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Surveying the Social Comfort of Body, Device, and Environment-Based Augmented Reality Interactions in Confined Passenger Spaces Using Mixed Reality Composite Videos

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Fig. 1. Using the Oculus Mixed Reality Capture Tool, the composition of A (background), B (chromakey reality) and C (foreground) gives the final result D - where real video is composited in a way that respects the depth of the virtual imagery. In this way, we can create video clips that demonstrate an interaction technique in a specific context with high fidelity.

Augmented Reality (AR) headsets could significantly improve the passenger experience, freeing users from the restrictions of physical smartphones, tablets and seatback displays. However, the confined space of public transport and the varying proximity to other passengers may restrict what interaction techniques are deemed socially acceptable for AR users - particularly considering current reliance on mid-air interactions in consumer headsets. We contribute and utilize a novel approach to social acceptability video surveys, employing mixed reality composited videos to present a real user performing interactions across different virtual transport environments. This approach allows for controlled evaluation of perceived social acceptability whilst freeing researchers to present interactions in any simulated context. Our resulting survey (N=131) explores the social comfort of body, device, and environment-based interactions across seven transit seating arrangements. We reflect on the advantages of discreet inputs over mid-air and the unique challenges of face-to-face seating for passenger AR.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**; *Gestural input*; *Empirical studies in HCI*.

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1 INTRODUCTION

Augmented reality (AR) headsets are moving ever closer to everyday, fashionable, wearable, consumer-friendly form factors. Consequently, these devices have the potential for mass adoption and usage in real-world contexts in the near future, positively impacting productivity [55] and entertainment [1, 107] when on the move.

Travel plays a significant role in our daily lives with a large proportion being spent on public transport, from local commutes in taxis and subways to longer commutes over greater distances in trains and planes. Passengers in the UK, for example, travelled over 873 billion kilometres in 2019 [96]. The need to support passengers to fill their travel time usefully and productively continues to be a critical economic and societal challenge. AR devices enable users to move away from small, un-ergonomic devices (e.g. mobile phones, tablets) and reproduce their work environments in a small form factor. AR allows for immersive virtual content to be rendered anywhere around the user, suggesting that passenger experiences in public transport [57] will uniquely benefit from everyday AR.

However, public transport also poses unique challenges to the adoption of AR headsets [57]. Interaction while travelling generally occurs in constrained spaces assigned to passengers in close proximity to other passengers. This creates challenges for social comfort [18, 91] and acceptability more generally [92, 114], such as the potential for embarrassing interactions [15], that are unique from other public contexts [25]. A key challenge for designing input techniques for such constrained spaces is taking the physical space, such as objects and other passengers, into account [25, 89]. For example, pointing to virtual content with a handheld controller or gesturing in mid-air could lead to physical collisions between passengers. These techniques can also be uncomfortable and socially awkward as the actions are highly visible, but the content is only seen by the user experiencing it [80, 113]. Feelings of social discomfort risk leading people to reject the AR interaction techniques currently relied upon, instigated either by the reactions of bystanders, or the self-perception and anxieties of users. Such a rejection could hinder the adoption of AR headsets, or diminish usability by restricting how we interact, preventing passengers from making the fullest use of AR to fill their travel time usefully and productively.

We propose that smaller, more discreet/subtle interactions [75] will improve the usability, comfort, and acceptance of AR headsets in public transport. Previous research has shown that locations and audiences impact the social acceptability of virtual reality (VR) use in transit [9, 92, 115] but they only focused on a limited number of contexts. Moreover, the social acceptability of specific interactions for AR use in confined shared passenger spaces has received little attention in the literature so far. This lack of attention may be explained by the unique affordances related to elements of each mode of transport, such as seating arrangements and the presence and proximity of strangers. Compounding this is the breadth of interaction techniques that could be considered for use in such contexts and their impact on people's perceived social acceptability, both for the user performing the action(s) and bystanders as defacto audiences to them.

To address this knowledge gap, we utilize composited videos (see Figure 1, captured using the Oculus Mixed Reality Capture Tool [76]) to place a real person performing the given interaction into a computer-generated virtual passenger environment. Using this mixed reality compositing approach, we generated 75 video clips spanning **7 unique virtual transportation seating arrangements** and **12 interaction techniques** (based on previous work from a set of body, device and environment-based interactions). This use of mixed reality video compositing represents a novel extension to online social acceptability video survey methodology [41], enabling practitioners to embed controlled, real performances and user interactions into any available virtual environment or context, freeing practitioners from previous limitations regarding finding or physically re-creating existing real-world contexts for such surveys. We utilize this approach to assess the social comfort of a variety of interaction techniques across several passenger contexts representative of a breadth of seating arrangements found in public transit around the world - something previously not feasible to survey in this manner. In an online survey, participants were shown each of the clips and asked to rate their *social comfort* [18, 91] for a given interaction technique/seating location, both as an AR user and as a bystander viewing an AR user. We focus on social comfort rather than acceptability as interaction techniques can be perceived as acceptable but can nonetheless lead to performer/bystander discomfort that could still hinder adoption.

Broadly, we found no statistical differences in the perceived social comfort of interaction techniques and locations between bystander and performer roles. However the seating layout/location did impact the perceived comfort towards interaction techniques, with discreet interactions featuring less encroachment into others' perceived personal space preferred. In addition, environment-based interactions, such as appropriating the armrest, show significant promise, whilst body-based interactions, such as foot-tapping and touching the face, were problematic with respect to social comfort. Finally, the surveyed differences affirm the utility of mixed reality composited video for online video surveys, enabling a controlled evaluation of different user performances across a breadth of locations. This approach provided formative insights into the role that the public transportation seating layout and location could play in moderating the perceived social comfort of AR interaction techniques. Such insights, whilst subject to careful interpretation regarding the ecological validity limitations common in social acceptability video surveys [41, 87], help inform future research into the challenges posed by AR passenger interactions in constrained social spaces prior to costly in-situ deployments or simulated evaluations.

2 RELATED WORK

2.1 Passenger XR, VR, AR

A growing body of research has been examining the utility, usability and acceptability of Extended Reality (XR) headsets for use by passengers, supporting productivity [28, 35, 49, 62, 63, 68], gaming [32, 58, 100, 116], entertainment [28, 56, 115], relaxation [48] and more. Whilst much of this research has focused on passenger use of occlusive VR headsets and the unique challenges they pose in passenger contexts [57], the prospect of everyday Augmented Reality [70], first in glasses-like form factors, offers a route towards virtual spatial interactive content being rendered anywhere around the passenger, giving users a chance to move away from the constraints of more traditional mobile devices such as tablets, smartphones, and laptops and enabling a breadth of future mobility use cases [7, 84]. AR allows passengers to, in theory, more significantly appropriate or occlude their surrounding space for the display of virtual content e.g. being used to create virtual shields or barriers for privacy [62] or appropriate the surrounding environment for gameplay [100]. As the technology evolves and the form factor of AR headsets tends towards all-day use and wear, we could reasonably expect use of such devices in autonomous cars, planes, trains and other modes of public transport in the near future.

