The Passenger Experience of Mixed Reality Virtual Display Layouts in Airplane Environments

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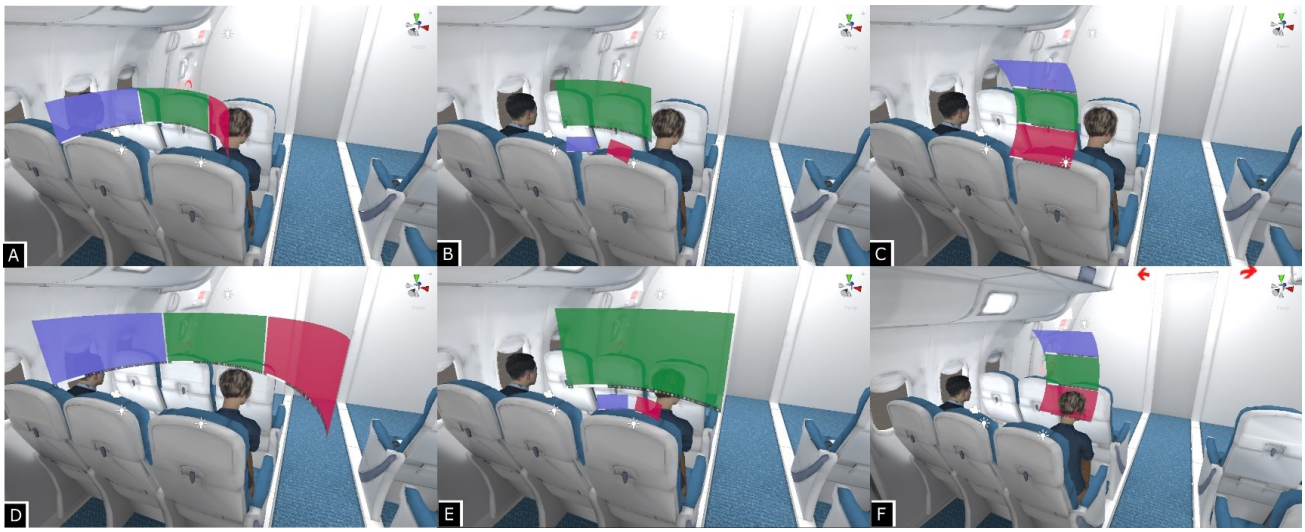

Figure 1 – The display layouts tested in Part 1 of our experiment: (**A**) *Near Horizontal*, (**B**) *Near Focus* and (**C**) *Near Vertical*. The "pushed out" layouts tested in Part 2 of our experiment: (**D**) *Far Horizontal*, (**E**) *Far Focus* and (**F**) *Far Vertical*.

Abstract

Augmented / Mixed Reality headsets will in-time see adoption and use in a variety of mobility and transit contexts, allowing users to view and interact with virtual content and displays for productivity and entertainment. However, little is known regarding how multi-display virtual workspaces should be presented in a transit context, nor to what extent the unique affordances of transit environments (e.g. the social presence of others) might influence passenger perception of virtual display layouts. Using a simulated VR passenger airplane environment, we evaluated three different AR-driven virtual display configurations (*Horizontal*, *Vertical*, and *Focus* main display with smaller secondary windows) at two different depths, exploring their usability, user preferences, and the underlying factors that influenced those preferences. We found that the perception of invading other's personal space significantly influenced preferred layouts in transit contexts. Based on our findings, we reflect on the unique challenges posed by passenger contexts, provide recommendations regarding virtual display layout in the confined airplane environment, and expand on the significant benefits that AR offers over physical displays in said environments.

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1 Introduction

We all at varying times find ourselves travelling for work or leisure, sometimes for significant durations. The transit environment typically has some unique affordances that directly impact our comfort and capability to use this travel time effectively. Passengers typically find themselves in constrained and restrictive spaces (e.g. economy airplane seating), interacting with digital content through physical displays (seatback, laptop, tablet etc.) with limited ergonomics, comfort, size, and capacity for supporting multi-display awareness and multi-tasking. This contributes to a lack of parity and capability when compared to productivity outside of transit environments.

However, as Virtual and Augmented Reality (VR/AR) headsets become more lightweight, portable, and wearable throughout the day, they will enable passengers to move beyond the limitations of physical displays [36], having the capacity to render virtual content anywhere around the user. AR, in particular, is likely to see significant adoption in supplementing or entirely supplanting existing physical displays [41], able to render entirely virtual displays in a variety of configurations [11]. Furthermore, Mixed Reality (MR) headsets demonstrated their capability of creating more ergonomic and accessible workspaces [35], offering particular benefits to passengers. However, whilst previous

research has studied virtual displays and desktops in seated office and room environments [35,38], the usability of even basic configurations of multi-display virtual desktops in transit contexts has yet to be examined. Beyond the confined space, transit contexts bring with them additional affordances – they are typically shared, social spaces, with the presence of others in close proximity to the passenger. Whilst prior research has examined the social acceptability of MR headset usage in these contexts [46], the impact this social presence might have on how we position and place virtual content around the user remains unexplored. For example, users may wish to avoid looking at virtual content placed within other passengers' personal space, which in turn could suggest that standard wide multi-display configurations, based on common physical display configurations and as seen in Oculus Home or research [35] are less well suited for passengers in shared environments. Furthermore, the positioning of virtual and augmented displays is less well-studied for passengers in airplanes. Our findings can also inform designers and researchers of the potentially effective configurations of AR/VR displays for other modes of transport, such as when travelling on a bus or a train.

