Exploring User Placement for VR Remote Collaboration in a Constrained Passenger Space

Daniel Medeiros
Télécom Paris, LTCI, IPParis
Palaiseau,France
daniel.pires@telecom-paris.fr

Graham Wilson
University of Glasgow
Glasgow, United Kingdom
graham.wilson@glasgow.ac.uk

Mauricio Sousa
University of Toronto
Toronto, Canada
mauricio@dgp.utoronto.edu

Nadia Pantidi
Victoria University of Wellington
Wellington, New Zealand
nadia.pantidi@vuw.ac.nz

Diego Drago
University of Glasgow
Glasgow, United Kingdom
diego.drago@glasgow.ac.uk

Mark McGill
University of Glasgow
Glasgow, United Kingdom
mark.mcgill@glasgow.ac.uk

Stephen Brewster
University of Glasgow
Glasgow, United Kingdom
stephen.brewster@glasgow.ac.uk

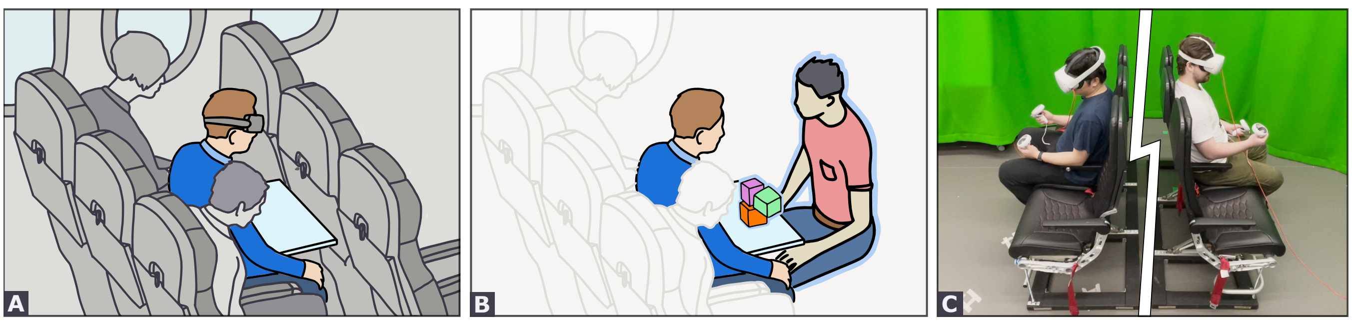

Figure 1: *Left*: Our envisaged scenario, where a VR user sits in a constrained, shared transit environment such as a plane, and engages in remote collaboration. *Middle*: The setup for our study, where pairs of participants in constrained economy plane seats engaged in a series of remote VR collaboration tasks, experiencing different f-formations in VR.*Right*: Mockup of the setup used in our study, where users where seated in real airplane seats in two opposite sides of the same room.

Abstract

Extended Reality (XR) offers the potential to transform the passenger experience by allowing users to inhabit varied virtual spaces for entertainment, work or social interaction, whilst escaping the constrained transit environment. XR allows remote collaborators to feel like they are together and enables them to perform complex 3D tasks. However, the social and physical constraints of the passenger space pose unique challenges to productive and socially acceptable collaboration. Using a collaborative VR puzzle task, we examined the effects of five different f-formations of collaborator placement and orientation in an interactive workspace on social presence, task workload, and implications for social acceptability. Our quantitative and qualitative results showed that face-to-face formations were preferred for tasks with a high need for verbal communication but may lead to *social collisions*, such as inadvertently staring at a neighbouring passenger, or *physical intrusions*, such as gesturing in another passenger's personal space. More restrictive f-formations, however, were preferred for passenger use as they caused fewer intrusions on other passengers' visual and physical space.

CCS Concepts

• **Human-centered computing → Mixed / augmented reality**; **Empirical studies in collaborative and social computing**.

Keywords

Virtual Reality, Mixed Reality, Collaboration, Social Acceptability, Constrained Spaces, Passenger Spaces

ACM Reference Format:

Daniel Medeiros, Graham Wilson, Mauricio Sousa, Nadia Pantidi, Diego Drago, Mark McGill, and Stephen Brewster. 2024. Exploring User Placement for VR Remote Collaboration in a Constrained Passenger Space . In *30th*

VRST '24, October 09–11, 2024, Trier, Germany

ACM ISBN 979-8-4007-0535-9/24/10
https://doi.org/10.1145/3641825.3687722

ACM Symposium on Virtual Reality Software and Technology (VRST '24), October 09–11, 2024, Trier, Germany. ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3641825.3687722

1 Introduction

Virtual Reality (VR) has the potential to enable people to escape the confines of their seat and the wider shared transit environment, instead inhabiting a host of rich virtual environments (VEs). Recent research has explored how passengers can reconfigure their VE to their needs whilst accommodating their shared physical passenger environment. This can be used to support wellbeing [27, 41], productivity [26, 28, 37, 38], and even gaming [19, 51, 58]. Yet, despite our increasing reliance on VR to support remote communication [7] and collaboration across a host of applications, from engineering [44], to architecture [10] to medicine [8], research has yet to consider the feasibility and practicality of supporting remote collaboration in shared and constrained passenger environments. People spend significant amounts of time as passengers and VR could allow this time to be used in new ways to collaborate with others.

Both Virtual and Augmented Reality (which constitute XR) have had a significant impact on our capacity to communicate and collaborate remotely, bestowing a sense of collocation with remote partners (known as social presence [39]) and allowing rich non-verbal cues such as gaze, pointing and deictic gestures for interaction [14, 48]. Consequently, VR has the potential to revolutionise passenger transit activities by enabling embodied, remote collaboration in new environments, such as autonomous vehicles and aircrafts, anywhere, at any time. However, the passenger context also poses unique challenges. Previous work has shown that the physical proximity and presence of nearby passengers in the real world influences how VR users interact with virtual content [36, 57]. Passengers desire to minimise the awkwardness of *social collisions* - events that may adversely impact social comfort or acceptability - caused by 'staring' at (i.e. head pose oriented towards) other people sitting to their sides or in front of them. Moreover, the limited physical space that is available impedes VR interaction [58], a particular problem for many VR activities that require precise selection and manipulation of 3D virtual objects laid out in space [10, 44]. These issues have been studied to a limited extent for single-user VR, leaving unexplored the issue of how to enable remote collaboration in such a limited real-world space and what impact the affordances of the passenger space could have on collaborative activities.

While collaborating, people commonly arrange themselves so that their proximity and orientation around a shared task provide equal access and sightlines, known as the f-formation [6, 30, 46]. However, depending on the relative positions of collaborators and tasks in the VR space, passengers risk both physical and social collisions from their head and arm movements in physical transit space. F-formations have been well studied in the literature for VR and tabletop research [29], leaving physically constrained spaces unexplored and to what extent the placement of remote users can affect collaboration and social acceptability.

This paper contributes formative insights into the experience of VR remote collaboration for passenger spaces, something not yet studied in previous collaborative XR research. In a user study, pairs of remotely-located VR users experienced varying f-formations while performing a task representative of non-restrictive scenarios, including search, selection and manipulation. In our study, we recreated economy airplane seating in reality, mimicking the physical constraints of a passenger context. We explore 1) the influence of f-formations on the effectiveness of VR collaboration and the perceptions of virtual collaborators; 2) the impact that collaborative activities in virtuality and resultant physical actions in reality could have on other collocated passengers. We found that collaborative activities exacerbate the potential for *social collisions*, caused by staring at, physically colliding with, or invading the personal space of other participants. Based on this, we derive challenges to be overcome - including adapting the interactions, boundaries and f-formation used - if we are to enable passengers in constrained spaces to engage in embodied VR collaboration whilst accommodating the social norms and pressures of shared transit contexts.

2 Related Work

2.1 User Placement in Collaborative VR

When people collaborate, proxemics [17] (the appropriate amount of space between people) play a significant role in the spatial relationship between collaborators and their environment. Proxemics show that the engagement between someone and their environment and other people present is partially given by the proximity between the person and a given subject.

