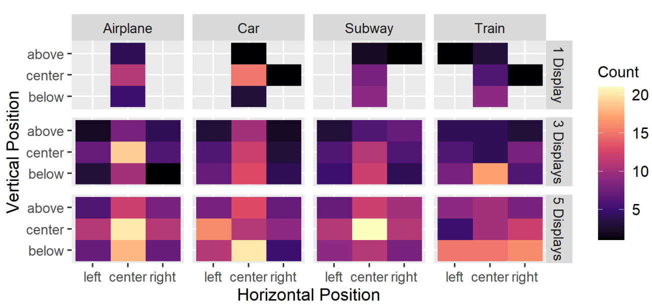


Fig. 5: Heatmap representing the positioning of displays in relation to the participant's field of view in the Vertical (above,centre,below) and Horizontal (right,centre,left) axes. The heatmap is subdivided based on the number of displays and Mode of Transport, with lighter colours indicating higher incidence of a display.

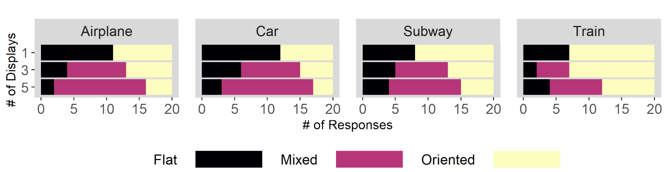


Fig. 6: Summary of the orientation of layouts created. *Flat* indicates layouts that are flat in space, *Mixed* contain a mix of flat and oriented displays, and *Oriented* only displays oriented toward the user.

was adopted in most combinations of Mode of Transport and Number of displays. In layouts with one display, for instance, all users created a large main display. As the number of displays increased, the central display tended to decrease in size, but still remained larger than the others in that layout. This behaviour demonstrates that the number of displays affected content positioning (RQ2). Regarding depth, Table 1 shows that participants used a narrow depth range for their displays, respecting the environment boundaries,for example, not putting content beyond the seats in front in the car, or below the table in the train (RQ1).

In the semi-structured interviews that took place after all the conditions had taken place, participants were asked to discuss their display arrangement choices with regards to each transport scenario. Their responses offered nuanced considerations around: social etiquette, such as avoiding other passengers' faces and personal space; specific aspects of comfort, both physical and social; transport type and spatial affordances, such as avoiding windows and opting for back of seats. Participants reasoning around their choices of where (not) to place displays was found to prioritise social norms and etiquette, followed by comfort, familiarity and safety over other spatial or functional considerations.

#### 4.1.4 Transport type and spatial affordances

Both the Mode of Transport and Number of displays informed participants' decisions with regards to placing the virtual displays. Participant responses offered nuanced considerations around specific aspects of transport type and spatial affordances, such as windows and corridors, that were not anticipated. It was evident from participants' responses that the number of displays often made it difficult to create a good layout, with screens being reduced in size to fit, or moving them around to squeeze them in (potentially to less usable locations):

> *"The size of the screens couldn't be too big; otherwise, you wouldn't have enough space to have all 5 or all 3 of the pictures." (P20)*

In terms of Mode of Transport type, participants found the car and airplane more constrained compared to the train and subway. This was more prominent when having to place more virtual displays:

> *"Yeah, I was more comfortable having more screens in bigger open areas, especially for productivity which 5 screens were OK, especially in the subway and the train, but it wasn't that nice in the car or in the airplane as there wasn't much space around me." (P12)*

The subway and the train were described as more open (and also busier in terms of avatars) which resulted in different placement strategies, such as widening display size and 'spreading' them in a horizontal array compared to vertical stacking that was utilised more in the plane and car:

> *"On the plane, I took the avatars into account for some reason and tried to have everything directly in front of me stacked on top of each other vertically. On the train, I didn't care about the people; it was easier." (P13)*

The majority (16/20) of the participants further reported opting to use what they considered 'blank, 'unused' or 'underused' surfaces such as the back of chairs or the floor. Similar to the vertical stacking strategy above, this was more common in the car or the airplane where overall space was considered more limited:

> *"I tried to put displays where there was kinda nothing that I would want to see behind, like the backs of seats." (P1)*

> *"I was kind of using the surfaces I had to align things; in the plane and car, there is a seat, and I put the screens there and adjusted for the size more or less." (P18)*

In the subway, participants also discussed using the floor and the area above the windows both as they were void of distractions (such as other people moving), but also in accordance to common social etiquette that dictates looking down or up but not directly at others. As can also be seen in Fig. 7, several participants felt very strongly about avoiding placing virtual displays over the windows, corridors or spaces that provided views to doorways (airplane and train). Participants discussed how this was so they could see the scenery, keep aware of what is happening around them or if someone was trying to talk to them which suggests both safety and sociability considerations:

Fig. 7: Layouts created by participant P18 for the five display condition across modes of transport using a wider field-of-view camera to better represent both the displays and the environment. Here we see signs of avoiding placing content over windows in both the car and train environments, and using the virtual displays as a shield to others in the subway. (The red line represents the raycast from the controller).