A notable benefit of AR over VR for passengers is that VR headsets occlude the users' view of their surroundings entirely which can limit their situational awareness and thereby lead to decreased social acceptance while in public contexts [60, 114]. Consequently, we might consider that passenger use of AR headsets in public transportation could become commonplace in the near future, as their non-occlusive displays afford reality awareness, overcoming this challenge. However, in being aware of, and visible to, other passengers, interactive use of AR headsets could see a significant roadblock to adoption: the visibility and consequent perceived social acceptability of the *interactions* that AR passengers perform in these public, social spaces.

2.2 Social Acceptability

The passenger environment poses a number of challenges to the use of AR for presenting virtual workspaces and content. Assuming technical issues regarding fidelity and legibility can be overcome [74], social issues are likely to become increasingly prescient. Social acceptability is an issue when any new technology requires users to engage in highly visible or unusual behaviour in front of others [82]. In the confines of public transport, donning an AR headset and interacting with virtual content could be uncomfortable for both user and spectator. Passengers may be unwilling to wear a AR headset given worries about the opinions of other passengers regarding their actions [24]. Typical AR interactions as found in current generation consumer devices employ rested 3DoF (Degree of Freedom) or 6DoF controllers for raycasting/pointing interactions, or use direct touch mid-air interactions enacted through hand tracking or 6DoF controllers. Mid-air interactions in particular are believed to have a potential for social discomfort, as well as a risk of invading other passengers' perceived personal space [20, 46, 73, 95]. Indeed, such interactivity has recently been shown to impact acceptance of VR in such contexts [9, 105]. The social discomfort that may be experienced as a consequence of these activities could result in negative attitudes towards, and even rejection of, AR headsets by passengers.

Therefore, a key question for this paper is whether attitudes towards interaction techniques might vary based on social context - a combination of the user's perception of how others would interpret their actions or the device they are using [39], and how the user themselves would interpret such actions as a bystander passenger/spectator [37, 79, 92]. These questions have still been insufficiently answered in previous work by either addressing only part of the social spectrum of interaction in public contexts (i.e. AR user or bystander) [37, 39] or by limited description of AR technology using either text or still images [79, 92]. Moreover, the passenger context poses a unique challenge to social acceptability because of the proximity and exposure to other passengers, which can vary significantly based on the seating location. This has already been shown to impact AR passenger behaviours in e.g. decisions around how to place virtual displays and content in transit contexts [62]. Prior research has shown that "the seating layout of public transport forces people into an intimate distance with strangers, causing social discomfort" [99] which could be expected to impact attitudes towards AR-oriented interaction techniques.

2.3 Video Surveys

There is an extensive history of employing video survey methodology to assess social acceptability. Rico and Brewster [83] used video prototypes in a web survey to assess usable gestures for mobile interfaces. This work evaluated interaction techniques using video surveys with and without varying backgrounds which represented the context the recorded people were in. In these surveys, participants were asked about their willingness to employ such gestures in different locations (home, pavement, as a passenger, at the workplace) and in front of different audiences (alone, partner, friends, colleagues, strangers, family). They found lower acceptance rates as passengers and when driving, with a prevailing preference toward device-based gestures. Koelle *et al.* reviewed the methods, measures and design strategies for addressing social acceptability in HCI [41]. They found that videos have been "re-occurringly used as stimuli" for online surveys, typically requiring an "imaginary" component where participants are asked to reflect on how they would feel in a given social situation, instead of being *in situ*. Whilst such surveys have been criticised regarding ecological validity compared to *in situ* or laboratory studies [3, 85], Koelle *et al.* pointed out that they are still a "viable alternative to laboratory studies" that "allow for larger, and more regionally or culturally diverse samples, and thus can support generalizability". Moreover, Alallah *et al.* demonstrated that social acceptability data collected from crowd-sourcing activities did not significantly differ from the same data captured in laboratory settings [5].

Video surveys can be an efficient alternative to traditional surveys and even in-lab studies by enabling real users to view actions in realistic scenarios. These often employ actors in front of white walls or with a background superimposed depicting different, difficult-to-reproduce contexts [71, 77, 86]. Consequently, we would argue that addressing the "imagination gap" [41] is of particular importance. Using video content can enable cost-effective forms of demonstrating users' actions in different contexts/environments. Such a contribution becomes particularly relevant given both COVID-19 restrictions [27, 36, 106, 112] and the cost to reproduce a wide variety of interaction techniques *in situ* in different contexts, limiting the reproducibility of results.

3 MOBILE INTERACTION TECHNIQUES

A growing body of literature has investigated different input types for AR headsets. For example, Lee *et al.* [45] surveyed input methods for smart glasses, finding that some solutions were more or less relevant in the context of public transport. Voice input, for example, posed challenges in public transport as speaking loudly in a shared space could be perceived as inappropriate due to privacy concerns. Input techniques such as head movement [121] and gaze [123] present similar challenges, where such actions may have low acceptability [82], and spectators are likely to interpret these actions as directed towards them [68]. Other techniques using touchpads and other device-based cursor control inputs [23] and body-based gestures [88, 109] all have unique potential advantages and limitations when considered in the passenger context. In this study, we focused on twelve input modalities, which would be feasible to use in a public context, broken down into **body-based** input, **device-based** input, and **environment-based** input. We discuss the current research related to the social acceptability of each input technique in turn.

3.1 Body-Based Interaction Techniques

For these techniques participants do not require additional peripheral devices or contact with additional physical surfaces outside of their own body to perform an interaction. We focus on four examples of body-based interaction: palm, head, leg, and hand-based mid-air.

3.1.1 Hand / Palm (T4). The surface of the palm has been used predominantly to provide a source of haptic feedback for direct touch interactions when the user is interacting with projected content [42]. The palm enables gesturing for eyes-free input [16, 110]. It commonly uses the non-dominant hand's palm as an interaction surface [16, 26, 110], which can be used effectively for input in both conventional [16] and XR type devices [65].

3.1.2 Foot and Legs (T1, T3). Foot-based gestures are a simple way to interact with devices with limited degrees of freedom. Even though at first glance, foot movements are slower than comparable arm movements [33], Garcia *et al.* [21] suggested that this may be due to a lack of training with foot-based gestures. Foot-based techniques are always-available gestures which can be used in a wide variety of contexts, while seated [94, 104], standing [66, 88], and walking/running [119], specially for highly demanding tasks [6]. These include foot-tapping gestures with both feet, for interacting with menus [14] and confirming mid-air selections [124]. Common techniques also use the feet to perform higher precision tasks such as virtually walking while seated [67] or manipulating objects in mid-air [51]. Foot-based interaction techniques have proven to be highly socially acceptable [6] as they resemble actions in daily life with small, unobtrusive movements [82].

Another part of the leg that can be used as an interaction surface is the thigh. Whether standing, sitting or moving, the thigh provides a large surface for haptic feedback for direct touch interactions [38], and sensors can be embedded into clothing [17, 81]. Regarding social acceptability of leg-based interactions, Wagner *et al.* [108] found that thighs are highly socially acceptable body parts to be used as input techniques, with a preference for the thigh of the dominant leg. Further work also identified the thigh as being a highly acceptable technique [34, 103], with the upper thigh being the preferred region to be used as input when sitting, kneeling, or standing [98].

3.1.3 Face (T2). The face offers a large surface area for interaction with haptic feedback. In particular, the cheek offers an unobstructed surface area, compared to other parts of the face that might be obscured by hair, glasses or clothing [53, 118, 120]. However, the face can also potentially be awkward to touch, for example when the user is wearing makeup. Among different face regions, the cheeks were often preferred as an input surface [93], but when using a headset, this may not be socially acceptable [44].