In XR research, proxemics guide interaction not only with elements within the VE but also with elements from the outside space [4, 29] or even between different devices [4, 15, 16, 54, 55]. This can be applied to either co-located or remote people [49]. Proxemics show us that violating the expected norms around interpersonal distances can lead to social discomfort. Crucially, however, in the travel environment, a different set of norms exists by necessity, since the close proximity may increase violation of personal and intimate space, which can be exacerbated by VR activities [58].

2.1.1 Interpersonal Formations During Collaboration. An important aspect of collaboration is how collaborators are arranged around the VE, a concept known as *f-formations* [30, 31]. This is particularly important when users are collaborating on a common task and may differ in the level of awareness of the *task space* (i.e. where the task is located [6]). A common form of f-formation is *face-to-face*. Here, the participants in a remote meeting are in front of each other. This formation particularly encourages the use of voice and other types of nonverbal communication, as it is easy for users to glance at each other while being aware of the whole VE. However, since people face each other, they share opposing views of the same workspace, which may hinder awareness of what the other person is referencing [22]. This issue can be mitigated by using a side-by-side or a corner-to-corner formation [23]. In the side-by-side formation, participants share the same frame of reference, as they are located next to each other while sharing a similar point of view.In the corner-to-corner formation, users are oriented at 90 degrees to each other, enabling people to glance at each other while having a similar awareness of the workspace, and may be used to avoid social collisions.

The flexibility of VEs also opens up formations not possible in reality, such as a *coupled view* [43, 50], where collaborators are rendered in the same location. This allows participants to share the same viewpoint, giving equal workspace awareness without the risk of remote avatars causing social collisions through the gaze. However, this may reduce social presence, as people may feel awkward inhabiting another body, which makes social cues such as gaze difficult to represent.It also leaves open the question of how such formations can be used in passenger VR, as formations well-suited for such activities may have inadvertent, socially unacceptable impacts on other passengers in reality.

2.2 Remote Collaboration in XR

XR has been previously used in applications that require rich non-verbal cues for collaboration, such as gaze and deictic gestures [48]. It also enables collaboration with co-located and remote people. Users can be positioned in different portions of the Collaborative Virtual Environment (CVE), adapted to both real and virtual affordances. These systems also enable participants to select and manipulate objects, which is a requirement for more complex tasks that require 3D object manipulation. To enable effective collaboration, each user needs to be represented in the CVE to give them a unique identity and for body movements to be mapped onto their virtual counterparts [24].It is important to note, however, that not all collaborative activities leverage embodied social avatars. For example, with Coupled View collaboration [11], users are located at the same position, with rotational independence from each other. Users are shown an indication of where their collaborator is looking, and a render of their hands represents user actions. This perspective is especially effective for remote assistance and remote learning, as users share the same reference space and can give absolute instructions to their remote peers [11, 20, 43]. This is potentially beneficial for constrained space collaborations, as users are in the same position, and the VE can be fully used for collaboration.

2.3 XR Collaboration in Constrained Spaces

Despite the benefits of XR remote collaboration, research has not yet explored how passengers might take advantage of this capability. Passengers often find themselves in the constrained spaces of planes, cars and other transportation for prolonged periods of time, perceived as wasted time [56]. Yet, with the advent of passenger XR, there becomes the possibility that passengers could not only use this time productively [36, 38, 42], but use it *collaboratively* - especially for VR, where the real environment is completely replaced by a virtual one, allowing people to escape the transit environment to socialise and work with others. However, the passenger cabin poses a number of problems to this use case:

2.3.1 Adapting Interactions. With respect to interaction, the interface needs to be adapted to the constrained space [57, 58]. Such interfaces allow people to escape the constrained space of passenger public spaces while enabling powerful means to visualise and interact with 3D content [45]. In recent years, research has tackled the passenger design space, both in visualising virtual content [36, 38] and interaction with spatial content [52, 58]. Previous work [38] showed XR as an alternative to devices such as laptops for mobile productivity in constrained spaces. In such spaces, people often preferred social comfort, avoiding staring at or colliding with other passengers, over physical comfort. Further work [35] shows that more discreet techniques may be preferred for social comfort but limit more complex interactions in collaborative VR.

2.3.2 Adapting for Social Collisions and Social Comfort. The close proximity of other passengers, seatbacks, and windows also poses challenges around the need to represent the physical real-world space available (e.g. through *Reality Anchors* [3, 57] to avoid physical collisions with the environment or other people, for example, when enacting mid-air interactions [58]. Moreover, social collisions may occur, as a user may face a virtual element in VR but inadvertently orient their head to 'stare' at neighbouring passengers around them in reality, which could be seen as problematic, as passengers may resort to shielding behaviours and placing virtual content to avoid social collisions [36]. However, the impact of VR collaboration on social comfort and the risk of physical/social collisions remains unexplored - interactions with virtual collaborators could exacerbate social comfort challenges in constrained passenger spaces.

3 User Study

We investigate the problem of how to position two users around each other in a collaborative VR task and the resulting effects on how they collaborate in a physically restrictive (50x50cm) passenger setting. To do so, we explore five different VR f-formations for collaborating in a constrained space. These *formations* differ in where workspaces are placed, the distance between collaborators, and their orientation. We investigate their effects on social presence, embodiment, task effectiveness, social collisions and social acceptability. Therefore, we arrived at the following research questions: *How does workspace placement, orientation, and proximity of a remote collaborator in VR affect ... (**RQ1**) perceived spatial and social presence? (**RQ2**) task performance and effectiveness of collaboration? and (**RQ3**) social collisions and social acceptability?*

3.1 Interaction Scenario

Environment. Transit settings can have seating with varying arrangements and number of passengers [35]. We used a scenario of an economy class plane with 50x50cm of physical space [58], where an immersed passenger is sitting in the middle of a row of three, with users on both sides (Figure 1 - A). We wanted to understand if there are f-formations that are better suited for effective and socially acceptable VR remote collaboration in passenger spaces.

Task. In our scenario, we explored the situation in which users are fully immersed in VR and may forget about their real, physical surroundings. Each participant did the task twice, once in each of the roles, totalling six minutes per f-formation.

Presence of Other Passengers. We chose not to have other real passenger actors or participants, or indeed physical passenger proxies such as mannequins, primarily for reasons of ethics and safety, given the risk of physical collisions occurring during interaction, potentially causing harm to the immersed user (or bystander). This design would also give us valuable baseline data about what was likely to happen when VR users *were* fully immersed as passengers - given the expectation that, once immersed and without any additional bystander awareness mechanisms [36, 39, 40], it would be reasonable to assume passengers would forget about their underlying reality and the close proximity of other real passengers.

Instead of using dummies or bystanders, we grounded our interaction scenario by showing a 360° video of our real-world scenario in VR, including other passengers, before each condition, setting the context for users that they were in a public airplane context before becoming immersed in the VR collaboration task.

3.2 Chosen F-formations

Our scenario explores the collaboration between two remotely located VR users, each situated in a different row of a plane in a shared VE. In all of our conditions, we utilize an *Interaction Space*, the constrained environment within the seating area of approximately 50x50cm [58]. Within the *Interaction Space*, a user avatar and a horizontal plane tray table are rendered. The horizontal plane is used as the *workspace*, where a blueprint containing the objects to be assembled is positioned (Figure 4-A). The *Interaction Space* boundary guardian was only shown when the users' arms were close to it (Figure 2-B).