> *"For instance, I was trying to see out the windows or at the top of the subway car." (P1)*
>
> *"firstly I tried to keep the screens away from people or entrances or windows so that I can have an idea of what's happening around me." (P3)*

#### 4.1.5 Comfort

Participants' responses disclosed a range of notions around comfort as part of their considerations for display placement. Many (14/20) discussed placing their screens right in front of them or in a front facing range that ensured a comfortable posture, where there was no eye or neck strain, as P13's excerpt illustrates:

> *"More just so I can easily view the displays and have them in the centre view, so I don't need to strain my neck from side to side, and the main display would be right in the middle of my field of view." (P13)*

Comfort also involved positioning and adjusting size and distance based on what was considered best or most efficient for the primary task, such as making a display big enough to be readable or front in field of view:

> *"Keeping things that were important for productivity or entertainment, I wanted them to be eye-level, and everything else could be scattered around." (P9)*
>
> *"Secondly I tried to place the screens in a way that follow a comfortable flow of reading and position them based on the interest I had in the topic on the screen itself." (P3)*

Moreover, comfort considerations related to familiarity and existing practices as participants discussed how they replicated the kinds of multi-display setups common in the home or office:

> *"Mostly it was how I would use it on my desktop as well, if I had 3 screens, it was like I had my desktop computer in front of me, and for the 5 screen one I was focusing on the main screen to be the closest to me, and the ones I don't really care about were further away." (P12)*

...or in public transport settings such as participants placing displays on the train table as is where they would normally place their laptops:

> *"I put things more on the tables as if you had a laptop working, so I was using other spaces as well, but first of all, I used the table right in front of me where I would have an open laptop." (P18)*
>
> *"What influenced me most with the table was using it as a desk, so I could use the surface as somewhere to put the screens to." (P17)*

It is important to note that considerations of comfort and, in particular, physical comfort were applied when possible (e.g. depending on the number of displays and type of transport) or when socially acceptable, which was a high priority consideration.

#### 4.1.6 Social Acceptability

Participant responses revealed notable considerations relating to social norms and etiquette as part of where they chose to place or, more significantly, *not* place the displays. Most people (18/20) discussed the importance to avoid placing any displays over other passengers' faces and bodies, towards the sides where others were seated, and to avoid overlaying displays on top of other people's belongings or what was perceived as their personal space. A primary consideration of where they would place the displays was other passengers:

> *"Firstly, I tried to keep the screens away from people." (P3)*

Participants discussed of purposefully avoiding placing displays on other passengers' faces and general body area for reasons of social awkwardness:

> *"Of course, first, I will not place any screen in the range of the people. Otherwise, it's like I'm staring at them, so the face and the upper part of the body were excluded for me as places to put them." (P2)*

Or reasons of situational awareness:

> *"I didn't like putting screens on people when they were covering all of the people or specifically their faces as I think you can get some clues of what's happening around you and what other people are doing." (P3)*

Or social politeness and consideration of being able to interact and converse with others:

> *"Taking into account where the virtual users where I always placed the screens (...)in places where they would not interrupt the flow of conversation with the other users." (P6)*

In cases, such as the subway, where there was a large numbers of co-passengers, some participants (8/20) expressed being more open and willing to placing their displays in front of the passengers across from them. In particular, when they had to place multiple displays. In the same context, participants discussed actively using the displays as 'interaction shields' so that they could avoid having to interact with other passengers or be disrupted while they were working:

> *"In the subway and the train, you just had to accept you were going to put a screen over people's faces, so they didn't impact it as much there." (P7)*
>
> *"I don't really like to see them in their eyes or face or what they are looking at." (P8)*

In contrast, across all types of transport, participants were very mindful of not placing displays to the sides where where other passengers were seated as they felt it would be weird or inappropriate:

> *"It was kinda weird because obviously, I knew like the people at either side of me couldn't see my screen, but I didn't want to stick them in front of them, and I don't know if that's because it would be weird staring at them and tried to get it on the back of the seat or above it."* (P1)

Several participants (7/20) discussed their choice of purposefully not placing anything on top of other passengers' belongings or what they perceived as their 'personal' space, even if empty. This, was both out of respect of others' space but most importantly because they felt it would be inappropriate if, or it looked as if, they are staring at others' belongings. This was the case both in more open and shared settings (e.g. train) and more constrained, shared settings (i.e. plane):