Therefore, we conducted a novel remote study that compared three different AR-oriented multi-display configurations in a simulated VR plane environment to explore these challenges. The layouts were based on (1) common/standard display configurations that are found in current MR headsets and (2) more novel arrangements that are influenced by previous work on MR display configurations [10,11,35] and a plane's seating constraints. We simulated AR by adding a small degree of transparency to the virtual displays so users could always see through the displays and judge where objects (such as the seats in front, folding down tray tables and armrests) and other passengers (avatars) are in the virtual airplane environment. Furthermore, AR headsets are unlikely to be 100% occlusive, so we added transparency to increase the realism of using AR technology.

We also varied the distance in which the virtual display configurations were placed from the user's view - in other words, virtual displays that respect the depth of the seats in front of the user, and virtual displays that ignore this restriction and are located beyond any immediate objects or passengers. This allowed us to observe any effects caused by the display distance depth and size (larger displays can be deployed the further away the displays are positioned from the user) in the virtual airplane environment. The results from our study highlighted a preference for vertical layouts for productivity, in part driven by the perception that horizontal layouts were socially unacceptable, effectively invading the personal space of other passengers. Based on our findings, we reflect on the unique challenges posed by passenger contexts, provide recommendations regarding virtual display layout for the confined airplane environment, and add further evidence to the significant benefits AR offers over physical displays for passengers.

2 Background

This section will discuss previous work that has examined virtual multi-display workspaces in different contexts.

2.1 Multi-Display Workspaces

The benefits [1] and drawbacks [21] of multi-display environments [16] have been extensively discussed. Users show a "unanimous 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' " [4]. Multi-display workspaces allow us to access more information [9], facilitate peripheral awareness of information [19] and increase productivity by enabling more efficient multi-tasking [8]. In effect, they "improve efficiency in ways that are difficult to measure yet can have substantial subjective benefit" [19], providing "space to think" [2,3]. Czerwinski *et al.* [7] suggested that multi-display environments allowed users to "engage in more complex multitasking behavior", whilst others have noted the benefits of "abundant" display spaces [25] in terms of spatial memory [42] and performance across a variety of productivity tasks [5,23,24,30,39,44]. So as MR, AR and VR headsets become more lightweight and portable, users are more likely to use multi-display configurations while travelling or on the move.

However, larger display spaces do have drawbacks [21]. The necessity of such a space is sometimes questionable, with Endert et al. noting that often "the ability to see all of (the workspace) all the time is not needed" [9]. And [20] noted "often times a user preferred a display that did not match optimal performance". There are also diminishing returns in adding more displays [37]. In our study, we hope to find out if there is a preference in the size of virtual displays when used in a plane environment.

2.2 Virtual / "Ethereal" Workspaces

When rendered by XR headsets, virtual displays (typically referring to virtual containers for positioning 2/3D application content) have the potential to "break the physical rules and constraints of physical display spaces" to the benefit of usability and ergonomics [35]. These displays are dynamically configurable, with layouts being unconstrained in terms of layout, orientation, depth and scale, able to either supplement or replace existing physical displays [41]. These features have been previously exploited to notable effect by McGill *et al.* [35] in particular, where horizontal/wide three/five display virtual workspaces were dynamically actuated based on head movements to improve the ergonomics of interacting with more peripheral displays. Ens *et al.* referred to such virtual displays as "Ethereal Planes", suggesting a breadth of potential exo- and ego-centric layouts of displays [10]; for the latter, research has envisioned content being placed around the user in a variety of configurations e.g. vertically [11] or horizontally, two-plus-two [31], or oriented toward the user as in the ``personal cockpit'' [11,12]. However, as shown in the personal cockpit, egocentric-type layouts are optimal when exocentrically placed, i.e. oriented around a fixed point in world space where the user's head is. This provides a display space that is effectively oriented and laid out around the user without inducing nausea due to moving with the user. We are unsure whether these findings are still valid when virtual displays are used in seated travelling situations. There is also the consideration that virtual displays as bounded containers for app content will be supplanted by un-docked, free-form layout of apps-as-displays [35]. However, we consider that findings for virtual displays are broadly applicable for the latter use case, and offer an understandable compromise to users in demonstrating the capabilities of virtual versus physical displays.

2.3 Passenger MR & Virtual Workspaces

For passengers in particular, virtual workspaces offer a chance to move away from the constraints of mobile devices such as tablets and smartphones, and more traditional work devices such as laptops, able to in theory more significantly appropriate or occlude the space around the user for display. Support for passenger use of XR headsets is growing, with research tackling the key blockers (motion sickness, maintaining alignment) [36]. As a result, we can expect that AR and VR headsets will, in the

near future, function effectively in autonomous cars, planes, trains and other modes of transport. Whilst VR will allow for passengers to entirely escape their physical environment [28], AR is of particular interest for this mobile productivity use case, as it is AR that companies such as Google, Microsoft and Apple are targeting for the next wave of wearable, everyday, personal computing.