In our study, we used pairs of participants to evaluate how people collaborate in public, constrained environments. According to Marquardt [30], observed that within groups of people, users position themselves in comparison to another person forming a pair to engage both in cooperative and collaborative tasks around a common task space [21, 31]. In our study, we decided to use pairs of people due to these findings. Also, in our scenario, we chose to make users remain in a static position instead of enabling free movement, forcing f-formations between the users and making it possible to use this as a variable in our study. Also, in a real scenario, the physical space itself would be in motion, and supporting virtual locomotion would introduce additional confounding effects (e.g., cybersickness incidence [33]) and break any sense of having a fixed meeting layout. In our study, we varied the f-formations user avatars and workspaces, basing these positions on different f-formations found in the literature and commonly used in reality, ranging from pure sociopetal (designed to bring people together, e.g. face-to-face) to sociofugal (designed to minimise contact between people, e.g. side by side) arrangements [47]. The formations used in our study were:

Face-to-Face with No Intersection (F2FN):. both users face each other at a distance of 81 cm, and their respective workspaces, represented by the tray table, are located directly in front, adjacent to each other along their top edges, but with no overlap (Figure 3-A)

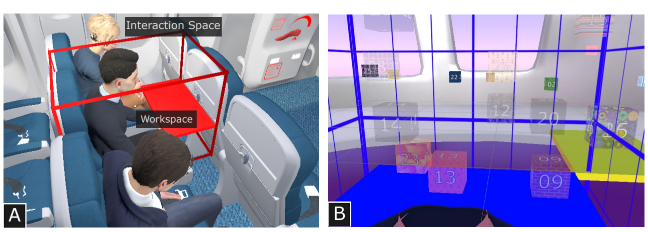

Figure 2: (A) The *Interaction Space* representative of commercial flights, displayed by the wireframe volume (50x50cm) and the traytable representing the workspace, the blue plane (B) representation of the *Interaction Space* guardian in VR.

Face-to-Face with Intersection (F2FI):. The workspace entirely overlaps (e.g. as used by Coeno [18]), and user avatars are at a distance of 49 cm from each other. The overlap in the workspace is the size of the available physical space between the person and the seatback in front, which is approximately 50x50cm (Figure 3-B).

Corner-to-Corner (C2C):. Collaborators are located at an angle of ninety degrees to each other, using a corner-to-corner f-formation (e.g. [13]), with no overlap between their workspaces [30] (Figure 3-C)

Side-by-Side (S2S):. Users are located side by side (Figure 3-D).

Coupled View (CV):. Both the local and remote users are located in the same position in the virtual environment (Figure 3-E) However, their head movements are decoupled, and the local user is able to have an indication of where the remote user is looking as well as their hand positions (Figure 3-F).

3.3 Setup and Apparatus

Each user wore a Meta Quest 2[1], an off-the-shelf VR headset with a 90° of the field of view and a resolution of 1920 x 1832 per eye. We used the built-in microphones to capture users' voices, transmitted over the network. To give ecological validity to our results, each participant sat in the middle seat of a 3-seat row of Hawk economy seats from Mirus. These were located in separate locations in a lab, 1.5m apart, facing away from each other (Figure 1-C).

3.4 Task Design

Rather than focus on a specific activity currently done in planes, we wanted a task whose components are widely applicable and encompass the key features of collaborative VR applications. We designed a task enabling collaboration, including typical VR mid-air interactions, such as raycasting and direct object selection/manipulation [25]. This task is representative of activities that require search, selection

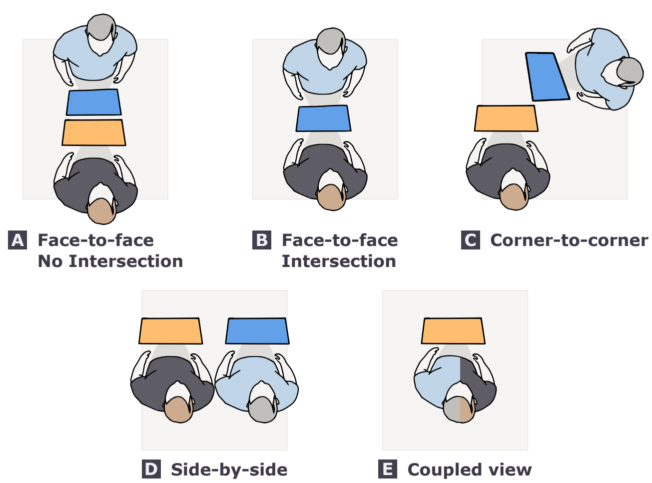

Figure 3: Overview of the different f-formations used: (A) Face-to-face No Intersection (B) Face-to-face Intersection (C) Corner to Corner (D) Side by Side (E) Coupled View.

[1] Meta Quest 2: https://store.facebook.com/gb/en/quest/products/quest-2/

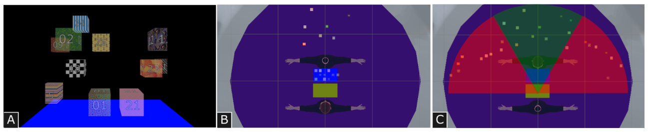

Figure 4: Top-down view of the workspace and the collaboration task: (A) Example of a blueprint in the *Assembler's* workspace, which contained cubes with a pattern and a number (B) View of the Assembler, that has the view of the blueprint (C) Overlaid green and red segments (in increments of 60 degrees) show the different segments where the puzzle pieces were positioned; the green area was directly in front of the Helper, and the red areas were to their right and their left. Each segment had the same number of puzzle pieces.

and manipulation, actions that are commonly used in applications in architecture [10], engineering [44] and medicine [53, 59].

The task consisted of a puzzle, where 27 virtual cubes were positioned around the VE, where each of the cubes had a number and a texture associated with them. To solve the task, participants would search for pieces matching a blueprint consisting of 9 pieces that changed for each task and were positioned on top of the workspace.

To maximise collaboration between users, we gave them separate roles, each with partial awareness of the VE.The *Assembler* had the solution blueprint and queried the *Helper*, who had to look for the puzzle pieces and place them in the Assembler workspace. Then, puzzle pieces were made visible to the *Assembler*, who could put them into the corresponding place on the blueprint.

To make the conditions consistent and avoid any of them to be harder or easier than each other, we distributed puzzle pieces in three segments surrounding the *Helper*. This approach also made users perform a *Search* around the VE, which could potentially lead to social collisions. The pieces were distributed in three different segments of 60 degrees, each containing nine pieces. The first segment was located directly in front of the *Helper* (between -30°and 30°), and two zones were located to their sides (-90°to -60°and 60°to 90°), needing them to turn their heads to locate the cubes.

Participants used direct manipulation to control the object's position when within arms reach, upon confirming it with the trigger button. When outside arm's reach, they could interact with objects via raycasting and confirming selection using the trigger. For all interactions, we locked the rotation of objects for both selection and manipulation of objects within and outside arms-reach. If needed, the users could adjust object rotation according to the hand rotation when within arms-reach by pressing the controller's grip button. These techniques were used in all conditions and inspired in previous work in the literature [1, 38].

3.5 Virtual Environment and Avatars

We used Unity3D to implement the tasks and the VE. Both users are represented in the VE using a customisable upper-body avatar that was implemented using the Meta Avatars SDK.These use the positions of the Quest 2 user's head and both controllers to animate the avatar using inverse kinematics. This SDK also animates the lips of the avatars when the person is speaking, and the avatars' hands are animated to match the controllers' position. We used Photon PUN2 Networking for synchronising the positions of the avatars and objects being interacted.We chose an open space for the VE with no objects that could potentially occlude the puzzle pieces. We displayed a grid to represent the boundaries of the physical passenger space, similar to the guardians used in commercial VR headsets and previous work [58]. This was rendered when a user was near any edge of the physical space.

In all of the conditions, both users had a coloured 29x50cm horizontal surface (within the total 50x50cm interaction space) (Figure 2-A). This represented the workspace where the Assembler placed the objects matching the blueprint. We rendered each of the workspaces in a different colour to identify which user it belonged to. An exception to this was in the **F2FI** and **CV** conditions, where only one workspace was rendered due to the overlap of the two.

3.6 Experimental Design and Data Collection

The study used a within-subjects design, with participants experiencing all conditions. The Independent Variables were *Role* (Assembler, Helper) and *F-Formation* (C2C, CV, F2FI, F2FN and S2S). Our Dependent Variables covered a range of quantitative and qualitative data to investigate our research questions fully.

3.6.1 *Qualitative Data.* After each condition we asked:

Social Presence. Social Presence Questionnaire (SoPQ) [5].

User Preferences. Questions related to *Acceptability*, and *awareness of the surroundings and interactions.*

Interviews. For gathering more detailed qualitative feedback, we performed semi-structured interviews at the end of the experiment and asked about overall preference, use in transport, awareness of surroundings, and the influence of knowledge of their partner in their preferred strategy. The semi-structured interviews were audio-recorded and then transcribed for purposes of analysis.