> *"Also, on the train, there was a table, and the table is normally shared supposedly, so I wouldn't place any in the space of others as otherwise, it would look like I was staring at their things."* (P2)

Finally, a variety of participants' responses hinted on potential misconceptions about how AR devices worked. They expressed concerns about others being able to see the content of their displays and opted to position them in ways that supported privacy as much as possible, while others pictured AR as able to publicly project content to other passengers and considered viewing angles that shared well:

> *"I put one screen on either of the seats and one in the middle so everyone can see again it was based on the people." (P5)*

## 5 Discussion

Our study has, for the first time, examined strategies, attitudes and preferences towards the layout of AR workspaces for productivity across four different modes of transport. In doing so, results revealed novel insights regarding how the affordances of these different modes of transport, and the presence of others, directly impacted how AR virtual displays are positioned and utilised. Many of these findings are also likely to apply to other applications, such as entertainment. However, before we discuss some of the implications our research has for the future design of passenger AR productivity experiences, we note some key limitations and caveats that should be considered in the interpretation of these results.

### 5.1 Limitations and Caveats

#### 5.1.1 Validity of Simulated Passenger Experiences

Whilst our participants experienced high-fidelity recreations of real passenger contexts in VR, there are open questions regarding the experiential differences between an immersive recreation of a passenger experience (complete with virtual animated avatars representing other passengers) versus the real-life experience, with a variety of real passengers who might react to the activity of the AR user. We used the methodology of a simulated travel environment for a number of important reasons. There are significant practical hurdles to overcome in enabling a participant to experience high fidelity, wide field of view AR across such a range of passenger environments. There are very few current AR headsets capable of rendering such workspaces outside of VR-based video pass-through solutions, which bring their own caveats regarding the perception of reality. This is in contrast to the capabilities of VR headsets to render realistic environments, and present AR-representative content within them, with upwards of 100° field of view. These capabilities have recently been employed in other remote studies during the pandemic [42, 58] and to replicate automated vehicles [54] and airplane passenger contexts [47], emphasising that VR is a viable tool to expose and immerse participants in a scenario with a high degree of ecological validity. As shown by user comments and our quantitative findings, the positioning of the avatars highly influenced the content placement of virtual displays, with users avoiding placing content over the avatar's bodies or even completely shielding themselves from the avatars. Another concern pointed out by the participants was privacy, as they did not know if the avatars could see the content they were visualising. They also purposely avoided placing content directly in front of people or their belongings, as it would 'invade their personal space', which hints that they perceived the avatars as real people. These points suggest a degree of ecological validity to our study, emphasizing the utility of replicating the transit context in a controlled way in VR to understand the design space better. Furthermore, these results will guide us in conducting follow-up real-world user studies when practical and feasible. Nonetheless, care must be taken in the interpretation of results, particularly given noted perceptual differences between VR and optical see-through AR [56], and the underlying knowledge that the scenario portrayed is not real (e.g. potentially diminishing the reactions to simulated passenger avatars).

#### 5.1.2 Lack of Familiarity with AR

Whilst we explained what AR was and what it was capable of, there remains a lack of understanding of how AR headsets function. Some participants were concerned about the privacy of their AR displays, despite these displays being rendered privately by their own headset. That some participants did not have a perfect grasp of how AR might truly function, and how their content might be visible to other passengers, may have impacted their capacity to fully appreciate what kinds of layouts were possible.

#### 5.1.3 Influence of Interactivity on Layout Preference

Because we intended to concentrate on the display layouts, our productivity activity was not interactive. The interaction mechanisms employed in any real-world application, however, may have an impact on the layouts developed. A user who prefers mid-air direct touch input, for example, is more likely to ground virtual content against available surfaces or place virtual displays close to their body. In contrast, a user using a smartphone or touchpad-based cursor control may still be able to use a more traditional workspace layout. Our approach establishes a standard against which other interaction techniques can be measured.

#### 5.1.4 Influence of Exertion / Ergonomics on Layout Preference

As our participants did not interact with each layout for a prolonged period, they were unable to gauge the physical exertion likely to be experienced with a given layout. Prolonged interactive use can have significant impact in terms of physical exertion, as demonstrated for wide virtual workspaces by McGill *et al.* [43]. Accordingly, user preferences might change given longitudinal use.

### 5.2 RQ1 - Mode of Transport

Does the the Mode of Transport and proximity of other passengers significantly alter virtual display layouts? If so, what aspects of the environment influenced the layouts, and how? The quantitative and qualitative findings paint a clear picture - the travel environment directly impacted user choices for the virtual display layouts they created. In particular, we the conflict between *social discomfort* versus *physical comfort*, and prioritising *visibility of the transport environment*.