3.1.4 *Mid air / Freehand (T6).*

Mid-air interactions are typically touchless, relying on freehand input. Despite the undeniable advantages of mid-air interaction for enabling direct-touch interactions with virtual elements, such hand gestures may cause fatigue, when used for prolonged periods [8, 11, 31].

Whilst mid-air input can offer a quick and accurate 3D interaction technique, the social acceptability of these gestures has been questioned. For example, Tung *et al.* [102] found that mid-air gestures are seen as more socially acceptable than other popular interaction techniques, such as gaze-based gestures. However, this work identified challenges both from the users' and bystanders' point of view, showing that highly noticeable techniques are still less socially acceptable than their less noticeable counterparts. It is important to understand whether similar effects are also true in other, more crowded, public contexts such as public transport.

3.2 Device-Based Interaction Techniques

These techniques require peripherals for interaction.

3.2.1 *Finger-worn devices (T7).*

Finger-worn devices offer eye-free fast access inputs to interact with the AR content. In addition, such devices allow one-handed gestures, and their compact size makes interactions with them relatively discreet, especially when they look like real jewellery [64], such as rings, nail-based touchpads or textile interfaces [122]. Although previous work explored different techniques and devices that enable a relatively small form factor and precise interactions [12, 19], there is still a lack of work on its use in public settings.

3.2.2 *Wrist-worn devices (T5).*

Wrist-worn devices allow for one-handed or two-handed gestures and have a larger surface area compared to finger-worn devices. Their resemblance to, and ability to integrate with, watches may also make wrist-worn devices more comfortable to wear [78]. Several input methods such as smartwatch [81], wristband [29, 90] or skin-based devices [69] have been explored. Wrist-worn devices are highly socially acceptable, even when compared to devices worn in discreet locations such as the palm, fingers, legs and the back of the hands [102].

3.2.3 *Rested and Mid-Air Controllers (T8, T9).*

Controllers are the most common way to interact with VR/AR systems [13], largely inspired by the mass adoption of VR for gaming in recent years, supporting ballistic movements and multi-finger inputs. Such devices enable a high level of control over 3D content [43] as it allows for high-fidelity interaction using 6DoF. Its current form factor consists of a robust plastic chassis, well suited to frequent interactions and visible to spectators. However, such devices can be bulky [13] which might make them less suitable for interaction in public spaces due to it being considered socially awkward by bystanders [89] and may hinder interaction in confined spaces. This problem could be overcome by using the controllers in a rested arm pose, such as the armrest or table present in the travel environment. This may hinder one's ability to interact with virtual content (e.g., both direct and indirect raycast-based interactions [50]) however it could also improve the social acceptability in public settings [82]. We included both rested and mid-air controller interaction techniques in our survey, as they are the most common forms of interaction in consumer VR systems.

3.3 Environment-Based Interaction Techniques

The proximity between the user and the physical environment on public transport enables users to appropriate a high number of physical features to support input, as suggested by Schmelter *et al.* [89]. For example, a seat, a table, a window or an armrest could all varyingly support touch input with haptic feedback, which may improve one's experience and increase presence [30, 117] while interacting with virtual content. We included touching the armrest (T10), table (T11) and seatback (T12) as input techniques.

3.4 Summary and Contribution

The use of AR headsets by passengers is likely to see increasing adoption in the coming years, with discreet, glasses-like AR headsets offering more ergonomic, comfortable alternatives to existing mobile device displays. A breadth of interaction techniques have been proposed for mobile AR, however, techniques are predominantly considered for their usability and utility, with a lack of consideration regarding their perceived social comfort. In particular, we posit that the social comfort of a given AR-oriented interaction technique could vary significantly (both from the user and bystander perspective) within the passenger context, based on the extent of spectatorship the user is exposed to in varying seating configurations.

However, systematically evaluating a breadth of interaction techniques across a range of passenger seating locations poses significant methodological challenges. These include prolonged, controlled access to public transportation; the feasibility of conducting such a study in-situ (requiring several hours of evaluation per participant for a more traditional usability study); and the inability to find a single representative train or bus that features every predominant seating configuration commonly available across transit types.

Consequently, in this paper, we extend social acceptance video survey methodology to use mixed reality-composited clips - allowing the re-creation and portrayal of a breadth of passenger scenarios and interaction techniques in a controlled fashion. Using this approach, we surveyed (n=131) the social comfort of 12 interaction techniques (including body-, device-, and environment-based techniques) across seven seating configurations (common across a range of transportation). For the first time, we systematically examine the influence of interaction technique and seating configuration on social comfort for passenger use of AR.

4 VIDEO SURVEY: THE SOCIAL COMFORT OF AR INTERACTIONS IN PUBLIC TRANSPORT

AR headsets offer passengers the opportunity to better engage in entertainment and productivity activities, moving away from the restrictive screen space of hand-held mobile devices. However, a key potential impediment to their adoption will be their social perception by other passengers. Whilst there are a number of factors likely to contribute to this, such as the design of the headset, the presence of privacy-invasive sensing and so on, we chose to focus on examining how different interaction techniques were perceived. In doing so, we expected to identify where social acceptability barriers existed and consequently guide future research and development into interaction techniques that would enable passengers to use AR headsets in ways that do not risk public rejection.

We elected to pursue a video survey design, influenced by prior evidence regarding the validity of such approaches [22, 41], enabling us to survey a wide range of interaction techniques across a variety of different transportation contexts, providing a broad overview of the challenges faced by passenger AR interaction. This approach also allowed us to research the domain at a time when COVID-19 restrictions prohibited *in-situ* access to, and usage of, public transport. The survey followed all protocols and was approved by our University ethics commission, following the European General Data Protection Regulation guidelines on data anonymisation.

4.1 Public Transport Seating Configurations

Many variables can determine if an interaction technique is socially acceptable or not [41] particularly in a shared setting such as public transport, which may limit their widespread use. In considering the social impact of public transport, we identified a number of common sociopetal (i.e. conditions that promote social interaction) and sociofugal (i.e. conditions that discourage or prevent social interaction) [72] seating arrangements that feature across modes of transport, such as planes, trains, subways and buses. We identified seven different configurations (summarised in Figure 3) appearing to be the most common configurations used in public transportation around the world, as described by Schmelter *et al.* [89]. In all seating arrangements selected for our video survey, we depicted the users being seated in the aisle seat, as this is expected to be the most socially acceptable seating position [114]. We categorised our seating arrangements into four groups, based on three primary parameters:

(**1**) the number of neighbouring passengers on the side (0 or more), (**2**) the number of front-facing neighbours (0 or more) and (**3**) the presence of fixed tables. The selected seating arrangements were:

Single row (L1) The passenger has no neighbour and is facing the seat-back of the previous row.

Single face-to-face with table (L2) The passenger has no neighbouring passenger and is facing another passenger with a shared table.

Single face-to-face (L3) As above but without a shared table.

Multiple rows (L4) The passenger has at least one neighbour and is facing the seat-back of the previous row.

Multiple face-to-face far (L5) We consider this a special case, as the distance between the two rows facing each other is more extensive, intended to support standing room passengers e.g., on subways.