3.6.2 *Quantitative Data.* We captured:

Total Time. The time to perform our task from the instruction to start until the last cube was retrieved and placed (3 min max); and **Social Collision** metrics relating to how users may physically collide or stare at other people:

Gaze Intrusions. related to what extent a user's hands or head violated the bounds of the Interaction Space (Figure 2-A). For the *Gaze Intrusion* metric, we sampled both users' head orientation at 90Hz to calculate how it would invade the social space of those sitting nearby, based on previous work [38], which shows that people would prefer not to invade other people's space by staring at them. We define three different zones related to one immersed passenger: *Seatback Zone*: which is calculated according to the defined Interaction Space bounds (50x50cm) and equal to +-30 degrees horizontally; this area corresponds to the area where the users' head orientation is entirely within their own seating area; *Other person seatback area (mild intrusion)*: This area corresponds to the extent of users' head orientation where one's looking into the other person's seatback area; and *Gaze area (Extreme intrusion)*: the area where the user is staring directly at or very closely towards the physically located passenger next to them. For purposes of our analysis, we used the percentage of time each participant intruded on the three different zones and analysed them separately. Figure 5 shows a depiction of the different zones of gaze.

Boundary Intrusions. We used two different metrics to assess boundary intrusions, the *Total Time of Boundary Intrusion*, and the *Number of Boundary Intrusions*. For the *Total Time*, we calculated the total time user's body parts violated their boundary, each of these collisions was counted separately, so if the two arms were located outside the boundary of the interaction space, we summed the time of both boundary intrusions. For the *Number of Boundary Intrusions*, we calculated the number of times that a user's arms violated the boundary (Figure 2-A) between them and the seats of the passengers on either side of them, inspired by previous work [58].

3.7 Participants & Procedure

Twenty participants (13 females and seven males, mean age = 25.4 years, SD = 8), split into ten pairs, were recruited and paid £20 each for their time. Most (13 participants out of 20) had previous experience with VR headsets. At the start of the study, we greeted the participants and 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. Before each condition, users were shown a 360° video in the VR headset showing our interaction scenario of a passenger in economy class seating. In this video, they had the perspective of a passenger in an economy flight sitting in the middle, with people sitting to both sides.The conditions were counterbalanced using a balanced Latin Square design to reduce any learning effects. First, we collected demographic information with a short questionnaire. They were then seated in the middle seat of a row of three airplane seats and given the Quest headset. Once comfortable, participants performed a training session to familiarise themselves with the controls for manipulating the virtual objects. For the main experiment, each user completed the task once in the role of *Assembler* and once in the role of *Helper* for each seating configuration, giving 40 trials in total.

People were then asked to fill a questionnaire after each condition. After all conditions, they ranked their preferred conditions and finally we conducted a semi-structured interview with both participants to gather more subjective information.

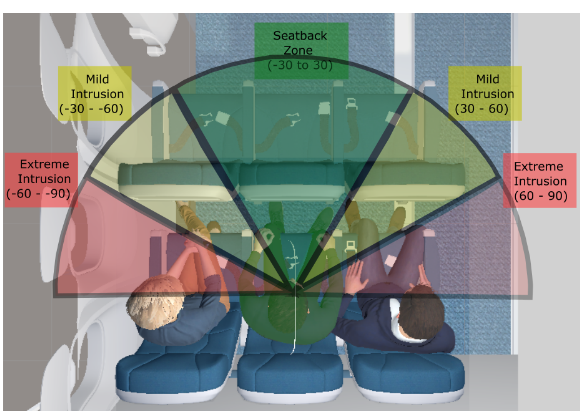

Figure 5: Depiction of the different Gaze Zones based on the position of other users

4 Results

4.1 Quantitative results

Fortime, we used a Shapiro-Wilk test to test for normality. Since the data did not follow a normal distribution, we performed a Friedman Non-parametric test followed by Wilcoxon signed ranks test for pairwise comparisons. For Social Collision metrics, since data did not follow a normal distribution, we used an Aligned Rank Transformation to transform the data and then performed an Two-Way Repeated Measures ANOVA with *Role* and *Condition* as factors, followed by contrasts.

4.1.1 Social Collisions - Gaze Intrusion.

Inside Seatback Bounds. For time inside bounds, we found a significant effect of *Formation* (F(4,17)=9.28 p<0.001), *Role* (F(1,20)=4.83 p=0.0483) and an interaction effect (F(4,17)=0.001). Regarding Role, users in the Assembler role spent more time inside the Seatback zone.Pairwise tests showed that overall, people spent less time inside gaze bounds in the **S2S** condition, in comparison to **C2C**r (p=0.0277), **F2FI** (p=0.029), **CV** (p<0.001), and **F2FN** (p=0.001).

Pairwise comparison showed that for the *Assembler*, there was no significant effect on time spent inside the seatback zone.For the *Helper* condition, there was a significant effect, and pairwise comparisons showed that people spent the most time inside the seatback zone in the **F2FN** condition when compared to **C2C** (Z=-2.094 p=0.036), **S2S** (Z=-3.750 p<0.001), and **F2FI** (Z=-2.321 p=0.02), but with no significance compared to the **CV** condition. Finally, the **S2S** condition had the lowest time inside the seatback zone, being lower than all conditions (**C2C**: Z=-2.224 p=0.026; **CV**: Z=-3.198 p=0.001; **F2FI**: Z=-2.646 p=0.008; **F2FN**: Z=-3.750 p<0.001).

Mild-Intrusion Zone. We also found significant effects of Role (F(1,20)=5.64 p=0.028), condition (F(4,17)=9.59 p<0.001), and a significant interaction effect. For the *Role*, people spent more time inside the Mild-Intrusion zone in the *Helper* role. Regarding *Formation*, people spent less time in the Mild-Instrusion zone in the **S2S** condition in comparison with the **C2C** (p=0.002), **F2FI** (p=0.0025), **CV** (p=0.016) and **F2FN** (p<0.001). Users also spent a less time (in %) in the Mild-Intrusion zone in the **CV** compared to the **F2FN** condition (p=0.033).

Post-hoc tests showed no significant effect for the *Assembler* role. For the *Helper* role, on the other hand, we found a significant effect of *Formation* ($\chi^2(4) = 19.018 p = 0.001$). The **S2S** condition was the one where people spent the most time inside the Mild-intrusion Zone, being statistically higher than **F2FI** (Z=-2.776 p=0.006), **F2FN** (Z=-3.912 p<0.001), **CV** (Z=-2.711 p=0.007) and **C2C** (Z=-2.321 p=0.02). The **F2FN**, on the other hand, was the condition with less *mild* intrusions, having significantly fewer intrusions than the **C2C** (Z=-2.321 p=0.002), **F2FI** (Z=-2.743 p=0.006), and **S2S** (Z=-2.776 p=0.006) conditions. There were no statistically significant differences in mild intrusions.

Extreme Intrusion Zone. We found a significant effect of *Formation* (F(4,17)=7.03 p<0.001). The **CV** was the condition with the smallest percentage of extreme intrusions, compared to all other *Formations*, including **C2C** (p<0.001), **F2FI** (p=0.01), and **S2S** (p=0.04). The **F2FI** also resulted in a higher percentage of time inside the Extreme Intrusion zone when compared to the **F2FN** (p=0.007).

4.1.2 Social Collisions - Boundary intrusions.

Time Boundary intrusions. For this metric, we found a significant effect of *Role* (F(1,20)=2.31 p<0.001) and a significant interaction effect (F(4,17)=3.94 p=0.008). People spent more time inside the boundary in the *Assembler* Role when compared to the *Helper* Role. There were no significant effects in the *Assembler* condition, but there was a significant effect between *Formations* in the *Helper* condition, where the users left the boundary for more time in the **S2S** condition compared to **F2FI** (Z=-2.902 p=0.004).

Number Boundary Intrusions. For this metric,there was an effect of *Role* (F(1,20)=73.21442 p<0.001), *Condition* (F(4,17)= 12.25838 p<0.001) and an interaction between variables (F(1,20)=8.32462 p<0.001). About the *Role*, we found that users violated more times the boundary in the *Helper* than in the *Assembler* role.