#### 5.2.1 Shielding Versus Avoidance: AR as a Cause or Solution to Social Discomfort

Our results reaffirm that the shielding behaviours seen in real physical environments, for example using in-flight entertainment to mask other passengers, also occurred with virtual displays. Participants used AR display layouts to create a social barrier or *shield* between themselves and the other virtual passengers (for example in the Subway in Figure 5) . However, this strategy was not universal, as shown from the quantitative and qualitative findings, with participants purposefully *avoiding* placing displays on other passengers' faces, eye line and general body area, either for reasons of social awkwardness or social politeness (see for example, the Train in Figure 7 and Section 4.2.3). There exists a tension between the bystander awareness of the user's AR activity, and how that activity is then perceived. For some participants, there was a fear of being perceived to be staring at the faces or bodies of their fellow passengers, when in fact staring at co-located virtual content.

#### 5.2.2 Tension Between Physical Comfort and Social Discomfort

The conflict between shielding and avoidance was further emphasised by users prioritising the perceived visual and ergonomic comfort of the display layout over any implications for social discomfort. For example, in the subway, a number of participants prioritised their optimal display layout despite the presence of passengers across from them who might interpret their activities as socially unacceptable staring (e.g. Figure 7). Conversely, some compromised their physical comfort to avoid socially uncomfortable encounters - and we might expect that such tensions would be amplified in real-life, busy public transport. This suggests a significant need to address bystander awareness mechanisms to help mitigate against such social discomfort. Whilst in time we would expect that increasing public familiarity of AR technology could partially resolve this conflict, as people become more aware of the fact that the AR user is likely staring at virtual content, there may remain the potential for abusive uses, for example actually staring at other passengers whilst wearing an AR headset.

The travel scenarios brought up issues of social etiquette in areas deemed as shared or belonging to the personal space of others. For example, most users oriented their displays vertically in the plane so as not to encroach on the personal space of their neighbours (Figure 7). Participants wanted to avoid the perception of invading others' personal space. As discussed, a body of research has reflected on what we interpret to be our private space [18, 33, 52, 55], and our findings add to this the importance of perception of a 3D personal space mixes with the affordances and constraints of the transport environment.

#### 5.2.3 Aligning Content to Physical Affordances

Preferences for positioning virtual displays were guided by the physical affordances of the Mode of Transport, for example, using the seatback of the seat in front as an anchor for displays in the plane and car environments. On the train, displays were aligned with the table, replicating the location that a user may put a laptop or other device in the real world. These affordances were not only used as guides but also as depth boundaries to where the displays would be positioned. Participants did not push beyond these physical surfaces, even though the AR displays enabled this. This meant that they did not always take full advantage of the display capabilities available to them through the headset.

Our findings also showed the use of avoidance techniques for certain physical characteristics of the various transportation settings. For example, windows and corridors were generally perceived as areas where virtual content should not be placed for reasons of situational awareness and safety, reconfirming previous findings [39].

### 5.3 RQ2 - Number of Displays

To what extent does the number of displays impact the user's capability to create, and preferences for using, a virtual display layout? The number of displays did significantly impact the capability to create a viable layout, as shown by the qualitative and quantitative data. As the display count increased, so too did the perceived difficulty of creating layouts, whilst satisfaction with the end result, perceived visual comfort, and likelihood of using this layout in reality all decreased.

Participants found it more difficult creating and using 5 display layouts, and preferred the 3 display condition. The 5 displays condition was included as an extreme, but nonetheless a feasible one for a power user with an AR headset. This result is interesting as an AR headset allows for the creation of very many displays placed all around the environment but, in this case, fewer displays were preferred. The interactions used to create each layout could have contributed to the perceived difficulty (e.g. the controls may not have been usable). However, participants were trained before the study commenced and were all implementations that commonly occur in VR apps (e.g. Mozilla Hubs.In the end, it is likely that fewer displays were easier to position as they caused less social and logistical problems in their placement.

## 6 Future Work: Considerations and Opportunities for Passenger AR Productivity

Reflecting on our findings, there are a number of routes by which we might further improve the passenger productivity experience using AR.

### 6.1 Adapting to the Changing Passenger Context

Difficulties in creating viable multi-display layouts suggest the need for tools to help users make successful layouts and further research into AR workspaces' automatic and adaptive structure. This builds on research into context-aware and adaptive layout creation [32, 35, 37, 51]. Adapting to the passenger context poses unique challenges: it is a dynamic social environment with varied seating layouts and differing needs for situational awareness. Our findings have demonstrated the impact that both the physical affordances of the environment and the social presence of others had on display layout preferences. These factors are essential in developing any mobile, context-aware AR workspace. Such a workspace could dynamically adapt to a person boarding a train or subway and sitting across from the AR user. Users could rearrange their virtual displays to provide awareness of, or block, the new passenger without undermining the usability or comfort of the layout.