However, the vehicular environment poses a number of challenges to the use of AR for presenting virtual workspaces. Assuming technical issues regarding fidelity and legibility can be overcome [41], social issues are likely to become increasingly prescient. Consider that in public transport we have a perception of personal space that can extend toward our seat and its affordances (e.g., the seatback directly in front of us, the arm rest). If we are to render wide horizontal workspaces, as we will be capable of doing, these workspaces could infringe upon the perceived personal space of others [14,27,40], introducing significant social acceptability concerns [46]. For example, if an AR user in the central seat of a plane is staring at a peripheral display that is aligned with bystander passenger, or a bystander passenger's media activity (e.g. a seatback display), there may be uncertainty for the bystander regarding whether the AR user is attending to virtual content, or violating the bystander's privacy. The impact of the affordances of the travel environment, and the presence of other passengers, on the layout of virtual workspaces is yet to be fully explored. However, for both user-specified and context-aware virtual workspace layouts [18,29] an understanding of the influence of the travel environment will be crucial to help guide appropriate workspace layout selection, avoiding (perceived, if not actualized) violations of social norms and privacy.

3 STUDY – INFLUENCE OF DISPLAY LAYOUT AND DEPTH ON PASSENGER EXPERIENCE

AR headsets are increasingly moving toward viable consumer products that will, over time, supplement and eventually supplant use of physical displays, for example rendering ergonomic virtual workspaces [35]. However, research has yet to consider the implications such an eventuality would have for passenger productivity. Compared to a seated desk environment, the transit context brings with it unique affordances in terms of the close proximity of other passengers; perception of personal space (and social norms related to defending said personal space); and the fundamentally constrained environment, particularly with respect to economy airplane travel. Would passengers be likely to adopt such technology if it meant moving away from seatback displays and personal laptops? And how might we present virtual displays in such environment? Based on our literature review, we elected to conduct a remote study to examine these questions. Due to COVID-19 restrictions, we chose to use a simulated virtual airplane environment to enable participants to explore attitudes and preferences toward virtual display layout. Whilst the intent behind this study was to gain a better understanding of how to effectively position virtual displays in confined travelling spaces, we did identify two research questions of note:

RQ1: Would familiar wide/horizontal layout configurations remain preferable in an airplane context?

RQ2: Should virtual displays respect the depth constraints of the passenger's physical environment?

To examine these RQs and gain broader insight into the passenger AR experience, our experiment was split into two parts due to concerns regarding user fatigue. In the first part, participants were asked to evaluate three layouts where the virtual displays were constrained to the depth of the seats in front of the user. We tested displays at this depth because in a real-world situation where users are interacting with MR or AR content, it is important to know where surrounding objects and other passengers are and where to project and place augmented content around the user in respect to nearby physical objects.

In the second part of the experiment, we invited a subset of the participants who took part in the first session to evaluate the three multi-display layouts again but this time, the displays were placed beyond the seats in front of the user. By placing the display layouts further out and unconstrainted by the surrounding seats and objects, virtual content would be more stable to view (i.e. the user would perceive less changes in viewing angle based on changes in head pose/posture within their seat) and would render the content at a depth (approximately 1.3m) that is considered to be more comfortable for prolonged viewing (e.g. based on Microsoft MR guidelines [13]). However, pushing the virtual content to a depth beyond that of the seatback in front of the user also introduces the potential for depth ambiguity. The mildly transparent display and seatback occupy the same visual space but at different depths, thus requiring different convergences. This problem could potentially result in discomfort or diplopia. In the following subsection, we describe the displays configurations in detail.

3.1 Multi-Display Layouts

We designed three display layouts (*Horizontal, Focus, Vertical*) at two depths (*Near, Far*), giving us a total of six unique layouts (type of layout * depth) (Figure 1). The design of these layouts was inspired by common designs found in the literature and the unique affordances of transit environments, such as the presence of other passengers and their constrained properties. Each layout had three curved virtual displays with slight transparency (*alpha* = 230) so that users can see the surroundings behind the displays in the virtual plane environment to simulate the effects of augmented reality. We used 16:9 aspect ratio for all displays in each layout. When we describe the distance of the layouts in relation to the participant, the user's camera position is at the origin (0,0,0). The six layouts we tested were:

A. *Near Horizontal*: three 60-degree curved displays were placed side by side, based on existing physical display layouts [35] (Figure 1-A). Each display measured (width x height) 60 x 33.8 cm. The layout was placed 46cm away from the participant and constrained by the seats in front. This layout is similar to the configurations found in VR headsets such as the Oculus desktop environment.

B. *Near Focus*: one primary 60-degree curved display which measure 80 x 45cm with two smaller secondary displays (also curved at 60 degrees), measuring 24 x 13.4cm, placed beneath the main display. The secondary displays were also tilted towards the user for better viewability. The layout was positioned 36cm away from the participant. This type of layout offered a counterpoint to arrangements that treated each virtual display equally with respect to size (Figure 1-B). We designed this layout for users who prefer a large main display but with smaller windows to show secondary content which is still in the user's peripheral view.

C. *Near Vertical*: three 40-degree curved displays stacked vertically on top of each other, based on a concept proposed by Ens and Irani [11]. From our pilot studies, we found that curving the display on the y-axis by 60 degrees made viewing the content difficult, so we reduce to a more comfortable viewing position and chose 40 degrees instead. Each display measured 45 x 25.3 cm. The layout was positioned 55cm away

from the participant (Figure 1-C). We tested this type of vertical layout because all content is within the user's personal space, minimizing the need to look at the passengers sitting nearby.