For *Condition*, on the other hand, we found that the **CV** was the condition with the least amount of boundary intrusions when compared to the **C2C** (p<0.001), **F2FI** (p=0.008), **F2FN**(p=0.0001), but with no statistical significance with the **S2S** condition. The **C2C** condition, on the other, had more intrusions when compared to **F2FI** (p=0.03) and **S2S** (p=0.003). To investigate further the interaction between the two factors, we conducted two separate analyses for conditions in the two different roles.We found significance between conditions on the *Helper* role ($\chi^2(4) = 19.473 p = 0.001$). Results between Formation conditions in the Helper role followed a similar pattern of the overall analysis, with the **CV** being the condition with less number of collisions (**C2C**:Z=-3.524 p<0.001, **F2FI**: Z=-2.444 p=0.015, **F2FN** (Z=-2.783 p=0.005) and **S2S** (Z=-2.176 p=0.03). The **S2S** also had fewer collisions overall in this Role when compared to **C2C** (Z=-3.524 p=0.03) and **F2FN** (Z=-2.4 p=0.016).

There were also effects on the *Assembler* role, but only with statistical significance between **C2C** and **F2FI** (Z=-2.158 p=0.031), with fewer intrusion times in the **C2C** in comparison with **F2FI**.

4.2 Qualitative Results

4.2.1 Questionnaires. We used Friedman Non-parametric tests with Bonferroni-corrected Wilcoxon Signed Rank *post hoc* tests.

Social Presence. We analysed Social Presence as a whole and for each of the sub-categories. We found a significant difference in overall Social Presence (($\chi^2(4) = 13.322 p = 0.001$). **F2FI** caused significantly higher feelings of social presence than **C2C** (Z=-2.917 p=0.004), **CV** (Z=-2.727 p=0.006) and **S2S** (Z=-2.437 p=0.015).

We only found statistical significance in questions regarding the *Co-presence* and *AA* sub-metrics. For example, there was a statistically significant difference regarding the “I noticed my partner" question ($\chi^2(4) = 9.556 p = 0.049$). *Post hoc* tests showed that in the CV, users noticed their partners less when compared to the **F2FI** condition (Z=-2.460 p=0.014). The Co-presence question “My partner's presence was obvious to me" was also statistically significant ($\chi^2(4) = 9.823 p = 0.044$). For that, participants stated they were able to better perceive their partners in the **F2FI** when compared to **C2C** (Z=-2.086 p=0.037), **CV** (Z=-2.729 p=0.006) and **S2S** (Z=-2.279 p=0.023). Finally, only one question related to the AA sub-metric was found to be significant, which was the one related to remaining focused on their partner, where they remained more focused in the**F2FI** condition when compared to the **CV**.

4.2.2 Interviews. Collaborators experienced five f-formations (see Figure 3). In the interview, participants were asked to discuss their preferred arrangement for the tested task and for performing a collaborative task on aircrafts. The majority of participants reported the side-by-side arrangement as their top preference for the task as it allowed them to see the objectives and manipulate the objects without their view being blocked by the other person's avatar. Having the other person next to them also offered a feeling of partnership, as it was "easier to control" and "seeing the objectives" (P1, Group 1). The F2FN was second in preference, with participants discussing how they liked being able to see the other person, while in comparison, the **F2FI** was not as preferred, as it did not provide enough space to move around and do the task. P1 of group 5, for instance, noted that “ *P1:"when you are interacting with another human you want more space;"* and P2 complemented *"No arms colliding with bodies. With intersect it got a bit messy, you would try to bring a block and then grab something else accidentally…"*.

The C2C offered similar advantages in that pairs could see each other to some extent but without strain or staring at each other; and shared some workspace but did not overlap fully. The least preferred option for most participants was the **CV** arrangement. Participants mentioned how they found they needed to communicate more when in this arrangement and it was weird being positioned in the same location within the VR environment, as it felt like being on top or inside each other. One of the participants even mentioned it being "claustrophobic" (P1,Group 5).

5 Discussion

5.1 RQ1: User Placement and Social Presence

For social presence, we can highlight users' preferences for conditions where they could interact and see an avatar, as it felt they were “working together". The Face-To-Face conditions were the best in that regard. However, users preferred the **F2FN** condition with a larger distance between collaborators, as the close proximity made it feel awkward, especially for extended periods of time.

The lack of awareness of the remote partner's avatar affected co-presence in the **CV** condition. This was explained as, in this condition, participants noticed the other remote partner's presence the least. Despite the reduced perceived social presence, people thought it to be viable for collaboration, particularly inside the limited area of a plane or other similar forms of transportation. Collaborators emphasised that because both participants share the same place with their partner, they would be less concerned about infringing on other people's spaces, something corraborated by the quantitative findings. We also find a lack of significance regarding task efficiency between conditions, suggesting that this technique could be useful for collaboration in confined spaces.

5.2 RQ2: User Placement and Task Efficiency

Regarding task efficiency and efficacy, we did not find an effect on the f-formation or the role being performed. This means that user orientation might not be an important aspect of completing a given task in the constrained space of passenger environments. This may be explained by the nature of the task, which adapts the content placement based on one of the users' position and orientation. In some cases, face-to-face dispositions occluded some objects, making

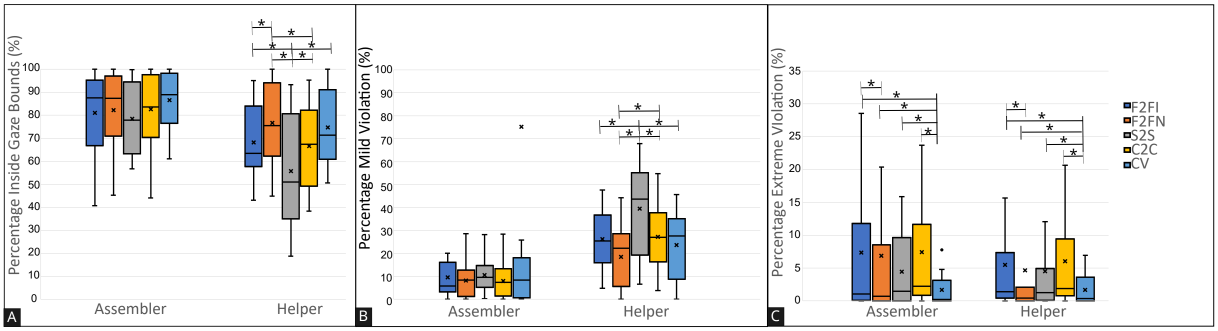

Figure 6: Boxplot results from the Percentage of time spent inside the three zones: (A) Inside Seat Bounds (B) Mild intrusion Zone (C) Extreme intrusion Zone. Boxplot shows the median, average (cross) and First and Third Interquartiles. * indicates statistical significance between conditions/

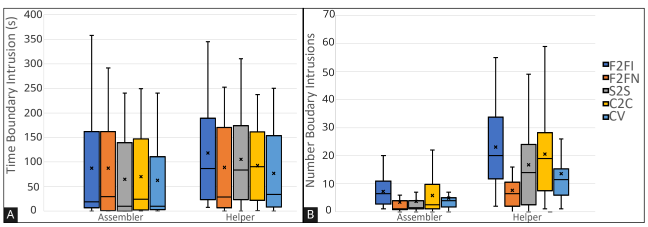

Figure 7: Boxplot data regarding (A) Time Violating Physical Boundaries and (B) Number of times users violated the physical bounds. * indicates statistical significance.

people look over the remote user to see the puzzle pieces, causing more body movement. This did not affect task completion, as we did not find any significant effects on task completion times and number of correct pieces assembled. Another important aspect is that, though not affecting task completion, users found S2S and CV more pleasant to perform the task, as they face the virtual environment, with nothing occluding their view.

5.3 RQ3: User placement and Social Collisions

We found no differences in the social comfort questions between the formations tested. This may be due to the lack of user representations or physical people sitting next to the immersed users. To further assess the prospective social impact of the formations tested on other passengers, we derived two *Social Collision* metrics: *Boundary Intrusion* and *Gaze Intrusion*.