However, other factors may influence such context-aware passenger AR—for example, the duration of the journey. For a short ride on a subway, appropriating the advertising space above other passengers might be a socially acceptable way of presenting virtual content. Using dedicated above eye-level areas might avoid the perception of staring at other passengers - albeit this would likely be inappropriate for longer durations of journey where neck fatigue may occur. Similarly, we might appropriate other spaces in the physical environment for display. Void spaces in the physical space can be used, or even created (e.g. manipulating physical window transparency in the car), providing socially acceptable areas for virtual content [14]. Finally, the placement of displays does not only need to consider the context the user is in, but also users' comfort. This is particularly important for long journeys, where users need to have a general overview and be able to access the entire work environment with no or minimal physical effort.

Additionally, we chose virtual environments that were chosen based in representative examples, populating them with avatars representative of moderate/non-peak travel times(when considering public journeys, such as trains and subways) and solo journeys (in the case of the car).Further work might consider the influence of creation of AR workspaces in variations of these passenger contexts, such as peak times, populated with more avatars, or different seating configurations for the different passenger environments tested.

### 6.2 Virtually or Physically Altering the Travel Environment

We witnessed participants adapting their workspaces to either shield or avoid the social presence of others - either prioritizing visual comfort over potential social discomfort, or *vice versa*. However, there are other viable routes towards mitigating social discomfort. From an AR perspective, researchers should consider additional augmentations intended to block out or shield the user from others by default [63], for example employing diminished reality approaches [46]. In addition, travellers could choose to apply virtual obfuscations of others based on their preferences (e.g. aggressively obfuscating others seated across from you) and current task (e.g. removing obfuscations when exiting the AR workspace). Conversely, if bystanders had increased awareness of the AR user's activity, the social discomfort issue may be alleviated. Our study focused on the needs of the traveller using AR, but further work is clearly needed from the bystander/spectator perspective [3].

The transport environment could also see physical re-design to facilitate passenger AR better. For example, consider autonomous rideshare vehicles in the future, where the interior environment features seating designed to block the visibility of others physically or includes physical structures designed to minimize visual saliency or improve AR fidelity (e.g. dynamic tinting of windows). Such environments would better accommodate AR-oriented virtual content and could be designed to facilitate this from the ground up.

### 6.3 Supporting Better Situational Awareness

A passenger's ability to use the space available for virtual content may also be supported by enhanced situational/context awareness [45, 63], removing the need to avoid blocking other people or windows, for example. The information displayed in the headset could include contextual information about their journey and about the physical space.Integrating this information into AR headsets might make users more comfortable to further appropriate the travel space for virtual content use.

## 7 Conclusion

Travel takes up a considerable portion of our daily lives, and our aim in this work was to enable passengers to make more productive use of this time. AR headsets offer the possibility of breaking free from the limitations of existing mobile devices, providing users with the capacity to surround themselves with virtual content and displays. However, whilst the technology may be limitless, other factors inhibit and direct passengers' use of this powerful technology. In this paper, we have presented a study exploring the design of AR virtual workspaces for productivity across four different travel environments (plane, car, train, subway), with varying numbers of virtual displays. In particular, we found that the travel environment played a significant role in how people positioned virtual displays in AR. The passenger environment and the presence of others contribute to unique challenges in the design of virtual workspaces, having implications in particular for context-aware AR interfaces. In addition, each mode of transport has specific affordances that need to be understood and designed for if we are to avoid social rejection of this powerful technology. This work takes the first steps towards understanding how AR workspaces should adapt to transit environments, enabling passengers to use their travel time in new, productive ways.

## Acknowledgments

This research received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (#835197, ViAjeRo).

## References

[1] N. Ahmadpour, M. Kühne, J.-M. Robert, and P. Vink. Attitudes towards personal and shared space during the flight. *WORK - Special Issue on Environmental Design*, 54(4):981–987, Sept. 2016. doi: 10/gmjg7j

[2] N. Ahmadpour, G. Lindgaard, J.-M. Robert, and B. Pownall. The thematic structure of passenger comfort experience and its relationship to the context features in the aircraft cabin. *Ergonomics*, 57(6):801–815, June 2014. Publisher: Taylor & Francis tex.bdsk-url-2: http://dx.doi.org/10.1080/00140139.2014.899632. doi: 10/gmjg7f

[3] F. Alallah, A. Neshati, Y. Sakamoto, K. Hasan, E. Lank, A. Bunt, and P. Irani. Performer vs. observer: whose comfort level should we consider when examining the social acceptability of input modalities for head-worn display? In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, VRST '18, pp. 1–9. Association for Computing Machinery, New York, NY, USA, Nov. 2018. doi: 10/gjbvdp

[4] J. A. Anderson, J. Hill, P. Parkin, and A. Garisson. Productivity, screens, and aspect ratios; a comparison of single, traditional aspect, dual, traditional aspect and single, widescreen aspect computer. *Illinois: NEC Display Solutions*, 2007.