Multiple face-to-face with table (L6) The passenger has at least one neighbour and is facing other passengers with a shared table.

Multiple face-to-face (L7) As above but without a shared table.

Regarding **environment-based interactions**, single and multiple rows both have tray tables, whilst the near face-to-face environments optionally feature a shared table between passengers. Taking into account the potential presence of tables, this meant we had 7 locations in total, representing the majority of typical passenger seating layouts.

4.2 Research Questions (RQs)

We identified three RQs to address in our video survey:

RQ1 - Seating Does the seating position/layout impact perceived social comfort of interaction techniques?

RQ2 - Interaction Which interaction technique(s) are the most socially comfortable for each seating location?

RQ3 - Types of Interaction Are there commonalities in attitudes towards different categorisations of interaction technique (body/device/environment) in passenger contexts?

The design of the RQs was motivated firstly by exploring a broad range of interaction techniques that varyingly utilized body-, environment-, and device-based input; and secondly by examining the impact that specific seating configurations might have on the social comfort of these interactions. The varying proximity and visibility of/exposure to other passengers imposed by these different seating configurations could influence the social comfort of the demonstrated interactions, and such a finding would inform future research into passenger

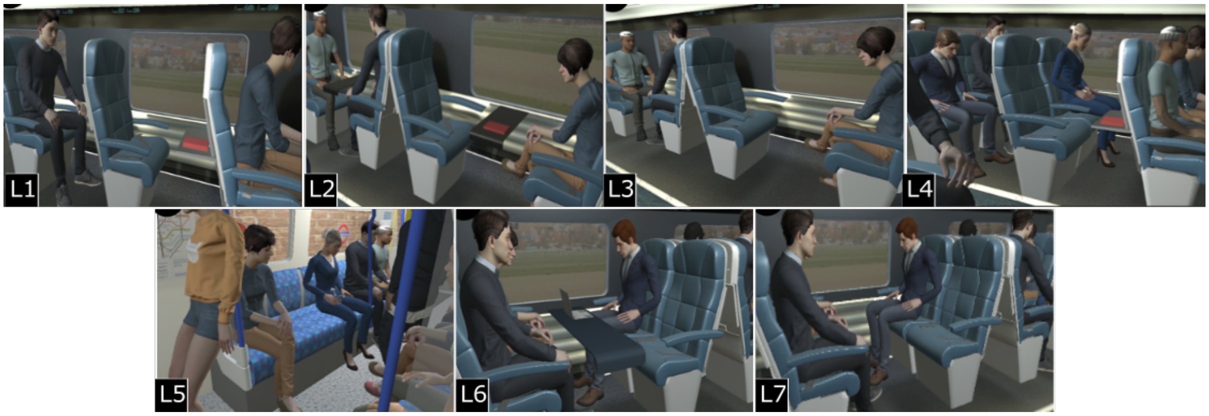

Fig. 2. Images illustrating each of the virtual transport seating locations evaluated, absent the AR user/performer (who is present in the empty seat in each location) for clarity. **L1**- Single Row; **L2**-Single Face-to-face with table; **L3**- Single Face-to-face; **L4**- Multiple Rows; **L5**- Multiple Face-to-face Far; **L6**- Multiple face-to-face with table; **L7**- Multiple face-to-face.

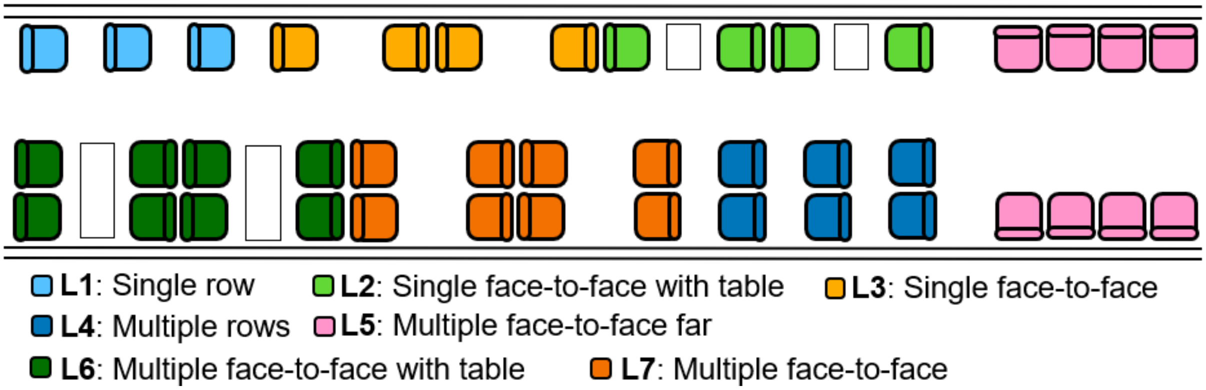

Fig. 3. Seating configurations used in our survey.

AR interaction design and provoke the potential for context-aware decisions to select appropriate interaction modalities for passenger AR users.

4.3 Portraying Interactions in Context

Since the environments used are public spaces, they are very unpredictable and many components in the scene can change suddenly, making it difficult to capture all the real environments in the same camera position and with the same number or density of people around the AR users. Because of that, to present each of the selected interaction techniques in each of the chosen seating locations, we used mixed reality compositing to create video GIFs combining a virtual transport environment with a real person performing the interaction. To create this composite, we captured real interactions with a live person against a green screen backdrop using OBS Studio[1]. Then, we followed the standard procedure for compositing real people into a virtual scene in Unity3D using the Mixed Reality Capture Tool[2] (MRCT). This was then imported into a custom Unity application that used the Meta/Oculus Quest 2 as a means to calibrate the virtual camera position to determine the depth position of the real person using an Oculus controller tracked by the headset and then performed rotations to the camera to fine-tune the virtual camera position to properly match the perspective of the superimposed person. The main advantage of using the MRCT is providing a configurable depth mask for the virtual environment (Figure 1-C), that we used to distinguish objects that were to be rendered in front of and behind the superimposed person, giving the illusion of being part of the virtual scene. This enables chroma-keyed real content to be superimposed on the virtual environment in a way that respects depth-based occlusions resultant from virtual elements, e.g. occluding the real person with a virtual table or armrest. This was crucial to portray our environment-based interactions in particular. The end result can be seen in Figure 1, where a video of the real person is seamlessly blended with a video of the virtual travel environment.