Regarding *Boundary Intrusions*, We found a decrease in intrusions in the **CV** condition, which aligns to user comments in the interview. Both FaceToFace conditions had more boundary intrusions than other formations when in the *Helper role*. As pointed out by some participants in the interviews, this can be explained by the avatar blocking some of the pieces of the puzzle, which required users to move to reach them, which resulted in boundary intrusions.However, there were very few boundary intrusions overall (see total intrusions in Figure 7, B). Therefore, even though there were no physical boundaries such as seat backs in front of the participants or people to their sides, they still largely stayed within this space.

For *Gaze Intrusions*, we found a strong effect on the *Role*, the *Formation*, and the interaction between the two. This may be explained by the nature of each of the roles, as in the *Helper* role, users needed to look for the pieces around the VE, which made them spend more time looking outside the seating visual bounds than in the Assembler role, especially in the Mild-Intrusion Zone. In the *Assembler* role, on the other hand, the interaction was confined to the seating volume, as the pieces were located right in front of the participant. We found, however, that since the *Assembler* had to ask for pieces from the Helper verbally, they would try and look at their face, which may explain the higher percentage of *Gaze Intrusions* in the Extreme-Intrusion zone for the **S2S** and **C2C** formations. Even though the **S2S** was one of the preferred conditions in the interviews, it might not be suited for passenger contexts due to the increased number of Gaze Intrusions. In such cases, the **CV** may be better suited, as participants share the same frame of reference and cause fewer social collisions, even with reduced social presence. Finally, there was an increased percentage of gaze intrusions in the **F2FI** condition. This may be explained by the fact that, since users were closely located, they avoided looking at the person's avatar as it was socially awkward, thus resulting in more Gaze Intrusions.

5.4 Summary

The choice of f-formation in constrained spaces needs to consider their real surroundings, especially on tasks that require interaction in a bigger virtual space than what is available in real life (as in the task performed in the Helper role). It also needs to adapt to the focus of the interaction: where increased remote users' awareness is needed, **F2FN** is recommended; however, in cases where workspace awareness is more important (e.g. guided tutorials), we suggest the CV formation, as it decreases social collisions. In more complex contexts, where both tasks are important, designers might enable switching between formations. However, some perceptual manipulations may be required to allow more consistent workspace references between formations [12, 48].

5.5 Limitations

One issue mentioned by participants was that some did not notice the guardian, who could intrude into the neighbouring space and potentially physically collide with them. Since our main goal was to provide an initial assessment of remote collaboration in constrained spaces, we used a standard guardian system based on commercially available VR devices and previous works [58]. People in some cases, forgot the physical environment altogether, but as we see in the results, we did not find significant differences between conditions, with the exception of the CV condition, since users were in the same position. Additionally, some participants saw value in seeing where other passengers were seated.We chose not to use visualisations of other passengers as, in our scenario, remote and physically co-located people could be located in the same position, making our experiment design more complex, as representing bystanders in passenger VR is not straightforward [3, 32, 57]. This may also compromise social presence with other remote users and the environment [34].

Furthermore, we used social collision metrics such as physical intrusions (previously used in [58], and deriving a novel metric for gaze intrusions, to measure to what extent formations could disrupt fellow passengers. We also see value in including sound and visual feedback [3, 34] or even real actors in future work. Also, while we focused on interaction techniques that were common in less restrictive XR scenarios, further techniques using bare-hand interaction or even surfaces may cause less social collisions [35] .

We acknowledge that the use of voice communication may be a problem in real settings, as some people may prefer not to talk to either disturb or be disturbed (and in forms of transport like buses and trains, speech communication is common). But, we highlight that such norms change over time with technology adoption. As such, we preferred to ensure that they actively collaborated rather than merely solving the task independently.

Finally, while our task represents a wide range of collaborative activities involving 3D selection and manipulation, such as those used in medicine, architecture, and engineering, it does not represent all possible collaborative activities. Different tasks involving locomotion, with different degrees of social engagement with collaborators and different numbers of collaborators beyond pairs, could impact results, and this should be taken into account when interpreting results to be applied to different collaborative contexts.

5.6 Challenges and Future Work

Previous studies on VR distant collaboration have frequently assumed that people need to work in private, unrestricted physical environments. However, in transit contexts, collaboration is under additional pressure due to the confined space, limited mobility, and passengers' proximity. This provokes the need to consider not just the arrangement of collaborators but, as our work evidence for the first time, the *cross-reality* [60] impact of the VR user's activities on their own and remote user's transit environments.

5.6.1 Social Comfort, Collisions and Cross-Reality Intrusions. Collaborative VR in constrained spaces between *n* users poses unique challenges due to there being (*n+1*) environments impacting the activity. Each collaborator has an underlying real-world arrangement (n), alongside the common VR environment and f-formation (assuming this is not personalised [12, 48]). With respect to *social collisions*, we have shown that the nature of this mixture of real and virtual environments can potentially instigate:

Gaze/head orientation intrusions where the VR user may be perceived to be looking at/in the direction of another passenger's space (e.g. their seatback display) or indeed the passenger themselves; **Physical encroachment** where the bounding box of the other passenger's seat may be encroached inadvertently during mid-air interactions, despite the visibility of safety boundaries (re-affirming the work of Wilson *et al.* [58]).

Moreover, when collaborators are in different spaces in reality, this also opens up the possibility of *cross-reality intrusions* affecting other nearby passengers. Consider that Alice places a virtual artefact to the far left of Bob and asks Bob to interact with it (e.g. reviewing or manipulating a 3D model). If Bob looks in that extreme direction, he may perform a gaze intrusion on the passenger to his left. Similarly, if Bob were to reach out and grab the object in mid-air, he may reach into the other passenger's personal space or even touch/collide with the passenger. In this way, Alice will have inadvertently or deliberately caused a cross-reality intrusion, influencing another individual's actions in virtuality in a way that negatively impacts their, or another's, underlying real-world environment. Addressing such challenges necessitates considering how we can adapt the *virtual f-formation*, *virtual content, interactions and guardian boundaries* and *underlying physical environment* to minimise social collisions, tensioned against ever-changing *social norms* in the increase in adoption of VR/XR, and the need to ensure *effective communication and effective collaboration.*

5.6.2 Adapting the Content, Interactions and Boundaries to the Physical Affordances of the Constrained Space. If we consider gaze intrusions and physical encroachment, there are a number of ways by which VR content and interactions could be adapted to minimize such social collisions. *Perceptual remapping*, from remapping room-scale environments of varying sizes [9] to remapping the constrained interaction space [37], could be leveraged to redirect and constrain both where the user looks, and the bounds within which they physically interact to avoid such collisions. Rotational gain could also be applied, either to specific elements or the whole scene, enabling a wider field of view whilst constraining head/neck movement to a narrower, more socially acceptable range. Finally, the work presented here was thought for the airplane cabin but can be applied to varying public spaces. However, other spaces, such as cars and buses [36, 38, 45], have specific challenges that need to be tackled in future work.

5.6.3 Adapting the f-Formation to Changing User Needs. Similarly, by manipulating others' perceptions [2, 12, 48], we may remove the constraint of a commonly shared f-formation, allowing f-formations customisation per collaborator. The ideal formation should match the limits of a certain collaborator's real-world setting, while other collaborators' perceived gaze and gestures should be adjusted to match. For example, in the worst-case situation, when passengers are on both sides, more restrictive f-formations might be employed, whereas less restrictive f-formations could be utilised in cases where fewer passengers are present or even for business class customers.

6 Conclusion

XR technology unlocks numerous possibilities for remote collaboration in transit enabling people to feel they are in the same location. However, social collisions may occur, due to the nature of the passenger space, by either physically colliding or staring at each other.In this paper, we explored how user placement impacts collaboration in XR and study the impact on presence, social acceptability and social collisions.

Our results showed that the formation used did not have an impact on task efficiency and workload, but Face-to-face formations were preferred for the collaborative activities. More restrictive ones, such as Coupled View, may be preferred for constrained spaces because they cause fewer gaze and physical intrusions into the space of nearby passengers, although with a negative impact on social presence in the VR activity. Moreover, with our results, we open the possibility of enabling remote collaboration in confined passenger spaces, even for more complex XR activities, by balancing awareness of the workspace and their conversational partner.