[5] L. Bajorunaite, S. Brewster, and J. R. Williamson. Virtual reality in transit: how acceptable is vr use on public transport? In *2021 IEEE Conference on Virtual Reality and 3D Spatial Interfaces Abstracts and Workshops (VRW)*, pp. 432–433, Mar. 2021. doi: 10/gmf8tr

[6] X. Bi and R. Balakrishnan. Comparing usage of a large high-resolution display to single or dual desktop displays for daily work. In *CHI '09 proceedings of the SIGCHI conference on human factors in computing systems*, pp. 1005–1014, 2009.

[7] V. Braun and V. Clarke. Using thematic analysis in psychology. *Qualitative research in psychology*, 3(2):77–101, 2006.

[8] M. Czerwinski, G. Smith, T. Regan, B. Meyers, G. Robertson, and G. Starkweather. Toward characterizing the productivity benefits of very large displays. *Interact*, 3:9–16, 2003. ISBN: 1586033638.

[9] P. Dragicevic. Fair statistical communication in hci. In *Modern statistical methods for HCI*, pp. 291–330. Springer, 2016.

[10] E. Dumur, Y. Barnard, and G. A. Boy. Designing for comfort. *undefined*, 2004.

[11] A. Endert, L. Bradel, J. Zeitz, C. Andrews, C. North, and V. Tech. Designing large high-resolution display workspaces. *AVI '12 Proceedings of the International Working Conference on Advanced Visual Interfaces*, pp. 58–65, 2012. ISBN: 9781450312875.

[12] B. Ens, J. D. Hincapié-Ramos, and P. Irani. Ethereal planes: A design framework for 2d information space in 3d mixed reality environments. *Proceedings of the 2nd ACM Symposium on Spatial User Interaction*, pp. 2–12, 2014. ISBN: 978-1-4503-2820-3. doi: 10/gj3dr4

[13] B. Ens and P. Irani. Spatial analytic interfaces: Spatial user interfaces for in situ visual analytics. *IEEE Computer Graphics and Applications*, 37(2):66–79, Mar. 2017. doi: 10/gj3drc

[14] B. Ens, E. Ofek, N. Bruce, and P. Irani. Shared façades: Surface-embedded layout management for ad hoc collaboration using head-worn displays. In *Collaboration meets interactive spaces*, pp. 153–176. Springer International Publishing, Cham, 2016. doi: 10.1007/978-3-319-45853-3_8

[15] B. M. Ens, R. Finnegan, and P. P. Irani. The personal cockpit: A spatial interface for effective task switching on head-worn displays. *Proceedings of the 32nd annual ACM conference on Human factors in computing systems - CHI '14*, (August 2016):3171–3180, 2014. ISBN: 9781450324731. doi: 10/gfvftw

[16] eurostat. Air transport statistics, 2019.

[17] eurostat. Railway passenger transport statistics - quarterly and annual data, 2021.

[18] G. W. Evans and R. E. Wener. Crowding and personal space invasion on the train: Please don't make me sit in the middle. *Journal of Environmental Psychology*, 27(1):90–94, 2007. Publisher: Elsevier. doi: 10/fkhbb8

[19] I. Fiorillo, M. Nasti, and A. Naddeo. Design for comfort and social interaction in future vehicles: A study on the leg space between facing-seats configuration. *International Journal of Industrial Ergonomics*, 83:103131, 2021.

[20] F. Garcia-Sanjuan, J. Jaen, and V. Nacher. Toward a general conceptualization of multi-display environments. *Frontiers in ICT*, 3:20, Sept. 2016. Publisher: Frontiers. doi: 10/gj3dr3

[21] R. Garland-Thomson. Ways of Staring. *Journal of Visual Culture*, 5(2):173–192, Aug. 2006. Publisher: SAGE Publications. doi: 10/c87474

[22] M. A. Gerber, M. Faramarzian, and R. Schroeter. *Inception of Perception—Augmented Reality in Virtual Reality: Prototyping Human–Machine Interfaces for Automated Driving*, pp. 477–503. Springer International Publishing, Cham, 2022. doi: 10.1007/978-3-030-77726-5_18

[23] E. Goffman. Behavior in public places; notes on the social organization of gatherings. Technical report, Free Press, 1963.