4.4 Interaction Techniques

Various gestures are possible to illustrate the interaction techniques previously discussed. To avoid introducing confounds regarding how different techniques were perceived, we enacted the same two gestures for each applicable technique: a swipe, followed by a tap. These interactions were selected from a range of interaction techniques explored in the related work section, from least visible (e.g., finger-worn techniques, wrist-based techniques) to more visible techniques (e.g., mid-air gestures). We did not include eye-gaze-based techniques

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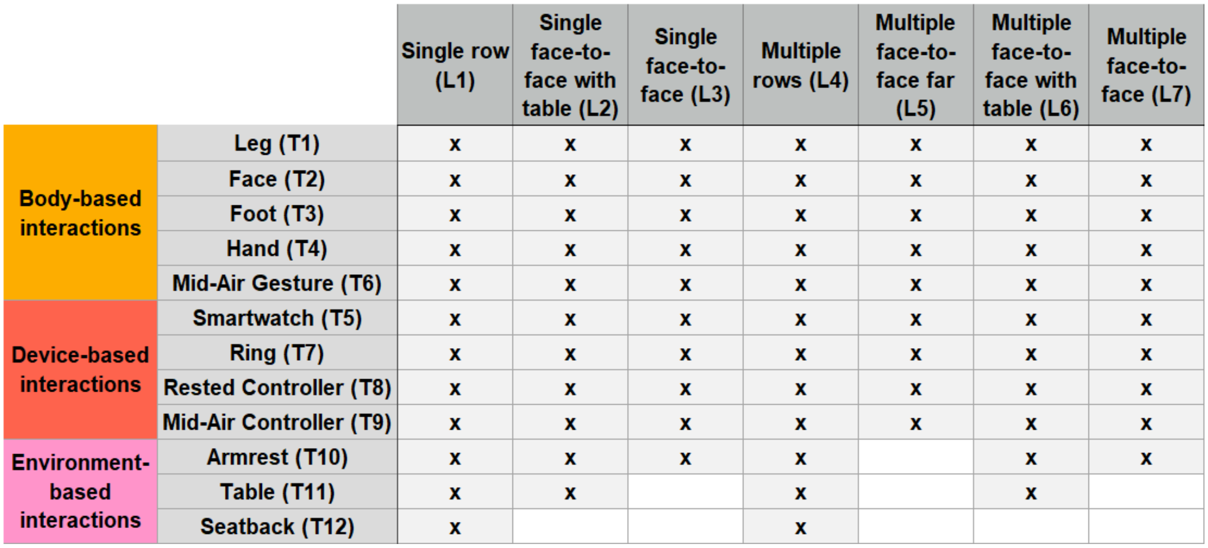
[1] https://obsproject.com/

[2] https://developer.oculus.com/downloads/package/mixed-reality-capture-tools/

- these discreet interactions are in part hidden by current AR headsets (e.g. NReal's semi-transparent lenses). Also, given our scenario examines interactions with spatial AR content projected in front of the passenger, such eye gaze movements would likely be indistinguishable from those enacted simply by viewing AR content. Moreover, recent work has shown gaze also introduces additional complications regarding social acceptability. It can be perceived as highly intrusive as users may invade other people's perceptual spaces by staring at them, causing social collisions [68, 114]. This issue characteristic would be impossible to convey given the third-person perspective of this video survey.

Not all interaction techniques were applicable for all locations. Specifically, the environment-based techniques (armrest, table, seatback) require the proximate presence of those physical affordances in the seating location. Consequently, not all combinations of location and interaction techniques were evaluated. Nine interaction techniques were shared between all locations (body-based and device-based) since all locations allowed people to perform these interactions. The three other techniques (environment-based) depended on the presence of the location's armrest, table, and seat-back (see Figure 4). In summary, participants answered 150 questions in total considering all the combinations of locations and interaction techniques.



		Single row (L1)	Single face-to-face with table (L2)	Single face-to-face (L3)	Multiple rows (L4)	Multiple face-to-face far (L5)	Multiple face-to-face with table (L6)	Multiple face-to-face (L7)
Body-based interactions	Leg (T1)	x	x	x	x	x	x	x
	Face (T2)	x	x	x	x	x	x	x
	Foot (T3)	x	x	x	x	x	x	x
	Hand (T4)	x	x	x	x	x	x	x
	Mid-Air Gesture (T6)	x	x	x	x	x	x	x
Device-based interactions	Smartwatch (T5)	x	x	x	x	x	x	x
	Ring (T7)	x	x	x	x	x	x	x
	Rested Controller (T8)	x	x	x	x	x	x	x
	Mid-Air Controller (T9)	x	x	x	x	x	x	x
Environment-based interactions	Armrest (T10)	x	x	x	x		x	x
	Table (T11)	x	x		x		x	
	Seatback (T12)	x			x			

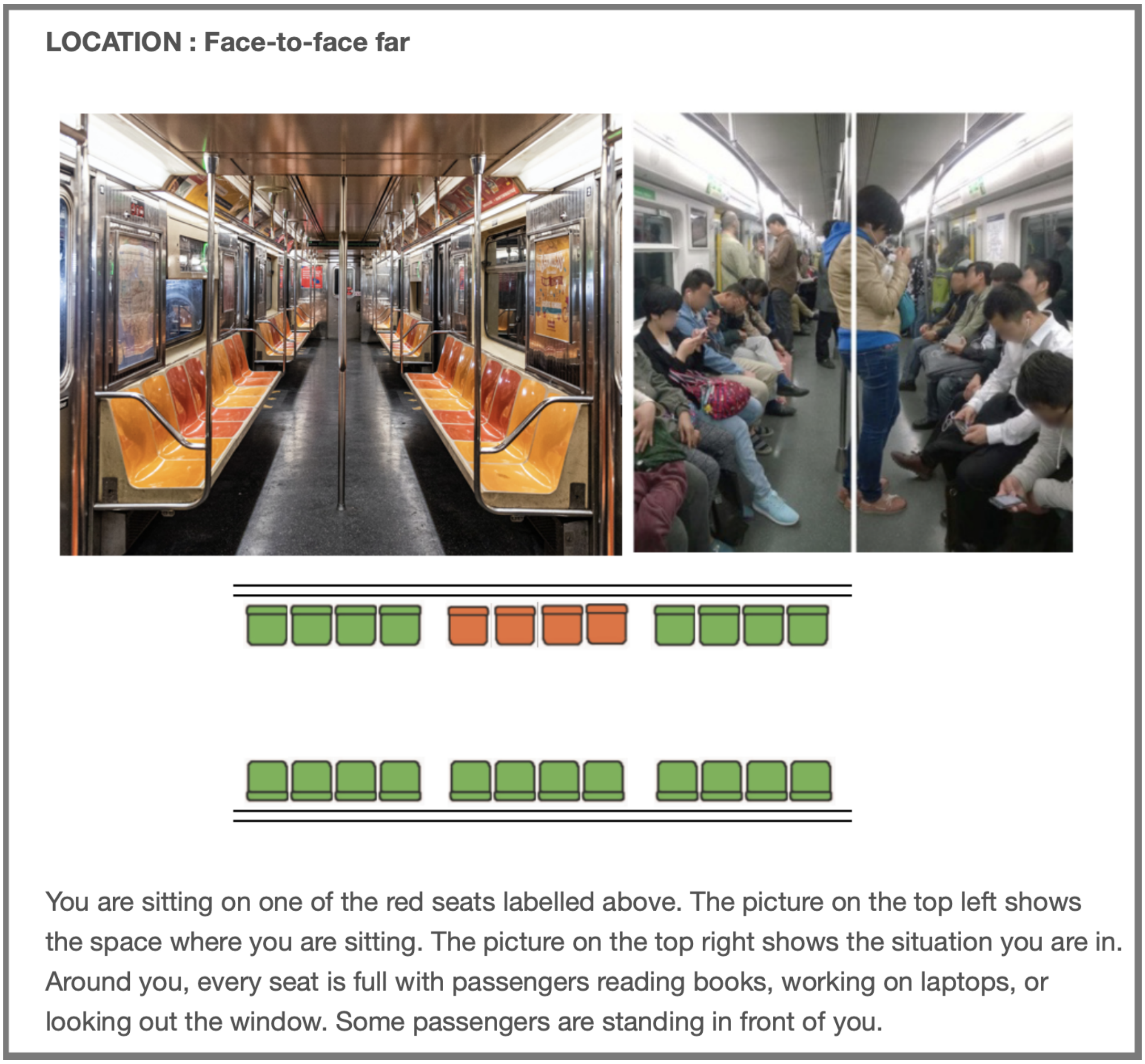
Fig. 4. Interaction techniques evaluated for each seating location.