D. *Far Horizontal*: same configuration as *Near Horizontal* but the layout was placed 124cm from the user and therefore beyond the seats in front. Each display can therefore be made larger. After conducting pilot tests, we decided to double the size of the displays to 120 x 67.6cm (Figure 1-D) so that the video content was readable and allowed us to compare smaller (but closer) displays with larger displays (but further out), while maintaining the same angular size.

E. *Far Focus*: similar to *Near Focus* but placed 132cm from the user. We kept the scaling consistent with the other layouts so doubled the size of each display. Therefore, the primary display was expanded to 160 x 90cm while the smaller secondary displays were resized to 48 x 26.8cm (Figure 1-E).

F. *Far Vertical*: similar to *Near Vertical* but we doubled the size of the displays to 90 x 50.6cm and placed the layout beyond the seats in front of the user at a distance of 132cm (Figure 1-F).

3.2 Virtual Airplane Environment and Avatars

To recreate the experience of travelling in an airplane, we used a virtual environment of an airplane interior with high level of visual fidelity [22]. We did not include any perceived motion of the virtual airplane to reduce any concerns caused by motion sickness. While motion sickness is an important issue to consider when using AR/VR headsets while travelling, the main focus of this paper is to examine the effectiveness of different virtual display configurations and their social implications. We also included animated virtual avatars which were placed on each side of the user to try and simulate the social interactions that may occur when sat in a real airplane (Figure 2). The virtual avatars were obtained from the Adobe Mixamo library (https://www.mixamo.com). This library includes human-like avatars and a wide variety of animations that simulate real-world behaviours. We selected two different characters, one male and one female, with high level of visual fidelity to avoid 'uncanny valley' side-effects. The avatar animations were randomized for each condition and represented different human behaviours (e.g. talking, moving their hands) to make them appear more life-like and to simulate realistic social situations.

Because of the remote nature of our experiment, we needed to run our software as a standalone application on Oculus Quest headsets. Due to the performance limitations of the Oculus Quest (when used as a standalone device) and to keep frame rate as recommended (minimum 70 frames per second), we reduced the environment and avatar polycount to approximately 220 thousand polygons while maintaining a high level of visual fidelity. Furthermore, we used lightmapping to precompute lighting behavior in the objects and guarantee an acceptable frame rate.

3.3 Experimental Task

For each layout, we asked the participants to watch a series of videos in the displays. The content were recordings from a desktop computer of tasks that a user would typically do for a holiday planning exercise. We chose a holiday planning exercise because it would normally promote the use of multiple displays or tabs to view and search for information from different applications. For each layout, there were three types of videos: (1) a YouTube clip of the potential city to visit, (2) searching for flights to the city on an airline website and (3) searching on Google Maps to find hotels in the destination city. Different cities (i.e. different content) were used for each layout to reduce learning effects. Each video was approximately 90 seconds in duration. Since our focus was on user preferences regarding the different layouts and their effects on social acceptability, we chose to use videos of pre-recorded tasks not to have any unwanted effects on the evaluation of the layouts.

To ensure the participants viewed (or at least looked at) all three displays within each layout, we designed the experimental task so that the participants had to switch content to the main central display within each layout. Each condition would start with a video playing in the middle display (in the case of the *Horizontal* and *Vertical* configurations at both depths) and the main display (in the *Focus* configuration) for 30 seconds. Once the clip has finished, the next video is shown on one of the other displays, and the participant had to use the joystick on the right controller to move the video content to the middle/main display. For *Horizontal* and *Focus* layouts, users moved the joystick left or right depending on where the next video content was displayed. To shift the video content in the *Vertical* layout, participants moved the joystick up or down. Once the new content was shifted to the middle display, the video would automatically play for another 30 seconds, and the process was repeated until all three videos in each layout had elapsed.

We decided to make the participants move the content to the middle or main virtual display because we believe users will most likely view and interact with MR content within their own personal space. Participants can also glance at peripheral displays, which in some layouts might intrude other passenger's personal space and can make themselves and other passengers feel uncomfortable. Furthermore, neck fatigue due to prolonged MR use is likely to make users view content in the middle or main display directly in front of them which would require less neck movement.

Figure 2 – Virtual environment of the airplane interior and the animated avatars located at each side of the VR user.

3.4 Experimental Design

Due to the COVID-19 pandemic and the restrictions on conducting face-to-face experiments in our university, we carried out an online experiment over Zoom. We recruited participants using different mailing lists who had access to an Oculus Quest headset and a device that can run Zoom so that we can instruct the participants in real-time on how to perform the experimental task and to interview them afterwards on their experiences. We sent our software to the participants to install onto their headset prior to the start of the experiment. We chose to run our experiment using Oculus Quest headsets because of their popularity, standalone capabilities, and the presence of a guardian system to avoid health and safety issues.

During the Zoom calls, we greeted the participants, presented them with a short description of the experiment and the tasks they were going to perform and then ask them to complete an online consent form. Once the participants had provided informed consent, they were asked to fill a short questionnaire to collect demographic information on their previous experience of using VR and AR. Before starting each condition, participants completed a short training session to familiarise themselves with the layout and the input controls for moving the content between the displays. Furthermore, during the experiment, we asked participants to sit on a non-swivel chair of their own and not turn their bodies to simulate the same effects of sitting in a confined airplane seat.