[24] S. Groening. 'No one likes to be a captive audience': Headphones and in-flight cinema. *Film History: An International Journal*, 2016.

[25] J. Grubert, T. Langlotz, S. Zollmann, and H. Regenbrecht. Towards pervasive augmented reality: Context-awareness in augmented reality. *IEEE transactions on visualization and computer graphics*, 23(6):1706–1724, 2016. Publisher: IEEE. doi: 10/f97hkg

[26] J. Grudin. Partitioning digital worlds: Focal and peripheral awareness in multiple monitor use. *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '01*, (3):458–465, 2001. ISBN: 1581133278.

[27] J. Gugenheimer, C. Mai, M. McGill, J. Williamson, F. Steinicke, and K. Perlin. Challenges using head-mounted displays in shared and social spaces. *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–8, May 2019. doi: 10/ghwfrq

[28] R. Haeuslschmid, B. Pfleging, and F. Alt. A design space to support the development of windshield applications for the car. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 5076–5091, 2016.

[29] E. T. Hall. *The hidden dimension*, vol. 609. Garden City, NY: Doubleday, 1966.

[30] C. House. Why I stopped using multiple monitors. 2017. Publication Title: Hacker noon.

[31] M. Jacobsen and S. Kristiansen. *The Social Thought of Erving Goffman*. Thousand Oaks, California, 2015. doi: 10.4135/9781483381725

[32] S. Krings, E. Yigitbas, I. Jovanovikj, S. Sauer, and G. Engels. Development framework for context-aware augmented reality applications. In *Companion Proceedings of the 12th ACM SIGCHI Symposium on Engineering Interactive Computing Systems*, EICS '20 Companion, pp. 1–6. Association for Computing Machinery, New York, NY, USA, June 2020. doi: 10/gmndc7

[33] L. Lewis, H. Patel, M. D'Cruz, and S. Cobb. What makes a space invader? Passenger perceptions of personal space invasion in aircraft travel. *Ergonomics*, 60(11):1461–1470, 2017. Publisher: Taylor & Francis. doi: 10/gj3dwc

[34] J. Li, C. George, A. Ngao, K. Holländer, S. Mayer, and A. Butz. Rear-seat productivity in virtual reality: Investigating vr interaction in the confined space of a car. *Multimodal Technologies and Interaction*, 5(4):15, Apr. 2021. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute. doi: 10/gj3dh7

[35] D. Lindlbauer, A. M. Feit, and O. Hilliges. Context-aware online adaptation of mixed reality interfaces. In *Proceedings of the 32nd UIST*, pp. 147–160, 2019. doi: 10/gj3dqx

[36] L. Lischke, S. Mayer, K. Wolf, N. Henze, H. Reiterer, and A. Schmidt. Screen arrangements and interaction areas for large display work places. *Proceedings of the 5th ACM International Symposium on Pervasive Displays - PerDis '16*, pp. 228–234, 2016. ISBN: 9781450343664. doi: 10/gj27wt

[37] J. Liu. Semantic Mapping: A Semantics-based Approach to virtual Content Placement for Immersive Environments. In *2021 17th International Conference on Intelligent Environments (IE)*, pp. 1–8, June 2021. ISSN: 2472-7571. doi: 10/gmndc8

[38] M. Lokhandwala and H. Cai. Dynamic ride sharing using traditional taxis and shared autonomous taxis: A case study of NYC. *Transportation Research Part C: Emerging Technologies*, 97:45–60, Dec. 2018. doi: 10/gjp469

[39] C. Mai and M. Khamis. Public hmds: Modeling and understanding user behavior around public head-mounted displays. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays*, pp. 1–9, 2018.

[40] V. Mäkelä, R. Radiah, S. Alsherif, M. Khamis, C. Xiao, L. Borchert, A. Schmidt, and F. Alt. *Virtual Field Studies: Conducting Studies on Public Displays in Virtual Reality*, p. 1–15. Association for Computing Machinery, New York, NY, USA, 2020.

[41] F. Mathis, K. E. Vaniea, and M. Khamis. Can i borrow your atm? using virtual reality for (simulated) in situ authentication research. In *IEEE Conference on Virtual Reality and 3D User Interfaces (IEEE VR)*. IEEE, 2021.

[42] F. Mathis, X. Zhang, J. O'Hagan, D. Medeiros, P. Saeghe, M. McGill, S. Brewster, and M. Khamis. Remote xr studies: The Golden Future of hci Research? In *Proceedings of the CHI 2021 Workshop on XR Remote Research. http://www. mat. qmul. ac. uk/xr-chi-2021*, 2021.