4.5 Method

We counterbalanced the seven passenger transit locations using a Balanced Latin Square arrangement to avoid bias. Each seating arrangement was introduced with a brief text explaining the context in which participants were asked to imagine themselves. We included three images to illustrate our context: (**1**) the location setting without people, (**2**) the location setting with people present and (**3**) a schematic showing the seating arrangement of that location, see Figure 5. For each of the seven locations, respondents were asked to imagine themselves or other passengers performing the different physical actions to interact with an AR headset. We presented each gesture using a video GIF showing a user wearing Nreal Light AR glasses [2] and performing the interaction in the location (see supplementary video figure for more details).

4.6 Measures

Respondents were asked to rate **whether they would be comfortable: (Q1) performing these actions as a passenger and (Q2) seeing other passengers perform these actions** on 7-point Likert-type scales from 1



LOCATION : Face-to-face far

You are sitting on one of the red seats labelled above. The picture on the top left shows the space where you are sitting. The picture on the top right shows the situation you are in. Around you, every seat is full with passengers reading books, working on laptops, or looking out the window. Some passengers are standing in front of you.

Fig. 5. The descriptive images presented at the start of a location response, illustrating the real-world context, and highlighting and describing the seating position being evaluated. See supplemental materials for descriptions for other seating locations.

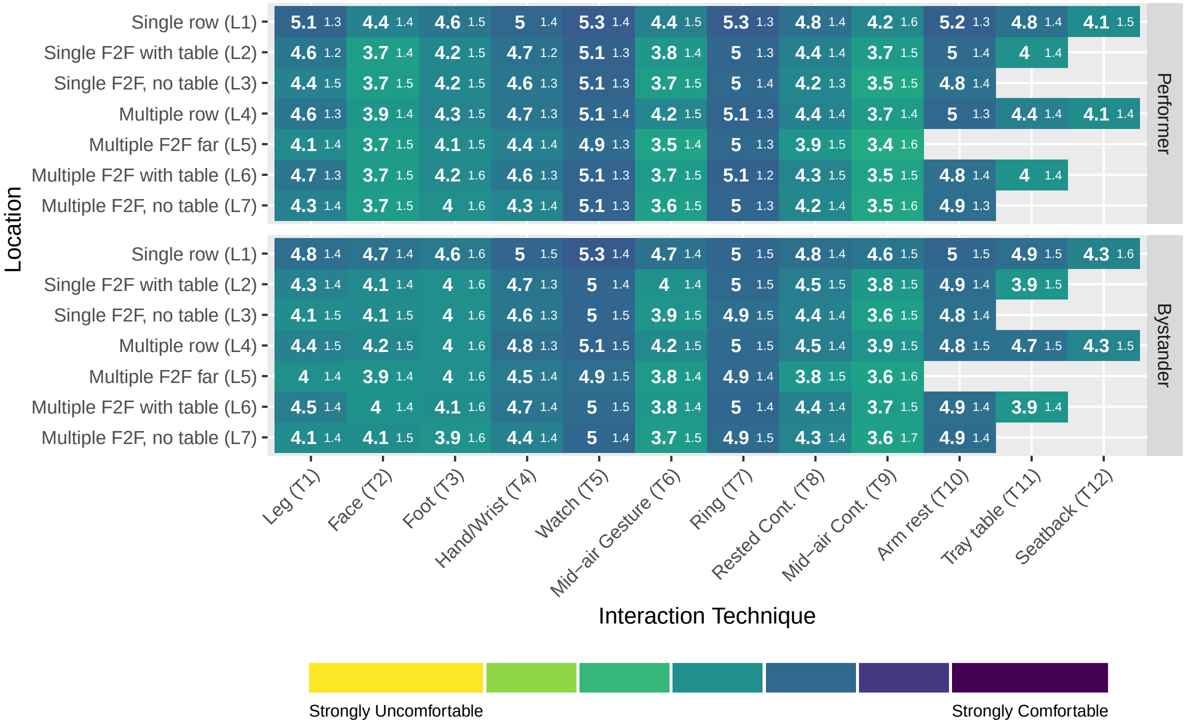
(Strongly Unacceptable) to 7 (Strongly Acceptable). We also included demographic questions related to but not limited to AR use and familiarity.

4.7 Participants and Inclusion Criteria

The questionnaires were distributed through social media, mailing lists, and other online communities over one week. Participants were offered the chance to win £20 worth of vouchers for taking part, that was determined by a single draw after all participants had taken part in the study. The data collected represent 156 survey respondents ranging in age from 18 to 57 year (M=28, SD = 7.8). Eighty-four of these identified as male, 72 as female, two as non-binary, one participant identified as a gender identity not listed and one preferred not to disclose their identity. Responses came from across 13 countries: U.K.: 91, France: 36, U.S.A: 14, Rest of World: 14. Participants took a mean of 17.3 minutes (Std.Dev=12.6 mins) to complete the survey. From these, we filtered out 25 participants that did not have any previous experience with AR systems. We suggest that any participant that does not understand the concept of AR could not reasonably assess the acceptability of each interaction technique from both the perspective of users and bystanders. This resulted in a data set consisting of 131 responses.

5 RESULTS

Nine interaction techniques were evaluated in the seven different seating arrangement configurations for perceived comfort for performers and bystanders. We excluded environment-based techniques from this analysis as they were not possible to perform in each seating arrangement. The three interaction types (Body-, Device-, and Environment-based) were evaluated in the seven different seating arrangements in relation to perceived comfort for Performer and Bystander questions. See Figure 6 for an overview of the social comfort scores across all three factors, and Figure 7 for an overview of social comfort with a focus on the significant Location and Interaction Technique factors.