After completing all the conditions, the participants filled in an online questionnaire that asked them to rate the layout in the order of most to least preferred. In addition to the questionnaire, we conducted a semi-structured interview to capture the participants' perceptions about the display configurations that they experienced and to get suggestions on how to design more effective virtual displays and windows for travelling airplane environments. Twenty-four participants were recruited to take part in the first session of the experiment. The mean age of the participants was 33.4 years (*SD* = 10.3) and eleven females took part in the first session. The first part of the experiment took approximately one hour to complete and participants were paid for their time. We ensured that participants took a break in between conditions to minimize VR- and motion- induced sickness.

For the second part of the experiment, we recruited eighteen participants from the first session to evaluate the three display layouts but this time the layouts were pushed further out and unconstrained by the seats in front of the user. The mean age of the participants was 33.2 years (*SD* = 11.1) and eight females took part in the second session. The second part of the experiment followed the same experimental procedure as the first session.

A within-subjects design was used for both parts of the experiment. The Independent Variables were **Type of Layout** (three levels: *Horizontal*, *Focus* and *Vertical*) and **Distance** (two levels: *Near* and *Far*). Hence, there was a total of six conditions across both parts of the experiment.

3.5 Data Collection

For both parts of the experiment, we collected quantitative subjective data and qualitative data. We gathered quantitative data in the form of a questionnaire completed after each condition, which comprised of seven nine-point Likert scale questions (see Figure 3) where '1' indicated a low score and '9' a high score. We selected three questions from the Nasa Task Load Index (NASA-TLX) questionnaire (*Mental Demand*, *Physical Demand* and *Effort*) that were deemed more appropriate for our task. In addition, we asked four more questions specific to our user study: (1) *Co-Presence of Avatars* to measure the participants' awareness of the virtual avatars in the airplane environment, (2) *Neck Fatigue* caused by looking at the displays, (3) *Visual Discomfort* in terms of how visually awkward it was to view the displays and (4) *Airplane Usage* in terms of the likelihood the participant would use the MR display layouts tested in our experiment in a real world travelling situation on an airplane.

The participants were also interviewed at the end of each session to find out more in-depth details on the experience they had with each layout. The questions focused on the most/least preferred layouts, the likes/dislikes of each layout and the areas where the layouts could be improved upon in the future. Unfortunately, due to technical issues with recording the participants' interviews, only a subset was fully transcribed for in-depth analysis.

4 Results

In this section, we describe the results collected for both quantitative and qualitative feedback from the questionnaires and interviews for both parts of the experiment.

4.1 Quantitative Results

Figure 3 shows a summary of the questionnaire responses of the seven questions we asked the participants after each condition was completed. To test for statistical significance, we first performed a Shapiro-Wilk test to test for normality. Since the data did not follow a normal distribution, we first used an Aligned Rank Transformation (ART) [47] to transform our data and then performed a two-factor (Type of Layout and Distance) repeated-measures ANOVA.

The results showed that there was no significant main effect for Distance, except for the *Co-Presence of Avatar* ($p=0.0033$). In this factor, the displays located near to the user had a higher score for co-presence when compared to the ones located further away ($p=0.0034$). When comparing between the three main types of layouts, we found a significant main effect in *Co-Presence of Avatars* in terms of distance ($p=0.0019$) between *Vertical* and *Horizontal* display layouts, where horizontal displays had a higher score in comparison with vertical displays ($p=0.0014$). We found main effects between the layouts in terms of overall workload ($p=0.011$) with *Vertical* displays had statistically significant lower score than both the *Horizontal* ($p=0.03$) and *Focus* ($p=0.02$) layouts.

When analysing each TLX factor separately, we also found statistically significant results. Regarding *Effort*, we found significant main-effects ($p=0.006$), where participants used significantly less effort with the *Vertical* layout when compared to both the *Horizontal* ($p=0.034$) and *Focused* ($p=0.0077$) arrangements. We also found significant main effects for *Physical Demand* ($p=0.015$), where participants felt the task to be more physically demanding with the *Horizontal* layout in comparison with the *Vertical* layout ($p=0.0121$). In addition, we did not find a significant main effect for the *Neck Fatigue* metric. There were also main effects observed in terms of *Mental Demand* between the layouts ($p=0.02$), with *Vertical* layout less mentally demanding than *Focus* displays ($p=0.02$). A similar behaviour was observed with the *Visual Discomfort* metric ($p<0.001$), where the *Focus* arrangement elicited more visual discomfort overall, but with statistical significance only between *Focus* and *Vertical* layouts ($p=0.0001$).

Lastly, we found significant main effects for the *Airplane Usage* metric ($p<0.001$), where participants reported to be more likely to use the *Vertical* layout than the *Horizontal* ($p=0.006$) and the *Focus* ($p<0.001$) display arrangements.