[43] M. Mcgill, A. Kehoe, E. Freeman, and S. Brewster. Expanding the bounds of seated vr workspaces. *ACM Transactions on Computer-Human Interaction*, 27(3):13:1–13:40, May 2020. doi: 10/ghwfhx

[44] M. McGill, J. Williamson, A. Ng, F. Pollick, and S. Brewster. Challenges in passenger use of mixed reality headsets in cars and other transportation. *Virtual Reality*, pp. 1–21, 2019. Publisher: Springer.

[45] D. Medeiros, R. d. Anjos, N. Pantidi, K. Huang, M. Sousa, C. Anslow, and J. Jorge. Promoting reality awareness in virtual reality through proxemics. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 21–30, 2021. doi: 10.1109/VR50410.2021.00022

[46] S. Mori, S. Ikeda, and H. Saito. A survey of diminished reality: Techniques for visually concealing, eliminating, and seeing through real objects. *IPSJ Transactions on Computer Vision and Applications*, 9(1):1–14, 2017.

[47] A. Ng, D. Medeiros, M. McGill, J. Williamson, and S. Brewster. The passenger experience of mixed reality virtual display layouts in airplane environments. In *Proceedings of the 2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 2021.

[48] E. Ofek, J. Grubert, M. Pahud, M. Phillips, and P. O. Kristensson. Towards a practical virtual office for mobile knowledge workers. *arXiv:2009.02947 [cs]*, Sept. 2020. arXiv: 2009.02947.

[49] C. S. Oh, J. N. Bailenson, and G. F. Welch. A systematic review of social presence: Definition, antecedents, and implications. *Frontiers in Robotics and AI*, p. 114, 2018.

[50] N. Osmers, M. Prilla, O. Blunk, G. George Brown, M. Janßen, and N. Kahrl. The role of social presence for cooperation in augmented reality on head mounted devices: A literature review. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–17, 2021.

[51] A. Oulasvirta, N. R. Dayama, M. Shiripour, M. John, and A. Karrenbauer. Combinatorial optimization of graphical spatial interface designs. *Proceedings of the IEEE*, 108(3):434–464, Mar. 2020. Conference Name: Proceedings of the IEEE. doi: 10/gmndc5

[52] H. Patel and M. D'Cruz. Passenger-centric factors influencing the experience of aircraft comfort. *Transport Reviews*, 38(2):252–269, 2018. Publisher: Taylor & Francis. doi: 10/gj3dv9

[53] L. Pavanatto, C. North, D. A. Bowman, C. Badea, and R. Stoakley. Do we still need physical monitors? an evaluation of the usability of ar virtual monitors for productivity work. In *2021 IEEE Virtual Reality and 3D Spatial Interfaces (VR)*, pp. 759–767. IEEE, 2021. doi: 10/gj3dh5

[54] A. Riegler, A. Riener, and C. Holzmann. A research agenda for mixed reality in automated vehicles. In *19th International Conference on Mobile and Ubiquitous Multimedia*, pp. 119–131, 2020.

[55] T. Schmelter and K. Hildebrand. 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)*, pp. 279–280, 2020. doi: 10.1109/VRW50115.2020.00058

[56] M. Smith, N. Doutcheva, J. L. Gabbard, and G. Burnett. Optical see-through head up displays' effect on depth judgments of real world objects. In *2015 IEEE Virtual Reality (VR)*, pp. 401–405. IEEE, 2015.

[57] N. Statistics. Transport Statistics Great Britain 2020. p. 6.

[58] A. Steed, F. R. Ortega, A. S. Williams, E. Kruijff, W. Stuerzlinger, A. U. Batmaz, A. S. Won, E. S. Rosenberg, A. L. Simeone, and A. Hayes. Evaluating immersive experiences during covid-19 and beyond. *interactions*, 27(4):62–67, 2020.

[59] J. A. P. K. Thomas. The social environment of public transport. 2009. Accepted: 2009-11-25T20:34:39Z Publisher: Victoria University of Wellington.

[60] M. Vergari, T. Kojić, F. Vona, F. Garzotto, S. Möller, and J.-N. Voigt-Antons. Influence of Interactivity and social Environments on spatial Experience and social acceptability in virtual reality. In *2021 IEEE Virtual Reality and 3D Spatial Interfaces (VR)*, pp. 695–704, Mar. 2021. ISSN: 2642-5254. doi: 10/gk6nfp

[61] J. R. Williamson, M. McGill, and K. Outram. Planevr: Social acceptability of virtual reality for aeroplane passengers. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, May 2019. doi: 10/gf3kx7

[62] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, p. 143. ACM Press, New York, New York, USA, May 2011. doi: 10/fqmgnm

[63] K.-T. Yang, C.-H. Wang, and L. Chan. Sharespace: Facilitating shared use of the physical space by both vr head-mounted display and external users. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pp. 499–509, 2018.