Location	Leg (T1)	Face (T2)	Foot (T3)	Hand/Wrist (T4)	Watch (T5)	Mid–air Gesture (T6)	Ring (T7)	Rested Cont. (T8)	Mid–air Cont. (T9)	Arm rest (T10)	Tray table (T11)	Seatback (T12)	
Single row (L1)	5.1 1.3	4.4 1.4	4.6 1.5	5 1.4	5.3 1.4	4.4 1.5	5.3 1.3	4.8 1.4	4.2 1.6	5.2 1.3	4.8 1.4	4.1 1.5	Performer
Single F2F with table (L2)	4.6 1.2	3.7 1.4	4.2 1.5	4.7 1.2	5.1 1.3	3.8 1.4	5 1.3	4.4 1.4	3.7 1.5	5 1.4	4 1.4		
Single F2F, no table (L3)	4.4 1.5	3.7 1.5	4.2 1.5	4.6 1.3	5.1 1.3	3.7 1.5	5 1.4	4.2 1.3	3.5 1.5	4.8 1.4			
Multiple row (L4)	4.6 1.3	3.9 1.4	4.3 1.5	4.7 1.3	5.1 1.4	4.2 1.5	5.1 1.3	4.4 1.4	3.7 1.4	5 1.3	4.4 1.4	4.1 1.4	
Multiple F2F far (L5)	4.1 1.4	3.7 1.5	4.1 1.5	4.4 1.4	4.9 1.3	3.5 1.4	5 1.3	3.9 1.5	3.4 1.6				
Multiple F2F with table (L6)	4.7 1.3	3.7 1.5	4.2 1.6	4.6 1.3	5.1 1.3	3.7 1.5	5.1 1.2	4.3 1.5	3.5 1.5	4.8 1.4	4 1.4		
Multiple F2F, no table (L7)	4.3 1.4	3.7 1.5	4 1.6	4.3 1.4	5.1 1.3	3.6 1.5	5 1.3	4.2 1.4	3.5 1.6	4.9 1.3			
Single row (L1)	4.8 1.4	4.7 1.4	4.6 1.6	5 1.5	5.3 1.4	4.7 1.4	5 1.5	4.8 1.4	4.6 1.5	5 1.5	4.9 1.5	4.3 1.6	Bystander
Single F2F with table (L2)	4.3 1.4	4.1 1.4	4 1.6	4.7 1.3	5 1.4	4 1.4	5 1.5	4.5 1.5	3.8 1.5	4.9 1.4	3.9 1.5		
Single F2F, no table (L3)	4.1 1.5	4.1 1.5	4 1.6	4.6 1.3	5 1.5	3.9 1.5	4.9 1.5	4.4 1.4	3.6 1.5	4.8 1.4			
Multiple row (L4)	4.4 1.5	4.2 1.5	4 1.6	4.8 1.3	5.1 1.5	4.2 1.5	5 1.5	4.5 1.4	3.9 1.5	4.8 1.5	4.7 1.5	4.3 1.5	
Multiple F2F far (L5)	4 1.4	3.9 1.4	4 1.6	4.5 1.4	4.9 1.5	3.8 1.4	4.9 1.4	3.8 1.5	3.6 1.6				
Multiple F2F with table (L6)	4.5 1.4	4 1.4	4.1 1.6	4.7 1.4	5 1.5	3.8 1.4	5 1.4	4.4 1.4	3.7 1.5	4.9 1.4	3.9 1.4		
Multiple F2F, no table (L7)	4.1 1.4	4.1 1.5	3.9 1.6	4.4 1.4	5 1.4	3.7 1.5	4.9 1.5	4.3 1.4	3.6 1.7	4.9 1.4			

Fig. 6. Heatmap visualizing mean social comfort in performing these actions as a passenger (performer), and seeing other passengers perform these actions (bystander), labelled with standard deviation in smaller text, across Location, Interaction Technique, and Role.

As data were not normally distributed and represented ordinal data, generalised linear mixed effect models (*glmer*) [10] were used to predict social comfort using a *poisson* distribution with *Technique*, *Location* and *Role* as predictors. Participant was included as a random effect in the models to account for variability in effects across participants. Additionally, informed by Lorah [52], Cohen's f^2 was calculated. This resulted in **significant main effects for *Interaction Technique*** ($\tilde{\chi}^2(8) = 735.83$ $p<0.001$ $f^2=0.05$), ***Location*** ($\tilde{\chi}^2(6) = 159.55$ $p<0.001$ $f^2=0.06$), but no significant effect of ***Role*** (Bystanders and Performers) ($\tilde{\chi}^2(1) = 0.28$ $p=0.284$) on social comfort scores.

We also found significant **Interaction Effects between *Location* and *Role*** ($\tilde{\chi}^2(1) = 31.32$ $p<0.001$ $f^2=0.01$). However, no significant effects of the interaction of *Location and Role* ($\tilde{\chi}^2(6) = 0.48$, $p=.998$) or *Location and*

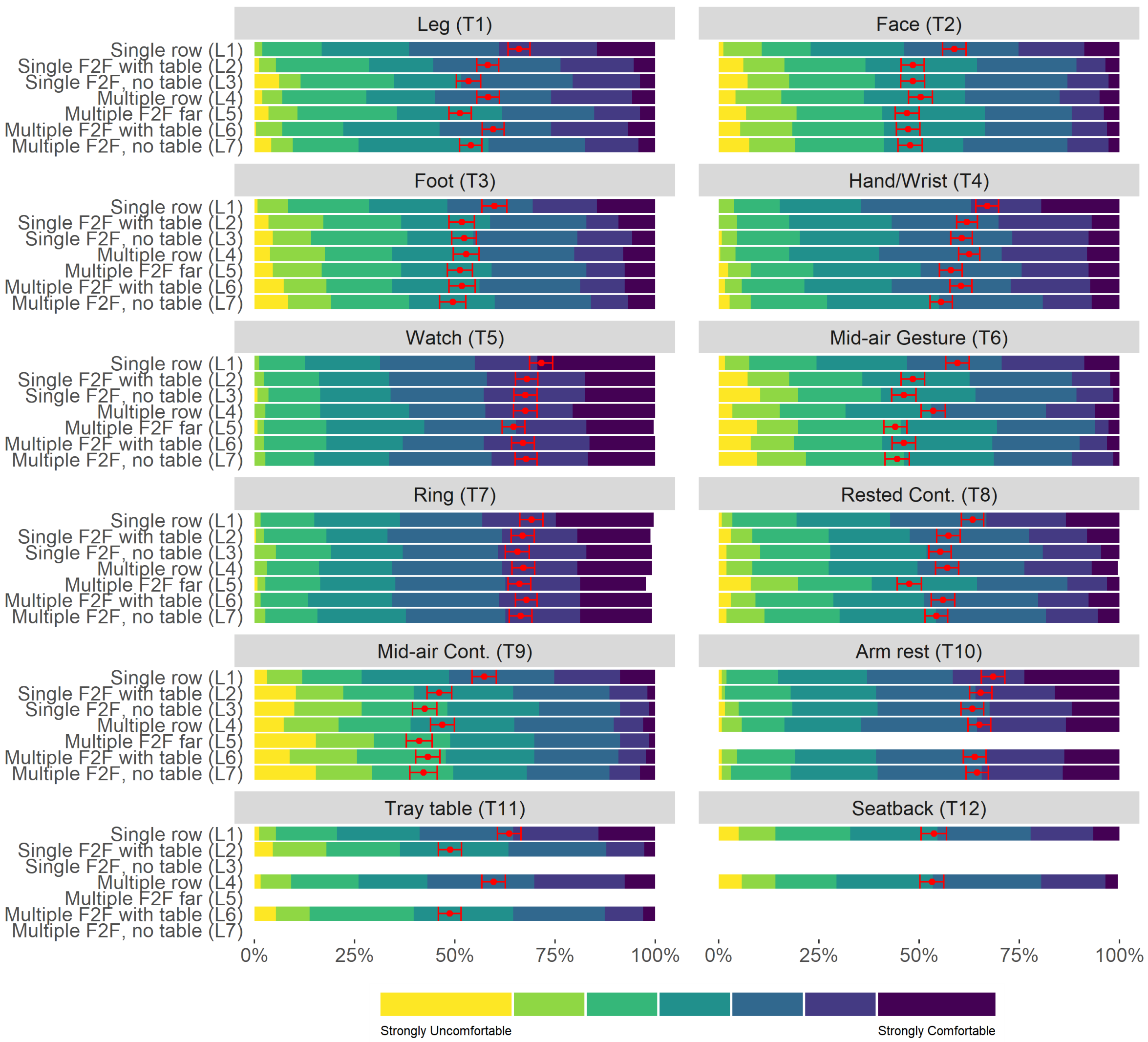


Fig. 7. Summary of the questionnaire responses regarding social comfort, combining performer and bystander responses. All plots show the total count of responses and 95% confidence intervals (red bars) for social comfort scores, with the darker colours indicating higher/more positive responses.