4.2 Qualitative Results

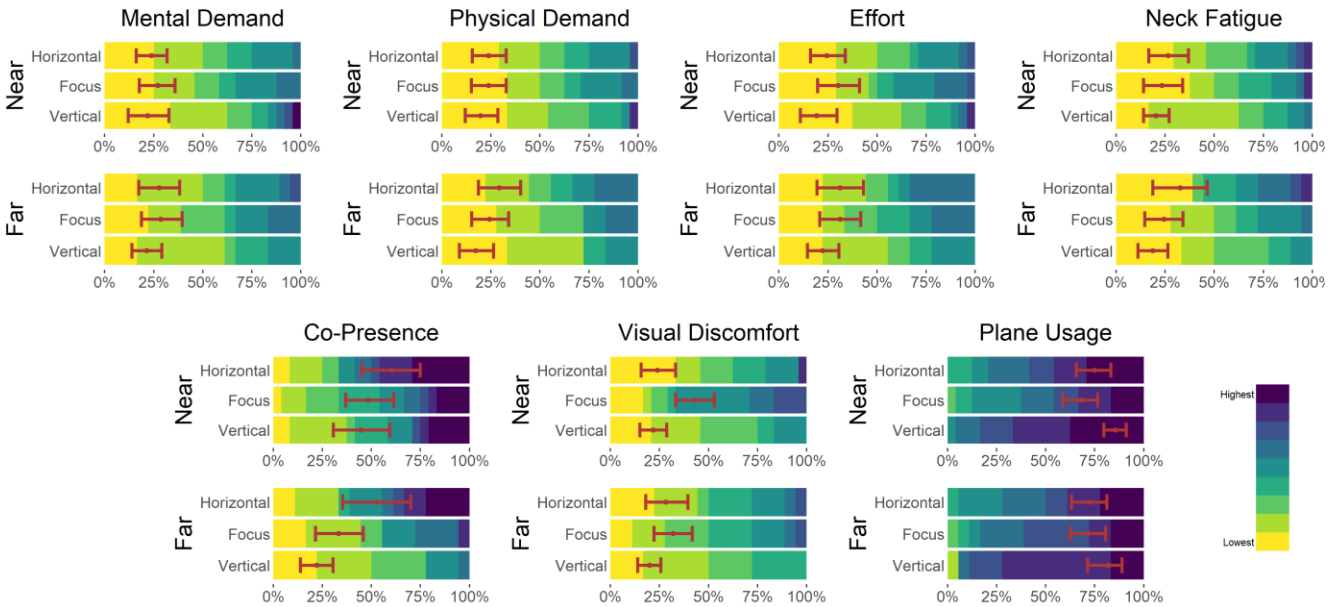

Figure 3 – Summary of the Questionnaires responses. All plots show % of responses (based on 24 participants for the *Near* (Part 1), and 18 for the *Far* (Part 2)) and 95% confidence intervals (red bars), with the darker colours indicating higher/stronger responses.

After completing the questionnaire, twelve participants then completed an in-depth semi-structured interview where we asked them more open-ended questions regarding their experience with the display layouts. In total, 4 hours and 50 minutes of qualitative interview data was recorded. Interview transcripts were analysed using a three-stage open, axial, and selective coding process [6].

4.2.1 Multitasking and Mixed Displays

Participants described how arranging multiple displays of varying sizes would make it possible to multitask in a virtual environment. P19 stated that "the screens are very good because you can leave an email open and watch something while waiting for an email for example." Multiple displays become more practical in a virtual environment, and space for displays extends fully around the user in ways that would be challenging for physical displays. Participants discussed the power of arranging multiple displays across a broad area, for example "I think it will be really great because I like the idea of having multiple screens and in VR you can have infinite screens around you" (P20).

In particular, the ability to simulate large displays alongside smaller peripheral displays creates new opportunities for combining display contents. P22 stated that "the big display, because it has a bigger view, so I can (have) more content at once, and the smaller ones as an aid, to leave the smaller screens for Twitter, another for Instagram and the bigger (display) for Facebook and switch between them, I prefer to see the biggest display as the biggest focus and the others as an aid." Unlike a laptop that would typically require tabbing between views, a virtual workspace can show different sized windows across a wider field of view simultaneously.

4.2.2 Comfort of Horizontal versus Vertical Content

Our vertical and horizontal display configurations highlighted the current limitations of input techniques and control in this environment. These layouts made use of vertical and horizontal space in front of the user, using neck movements to gaze at different areas where displays were placed. The neck typically has symmetrical horizontal flexibility side to side up to 90º. Vertical flexibility is not symmetrical, with up to 90º flexion and 70º extension [43]. Taking into account the field of view horizontally (89º) and vertically (93º) in Oculus Quest [48], neck movements in vertical and horizontal directions would create different experiences. Participants described the fatigue caused by these movements, highlighting the different ranges of comfortable motion across users when both horizontal and vertical neck movements are core to interaction.

Qualitative data indicated strong personal preferences, where both horizonal and vertical layouts were described as fatiguing, difficult, or uncomfortable. For example, "I liked the vertical display... I feel that the head movements up and down are easier to do" (P20) compared to "I liked the horizontal because it requires less physical effort" (P14). Beyond effort of comfort, participants described some more general benefits of these different layouts. P17 described how vertical layouts better afforded leaning forwards, which could be useful in the constrained seat of an airplane. Some participants described how the vertical displays could be confusing when implemented as natural or inverted scrolling, an issue that does not affect horizontal layouts when implemented correctly.

4.2.3 Personal Space and Collisions

One of the key challenges using these novel display configurations in a social travelling context was the fear of disrupting others or attracting unwanted attention. Social acceptance of VR in airplanes has been evaluated before [36,46], but these multi-display environments raise new issues when interaction is spread over a larger area. Horizontal layouts may be favourable with respect to ergonomics and neck range of motion, but this is worst for collisions with others. Participants discussed a commonly cited concern that they might collide with someone else, for example "I was almost concerned that if I looked right or left like in a real-world situation, I would be worried I would hit someone or they hit me unintentionally" (P20).