Acknowledgments

This research was funded by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement #835197: ViAjeRo).

References

[1] 2019. A survey on 3d virtual object manipulation: From the desktop to immersive virtual environments. In *Computer graphics forum*, Vol. 38. Wiley Online Library, 21–45.

[2] Rafael Kuffner dos Anjos, Maurício Sousa, Daniel Mendes, Daniel Medeiros, Mark Billinghurst, Craig Anslow, and Joaquim Jorge. 2019. Adventures in hologram space: exploring the design space of eye-to-eye volumetric telepresence. In *Proceedings of the 25th ACM Symposium on Virtual Reality Software and Technology*. 1–5.

[3] Laura Bajorunaite, Stephen Brewster, and Julie R. Williamson. 2022. "Reality Anchors": Bringing Cues from Reality into VR on Public Transport to Alleviate Safety and Comfort Concerns. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 383, 6 pages. https://doi.org/10.1145/3491101.3519696

[4] Till Ballendat, Nicolai Marquardt, and Saul Greenberg. 2010. Proxemic interaction: designing for a proximity and orientation-aware environment. In *ACM International Conference on Interactive Tabletops and Surfaces*. 121–130.

[5] Frank Biocca, Chad Harms, and Jenn Gregg. 2001. The networked minds measure of social presence: Pilot test of the factor structure and concurrent validity. In *4th annual international workshop on presence, Philadelphia, PA*. 1–9.

[6] Bill Buxton. 2009. Mediaspace–meaningspace–meetingspace. *Media space 20+ years of mediated life* (2009), 217–231.

[7] VR Chat. 2023. VR Chat. https://hello.vrchat.com/.

[8] Fabio Cofano, Giuseppe Di Perna, Marco Bozzaro, Alessandro Longo, Nicola Marengo, Francesco Zenga, Nicola Zullo, Matteo Cavalieri, Luca Damiani, Daniya J Boges, et al. 2021. Augmented reality in medical practice: from spine surgery to remote assistance. *Frontiers in Surgery* 8 (2021), 657901.

[9] Ben J Congdon, Tuanfeng Wang, and Anthony Steed. 2018. Merging environments for shared spaces in mixed reality. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*. 1–8.

[10] Rui de Klerk, André Mendes Duarte, Daniel Pires Medeiros, José Pinto Duarte, Joaquim Jorge, and Daniel Simões Lopes. 2019. Usability studies on building early stage architectural models in virtual reality. *Automation in Construction* 103 (2019), 104–116.

[11] Carmine Elvezio, Mengu Sukan, Ohan Oda, Steven Feiner, and Barbara Tversky. 2017. Remote collaboration in AR and VR using virtual replicas. In *ACM SIGGRAPH 2017 VR Village*. 1–2.

[12] Catarina G Fidalgo, Maurício Sousa, Daniel Mendes, Rafael Kuffner Dos Anjos, Daniel Medeiros, Karan Singh, and Joaquim Jorge. 2023. Magic: Manipulating avatars and gestures to improve remote collaboration. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*. IEEE, 438–448.

[13] Denise Y. Geiskkovitch, Daniel J. Rea, Agape Y. Seo, Stela H. Seo, Brittany Postnikoff, and James E. Young. 2020. Where Should I Sit? Exploring the Impact of Seating Arrangement in a Human-Robot Collaborative Task. In *Proceedings of the 8th International Conference on Human-Agent Interaction* (Virtual Event, USA) *(HAI '20)*. Association for Computing Machinery, New York, NY, USA, 41–49. https://doi.org/10.1145/3406499.3415080

[14] Jiangtao Gong, Jingjing Sun, Mengdi Chu, Xiaoye Wang, Minghao Luo, Yi Lu, Liuxin Zhang, Yaqiang Wu, Qianying Wang, and Can Liu. 2023. Side-by-Side vs Face-to-Face: Evaluating Colocated Collaboration via a Transparent Wall-sized Display. *Proceedings of the ACM on Human-Computer Interaction* 7, CSCW1 (2023), 1–29.

[15] Saul Greenberg, Nicolai Marquardt, Till Ballendat, Rob Diaz-Marino, and Miaosen Wang. 2011. Proxemic interactions: the new ubicomp? *interactions* 18, 1 (2011), 42–50.

[16] Jens Emil Grønbæk, Mille Skovhus Knudsen, Kenton O'Hara, Peter Gall Krogh, Jo Vermeulen, and Marianne Graves Petersen. 2020. Proxemics Beyond Proximity: Designing for Flexible Social Interaction Through Cross-Device Interaction. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376379

[17] Edward Twitchell Hall. 1966. *The hidden dimension*. Vol. 609. Garden City, NY: Doubleday.

[18] M. Haller, M. Billinghurst, J. Leithinger, D. Leitner, and T. Seifried. 2005. Coeno: Enhancing Face-to-Face Collaboration. In *Proceedings of the 2005 International Conference on Augmented Tele-Existence* (Christchurch, New Zealand) *(ICAT '05)*. Association for Computing Machinery, New York, NY, USA, 40–47. https://doi.org/10.1145/1152399.1152408

[19] Philipp Hock, Sebastian Benedikter, Jan Gugenheimer, and Enrico Rukzio. 2017. CarVR: Enabling In-Car Virtual Reality Entertainment. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4034–4044. https://doi.org/10.1145/3025453.3025665

[20] Kevin Huang, Jiannan Li, Mauricio Sousa, and Tovi Grossman. 2022. ImmersivePOV: Filming How-To Videos with a Head-Mounted 360° Action Camera. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 91, 13 pages. https://doi.org/10.1145/3491102.3517468

[21] Hayley Hung and Ben Kröse. 2011. Detecting F-formations as dominant sets. In *Proceedings of the 13th International Conference on Multimodal Interfaces* (Alicante, Spain) *(ICMI '11)*. Association for Computing Machinery, New York, NY, USA, 231–238. https://doi.org/10.1145/2070481.2070525

[22] Hiroshi Ishii and Minoru Kobayashi. 1992. Clearboard: A seamless medium for shared drawing and conversation with eye contact. In *Proceedings of the SIGCHI conference on Human factors in computing systems*. 525–532.

[23] Adam Kendon. 2010. *Spacing and Orientation in Co-present Interaction*. Springer Berlin Heidelberg, Berlin, Heidelberg, 1–15. https://doi.org/10.1007/978-3-642-12397-9_1

[24] Konstantina Kilteni, Raphaela Groten, and Mel Slater. 2012. The sense of embodiment in virtual reality. *Presence: Teleoperators and Virtual Environments* 21, 4 (2012), 373–387.

[25] Joseph J LaViola Jr, Ernst Kruijff, Ryan P McMahan, Doug Bowman, and Ivan P Poupyrev. 2017. *3D user interfaces: theory and practice*. Addison-Wesley Professional.

[26] Jingyi Li, Ceenu George, Andrea Ngao, Kai Holländer, Stefan Mayer, and Andreas Butz. 2021. Rear-seat productivity in virtual reality: Investigating vr interaction in the confined space of a car. *Multimodal Technologies and Interaction* 5, 4 (2021), 15.

[27] Jingyi Li, Yong Ma, Puzhen Li, and Andreas Butz. 2021. *A Journey Through Nature: Exploring Virtual Restorative Environments as a Means to Relax in Confined Spaces*. Association for Computing Machinery, New York, NY, USA. https://doi-org.emedien.ub.uni-muenchen.de/10.1145/3450741.3465248

[28] Jingyi Li, Luca Woik, and Andreas Butz. 2022. Designing mobile mr workspaces: Effects of reality degree and spatial configuration during passenger productivity in hmds. *Proceedings of the ACM on Human-Computer Interaction* 6, MHCI (2022), 1–17.

[29] Nicolai Marquardt and Saul Greenberg. 2015. Proxemic interactions: From theory to practice. *Synthesis Lectures on Human-Centered Informatics* 8, 1 (2015), 1–199.