Interaction with these displays could also create more subtle "social collisions" where private content collides with others. P22 and P14 spoke about how horizontal displays intruded on others, for example stating that "What I didn't really like was the horizontal one, because I had to look towards the passengers" (P22) and "It really gets a little inconvenient because people feel uncomfortable, because people might think that I would be inspecting them" (P14). These social collisions worried participants because unlike a physical collision which are easily noticed, they might be unaware how their interactions disrupted others.

Although vertical layouts presented challenges with respect to ergonomics, these were preferable when thinking about personal space. P20 described the vertical layouts as "it feels like it's more my space," demonstrating the importance of maintaining and remining within one's personal space even in virtual environments when used in public settings.

5 Discussion

This research explored for the first time the passenger use of MR headsets to provide virtual multi-display configurations in a transit context, namely the airplane. We have identified unique constraints to the layout of virtual displays in the passenger context that will inform the development of future AR interfaces that can best conform to their physical surroundings.

5.1 Limitations and Caveats

Our exploration was limited to immersive VR simulations of an airplane environment, and our findings should, when practical (post-COVID-19), be further examined in real-world deployments in the wild to lend greater validity to these results. Our use of virtual avatars for fellow passengers, and a virtual airplane environment, undoubtedly diminishes the ecological validity of our findings. However, we suggest that findings regarding social factors would likely lead to amplified results in real-world airplane environments. In addition, participants suggested that the airplane environment recreated the essential aspects of the in-flight experience, meaning that our insights, whilst preliminary, are nonetheless valuable in better understanding this context. There is also the consideration that our focus was on virtual displays, rather than undocked application content of varying sizes and depths. We might also consider layouts of content that took more significant advantage of the physical personal space of the passenger, for example docking/aligning content with the arm rests, seatback, tray table etc. Consequently, our findings represent only the initial steps toward appropriate MR content layouts adapted to transit environments, particularly focused on 2D virtual display containers as a basic and understandable use case. We envisage further research examining more free-form user-driven layouts, and the appropriation of the physical environment as being further fruitful avenues in moving toward the presentation of AR content in constrained transit environments.

5.2 For Passenger Contexts, AR Can Replace Physical Displays

Firstly, our work reaffirms the opinion that AR has the capacity to replace traditional physical screens for both entertainment and productivity. Participants in our study considered that the visual comfort provided by large heads-up virtual displays, as opposed to smaller seatback displays or more heads-down devices such as laptops, was a key benefit that motivated their preferences. Transit contexts such as economy airline seating have rarely been suited toward productivity, given the restricted size of displays, unergonomic viewing angles of personal devices, and a limited capacity for passengers to adjust their viewing pose over time (a key contributor to musculoskeletal issues). However, AR-driven virtual displays can ease many of these issues, able to render content at any depth, of any size, at any position/orientation around the user. It is yet to be determined to what extent they might improve usability in constrained transit contexts (i.e. would their benefits enable productivity for a full workday duration?), however they certainly offer sufficient benefits to suggest that, when AR hardware reaches consumers in affordable, wearable, fashionable form factors, it will have a positive effect on our capability to utilize travel time for work and entertainment.

5.3 Space Invaders - Reticence to Use Wide Layouts

However, hardware is not necessarily the limiting factor in passenger use of bounded, display-oriented AR content. Instead, a key motivator in preferences between horizontal and vertical layouts was the perception (or fear) that virtual content was encroaching on other passenger's personal space. The three-display horizontal layout was wide, with the peripheral displays being positioned such that they overlapped with the seatbacks of passengers either side of the participant. This layout was based on typical two or three monitor desk setups commonly found in workplaces – a reasonably familiar layout for power users for example. However, regarding **RQ1**, this layout performed the worst across multiple metrics. Conversely, the vertical display layout was largely preferred by participants, constraining the virtual displays to being rendered predominantly on the seatback directly in front of the participant passenger. Indeed, participants repeatedly mentioned that maintain the screens in their own space made them more comfortable, and that they did not want to be seen to be interfering with other passengers.

Despite the simulated setting and presence of virtual avatars rather than real fellow passengers, we have nonetheless demonstrated that the social pressure of being a "space invader" [27] extends to the placement of virtual content. Whilst we have only tentatively demonstrated this, we would suggest that travel contexts introduce significant scope for violating social norms through the placement of virtual content. For example, virtual content positioned such that it appears aligned with a physical display may create a perception of shoulder surfing, whilst when aligned with a fellow passenger this may introduce a feeling in that passenger that they are being stared at. Consequently, care must be taken in presenting virtual content that stays within expected and emergent social norms around the use of this technology. In time, bystanders may come to understand that they (or their devices) are not necessarily the focus of an AR user's fixation, but for our participants this social factor remains a significant concern.

5.4 Layout Should Adapt to Task

Our results also reaffirm that the AR content layout should reasonably adapt to the task at hand. Preferences varied amongst users between the vertical and main display layouts, with the former enabling more equal viewing between different display containers, whilst the latter was seen to benefit entertainment content due to the size of the display. The vertical layout was notably preferred for productivity (13 out of 24 for the layouts enclosed by the seat and 11 out of 24 for the ones located further away), where participant's activities such as reading e-mails, writing, and browsing the internet would benefit due to having multiple displays with which to manage such multi-tasking. The focused layout on the other hand was preferred for entertainment

purposes where users could more greatly immerse themselves into the content on the larger focus display, with the smaller peripheral/thumbnail displays enabling some awareness of other applications such as e-mail or social media.

Whilst such a finding is not particularly novel (e.g. see Lindlbauer et al. on context adaptive MR interfaces [29]) it perhaps takes on particular importance in the passenger context, where users are constrained to the same environment for often significant periods of time. Users may be tempted to "make do" with the current layout rather than going to the effort to adapt their layout to better suit a context/task switch. Consequently, further research will be required to home in on the most appropriate layouts for combinations of primary/secondary/tertiary tasks (e.g., watching a film whilst engaging with social media and browsing the web) and mechanisms by which we can enable users to customize layouts appropriately based on their needs whilst taking into account the aforementioned social factors. Participants also mentioned that the use of physical keyboards would highly benefit the usage of virtual displays, since most productivity tasks (e.g. e-mails, browsing the web) depends to some sort of symbolic/text input and MR-type devices alone still fail in providing a natural metaphor for such tasks [26].

5.5 Inconclusive Findings Regarding Use of Depth

Regarding **RQ2**, the depth of a layout did not appear to be a factor that strongly influenced perceptions regarding our tested layouts, with an exception regarding the awareness of the virtual avatars. However, we did see minor benefits (identified predominantly through qualitative data) regarding a perception that participants needed to turn their heads less in the "Far" conditions, making these more acceptable layouts. Ignoring the depth constraint of the physical seatback in front of the user poses some potentially unique problems and offers significant benefits. Concerning problems, there is the potential to induce diplopia due to the depth of the mildly transparent virtual content (well beyond the seat) and the depth of the seat (much closer), resulting in conflicting convergences. However, by pushing the virtual content further out, we do also ensure that viewing is more stable, with the influence of changes in head orientation/position in altering viewing angle diminished. This could offer significant benefits for passengers that might find themselves frequently adjusting their pose in an attempt to remain comfortable in economy seating for example. Prior industrial research has also discussed that users can feel content becomes somewhat claustrophobic when close to the user [17], which the use of depth could also resolve. However, these questions regarding display depth remain to be resolved, with our data failing to conclusively demonstrate the benefits. Our simulated AR setting, and the duration of our virtual display usage was likely insufficient in testing any depth-cue related conflicts fully, and we suggest further research is required.

5.6 Use of Virtual Simulation of Passenger Environments

More broadly, our use of a simulated airplane environment with AR content, evaluated in VR, builds upon recent related work regarding the use of VR as a means of remote evaluation [32–34,45], as well as experimental psychology work utilizing VR recreations of passenger contexts [15]. As noted previously, this does mean that our findings remain to be further validated in real-world contexts. However, participants emphasized that the environment recreated the essential aspects of the real environment (context, presence of other passengers) needed by the task. Our VR environment lowered costs (of particular concern compared to in-the-wild in-flight research) and ensured greater control over the experimental setting and made observing user behaviour more feasible, of particular benefit given COVID-19 restrictions. We believe this research demonstrates that there is significant value to be had in VR-based explorations of the HCI challenges posed by transit contexts, and their capability to put participants reliably and repeatedly into shared, social situations within those contexts.

5.7 Interaction and Replication for Other Travel Contexts

Control schemes for managing virtual layouts in ergonomic ways have been broached in the past [35], however the unique affordances of the constrained travel environment [36] mean that input techniques suitable for use hands free (for example when the user is encumbered during the serving of meals in-flight) may take on additional importance. This paper focused on the types of layout displays and their effects on social acceptability and comfort. The interaction technique used to switch attention between displays successfully focused on user preferences on these displays. However, different strategies for switching attention between displays and interaction with such displays should be considered in the future to study their effects on user preferences, social acceptability, and comfort. Moreover, we see significant benefit in replicating this research across different travel contexts (e.g. bus, train, autonomous vehicle), as a low-cost means to explore some of the experiential and situational challenges (e.g. transient events such as interactions with other passengers [15]) posed by these environments, and how users might varyingly appropriate said environments using AR/MR.

6 Conclusion

This paper has explored the use of AR/MR headsets for rendering virtual displays in a passenger context, the airplane. A user study in a simulated VR airplane environment evaluated three virtual display layouts (horizontal, focus, vertical) against two depths (near, far). These virtual displays were perceived as an exciting alternative to conventional physical displays such as laptops and seatback displays in airplanes, offering significant benefits in supporting a much larger environment for productivity and entertainment tasks. Moreover, we discovered that social factors play a significant role in user preferences regarding virtual display layout in this shared transit context. Most notably, layouts that users preferred were the ones that remained within the passenger's personal space / seating area. This issue predominantly occurred in the horizontal layout which could lead to behaviours that were considered awkward by other passengers, such as staring, as well as inducing increased physical demand and neck strain. The vertical layout was most preferred for productivity, being most compatible with this shared/social setting. Preferences also varied based on proposed task type, with our focus layout (one large display with smaller auxiliary displays) preferred for entertainment for example. Finally, we highlight the use of a virtual environment as an effective means of simulating real-world airplane experiences. Our paper contributes to new research directions in creating more usable passenger MR experiences.

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