[30] Nicolai Marquardt, Ken Hinckley, and Saul Greenberg. 2012. Cross-device interaction via micro-mobility and f-formations. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*. 13–22.

[31] Paul Marshall, Yvonne Rogers, and Nadia Pantidi. 2011. Using F-formations to analyse spatial patterns of interaction in physical environments. In *Proceedings of the ACM 2011 conference on Computer supported cooperative work*. 445–454.

[32] Mark McGill, Roderick Murray-Smith, Daniel Boland, and Stephen A. Brewster. 2015. A Dose of Reality: Overcoming Usability Challenges in VR Head-Mounted Displays. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI EA '15)*. Association for Computing Machinery, New York, NY, USA, 177. https://doi.org/10.1145/2702613.2732491

[33] Mark McGill, Graham Wilson, Daniel Medeiros, and Stephen Anthony Brewster. 2022. Passengxr: A low cost platform for any-car, multi-user, motion-based passenger xr experiences. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*. 1–15.

[34] Daniel Medeiros, Rafael Dos Anjos, Nadia Pantidi, Kun Huang, Maurício Sousa, Craig Anslow, and Joaquim Jorge. 2021. Promoting reality awareness in virtual reality through proxemics. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*. IEEE, 21–30.

[35] Daniel Medeiros, Romane Dubus, Julie Williamson, Graham Wilson, Katharina Pohlmann, and Mark McGill. 2023. Surveying the Social Comfort of Body, Device, and Environment-Based Augmented Reality Interactions in Confined Passenger Spaces Using Mixed Reality Composite Videos. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 7, 3 (2023), 1–35.

[36] Daniel Medeiros, Mark McGill, Alexander Ng, Robert McDermid, Nadia Pantidi, Julie Williamson, and Stephen Brewster. 2022. From Shielding to Avoidance: Passenger Augmented Reality and the Layout of Virtual Displays for Productivity in Shared Transit. *IEEE Transactions on Visualization and Computer Graphics* (2022).

[37] Daniel Medeiros, Graham Wilson, Mark Mcgill, and Stephen Anthony Brewster. 2023. The Benefits of Passive Haptics and Perceptual Manipulation for Extended Reality Interactions in Constrained Passenger Spaces. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. 1–19.

[38] Alexander Ng, Daniel Medeiros, Mark McGill, Julie Williamson, and Stephen Brewster. 2021. The Passenger Experience of Mixed Reality Virtual Display Layouts in Airplane Environments. In *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 265–274.

[39] Catherine S. Oh, Jeremy N. Bailenson, and Gregory F. Welch. 2018. A Systematic Review of Social Presence: Definition, Antecedents, and Implications. *Frontiers in Robotics and AI* 5 (2018). https://doi.org/10.3389/frobt.2018.00114

[40] Joseph O'Hagan, Julie R. Williamson, Florian Mathis, Mohamed Khamis, and Mark McGill. 2023. Re-Evaluating VR User Awareness Needs During Bystander Interactions. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 876, 17 pages. https://doi.org/10.1145/3544548.3581018

[41] Pablo E. Paredes, Stephanie Balters, Kyle Qian, Elizabeth L. Murnane, Francisco Ordóñez, Wendy Ju, and James A. Landay. 2018. Driving with the Fishes: Towards Calming and Mindful Virtual Reality Experiences for the Car. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 2, 4 (Dec. 2018), 1–21. https://doi.org/10.1145/3287062

[42] Leonardo Pavanatto, Chris North, Doug A. Bowman, Carmen Badea, and Richard Stoakley. 2021. 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)*. IEEE, 759–767. https://doi.org/10/gj3dh5

[43] Thammathip Piumsomboon, Arindam Day, Barrett Ens, Youngho Lee, Gun Lee, and Mark Billinghurst. 2017. Exploring enhancements for remote mixed reality collaboration. In *SIGGRAPH Asia 2017 Mobile Graphics & Interactive Applications*. ACM, 16.

[44] Alberto Raposo, Ismael Santos, Luciano Soares, Gustavo Wagner, Eduardo Corseuil, and Marcelo Gattass. 2009. Environ: integrating VR and CAD in engineering projects. *IEEE Computer Graphics and Applications* 29, 6 (2009), 91–95.

[45] Thereza Schmelter and Kristian Hildebrand. 2020. Analysis of Interaction Spaces for VR in Public Transport Systems. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, Atlanta, GA, USA, 279–280. https://doi.org/10.1109/VRW50115.2020.00058

[46] Stacey D Scott, M Sheelagh T Carpendale, and Kori Inkpen. 2004. Territoriality in collaborative tabletop workspaces. In *Proceedings of the 2004 ACM conference on Computer supported cooperative work*. 294–303.

[47] Robert Sommer. 1967. Sociofugal Space. *Amer. J. Sociology* 72, 6 (1967), 654–660. https://doi.org/10.1086/224402 arXiv:https://doi.org/10.1086/224402

[48] Maurício Sousa, Rafael Kufner dos Anjos, Daniel Mendes, Mark Billinghurst, and Joaquim Jorge. 2019. Warping deixis: distorting gestures to enhance collaboration. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–12.

[49] Maurício Sousa, Daniel Mendes, Daniel Medeiros, Alfredo Ferreira, João Madeiras Pereira, and Joaquim Jorge. 2016. Remote proxemics. *Collaboration meets interactive spaces* (2016), 47–73.

[50] Theophilus Teo, Louise Lawrence, Gun A Lee, Mark Billinghurst, and Matt Adcock. 2019. Mixed Reality Remote Collaboration Combining 360 Video and 3D Reconstruction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 201.

[51] Henry Togwell, Mark McGill, Graham Wilson, Daniel Medeiros, and Stephen Anthony Brewster. 2022. In-car gaming: Exploring the use of ar headsets to leverage passenger travel environments for mixed reality gameplay. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*. 1–7.

[52] Wen-Jie Tseng, Elise Bonnail, Mark McGill, Mohamed Khamis, Eric Lecolinet, Samuel Huron, and Jan Gugenheimer. 2022. The Dark Side of Perceptual Manipulations in Virtual Reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 612, 15 pages. https://doi.org/10.1145/3491102.3517728

[53] Neil Vaughan, Bodgan Gabrys, and Venketesh N Dubey. 2016. An overview of self-adaptive technologies within virtual reality training. *Computer Science Review* 22 (2016), 65–87.

[54] Jo Vermeulen, Kris Luyten, Karin Coninx, Nicolai Marquardt, and Jon Bird. 2015. Proxemic flow: Dynamic peripheral floor visualizations for revealing and mediating large surface interactions. In *IFIP Conference on Human-Computer Interaction*. Springer, 264–281.

[55] Daniel Vogel and Ravin Balakrishnan. 2004. Interactive public ambient displays: transitioning from implicit to explicit, public to personal, interaction with multiple users. In *Proceedings of the 17th annual ACM symposium on User interface software and technology*. 137–146.

[56] Laura Watts and John Urry. 2008. Moving Methods, Travelling Times. *Environment and Planning D: Society and Space* 26, 5 (2008), 860–874. https://doi.org/10.1068/d6707 arXiv:https://doi.org/10.1068/d6707

[57] Julie R Williamson, Mark McGill, and Khari Outram. 2019. Planevr: social acceptability of virtual reality for aeroplane passengers. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–14.

[58] Graham Wilson, Mark McGill, Daniel Medeiros, and Stephen Brewster. 2023. A Lack of Restraint: Comparing Virtual Reality Interaction Techniques for Constrained Transport Seating. *IEEE Transactions on Visualization and Computer Graphics* 29, 5 (2023), 2390–2400.

[59] Tzong-Hann Wu, Feng Wu, Ci-Jyun Liang, Yi-Fen Li, Ching-Mei Tseng, and Shih-Chung Kang. 2019. A virtual reality tool for training in global engineering collaboration. *Universal Access in the Information Society* 18 (2019), 243–255.

[60] Cindy Ziker, Barbara Truman, and Heather Dodds. 2021. Cross reality (XR): Challenges and opportunities across the spectrum. *Innovative learning environments in STEM higher education: Opportunities, challenges, and looking forward* (2021), 55–77.