Technique on social comfort ($\tilde{\chi}^2(48) = 54.45$, p =.242) scores was found. Similarly, no significant effect of the interaction between *Role, Technique and Location* on social comfort scores was found ($\tilde{\chi}^2(48) = 5.16$, p = 1.00).

Based on the significant interaction effect between *Location* and *Role* on social comfort scores, we performed an additional *glmer* model including *Location* and *Role* as predictors to further investigate potential differences in social comfort for the various locations between bystander and performer. Again, a **significant effect of *Technique*** on social comfort scores was found, ($\tilde{\chi}^2(8) = 736.88$, $p < .001$, $f^2 = .05$) and **Interaction effects between *Location* and *Role*** ($\tilde{\chi}^2(8) = 31.39$, $p < .001$, $f^2 = .002$). Pairwise comparisons showed that the only technique that had a significant interaction effect was the Foot technique ($p<0.001$), with participants feeling more comfortable performing this technique than being observed doing it.

As we did not find statistically significant interaction effects between roles, we grouped the data of both Roles together and performed an additional *glmer* model with *Location* and *Interaction Technique* as predictors. With this analysis, we found that social comfort scores were **significantly affected by *Location*** ($\tilde{\chi}^2(6)=159.52$ $p<0.001$ $f^2=0.06$) and ***Interaction Technique*** ($\tilde{\chi}^2(8)= 737.74$ $p<0.001$ $f^2=0.06$). There were no significant interaction effects between *Location* and *Interaction Technique* ($f^2(48)=54.48$ p=0.242. In the following subsections, we detail the post-hoc comparisons, separated by Technique and Location.

5.1 Location

Post-hoc tests revealed that L1 (Single Row) was considered to be the most socially comfortable seating configuration for AR use when compared to all other locations. This was followed by L4 (Multiple Row), which was more socially comfortable when compared to L3 (Single F2F), L5 (Multiple F2F far) and L7 (Multiple F2F). L2 (Single F2F w/table) was significantly more comfortable than L5 (Multiple F2F far) and L7 (Multiple F2F), while L6 (Multiple F2F w/table), was more socially comfortable than L5 (Multiple F2F far). L3 (Single F2F) was one of the less socially comfortable seating configurations, significantly higher only when compared to L5 (Multiple F2F far). Finally, L7 (Multiple F2F) and L5 (Multiple F2F far) were the least socially comfortable seating configurations, and were not significantly different from each other.

Table 1. Social Comfort separated by Location including 9 of the Interaction Techniques

Location	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**
L1: *Single Row,* M=4.78, SD=1.46						
L2: *Single F2F with table* M=4.37, SD=1.47	z=6.62, p=.001*					
L3: *Single F2F no table* M=4.26, SD=1.51	z=8.5, p=.001*	z=1.88, p=0.494				
L4: *Multiple row* M=4.38, SD=1.46	z=5.32, p=0.001*	z=1.30, p=0.854	z=3.18, p=0.025*			
L5: *Multiple F2F far* M=4.11, SD=1.54	z=11.51, p=0.001*	z=4.90, p=0.001*	z=3.02, p=0.041*	z=6.19, p=0.001*		
L6: *Multiple F2F with table* M=4.32, SD=1.51	z=7.64, p=.001*	z=1.02, p=.95	z=0.86, p=.978	z=2.31, p=0.237	z=3.88, p=0.002*	
L7: *Multiple F2F, no table* M=4.20, SD=1.54	z=10.2, p=.001*	z=3.58, p=.006*	z=1.7, p=0.615	z=4.88, p=0.001*	z=1.32, p=0.845	z=2.56, p=0.138

5.2 Technique

For each interaction technique, we address the social comfort score and present the interaction techniques ranked from best to worst in terms of this score. Means and Standard deviations can be found in Table 2.

Smartwatch (T5): Was rated as the most acceptable technique evaluated. It was significantly more socially comfortable than all other evaluated techniques, except for T7 Ring.

Ring (T7): Was one of the most comfortable interaction techniques. It was perceived as significantly more comfortable than T1 Leg, T2 Face, T3 Foot, T4 Hand , T6 Mid-air, T8 Controller Rested and T9 Controller Mid-air. It did not differ from T5 Watch.

Hand (T4): Was rated as being a moderately comfortable interaction technique, being more comfortable than T1 Leg, T2 Face , T3 Foot , T6 Mid-air, T8 Controller Rested and T9 Controller Mid-air. However, less comfortable than T5 Watch and T7 Ring.

Controller rested (T8): Was moderately comfortable, being significantly more comfortable than T6 Mid-air and T9 Controller Mid-air. However, it was rated less comfortable than T4 Hand, T5 Watch, and T7 Ring.

Leg (T1): This technique was rated as being moderately socially comfortable being significantly better than T9 Controller Mid-air, T3 Foot, T2 Face and T6 Mid-air. However, it was rated as being significantly less comfortable on average when compared to T4 Hand, T5 Watch and T7 Ring.

Face (T2): This technique was rated significantly higher on comfort when compared to T9 Controller Mid-air, however significantly lower when compared to T5 Watch, T7 Ring, T8 Controller Rested and T4 Hand.

Foot (T3): This technique was rated moderately on social comfort, being significantly more comfortable than T9 Controller Mid-air. However less comfortable than T1 Leg, T4 Hand, T5 Watch and T7 Ring.

Gesturing in Mid-air (T6): This technique was rated rather low on social comfort, being significantly less comfortable than T5 Watch, T7 Ring, T4 Hand, T1 Leg, T8 Controller Rested and T3 Foot.

Controller mid-air (T9): was overall rated as the least comfortable/worst technique, being significantly lower on social comfort compared to T1 Leg, T2 Face, T3 Foot, T4 Hand, T5 Watch, T7 Ring and T8 Controller Rested.

Table 2. Social Comfort separated by Technique

Technique	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**
T1: *Leg* M=4.43, SD=1.40								
T2: *Face* M=3.98, SD=1.47	$z=6.634$, $p=.001^*$							
T3: *Foot* M=4.16, SD=1.58	$z=3.886$, $p=0.003^*$	$z=-2.753$, $p=.13$						
T4: *Hand/Wrist* M=4.65, SD=1.35	$z=-3.132$, $p=0.045^*$	$z=-9.757$, $p=0.001^*$	$z=-7.015$, $p=0.001^*$					
T5: *Watch* M=5.06, SD=1.4	$z=-8.825$, $p=0.001^*$	$z=-15.413$, $p=0.001^*$	$z=-12.691$, $p=0.001^*$	$z=-5.702$, $p=0.001^*$				
T6: *Mid-air Gest.* M=3.93, SD=1.49	$z=7.429$, $p=0.001^*$	$z=0.9$, $p=.99$	$z=3.552$, $p=0.01^*$	$z=10.548$, $p=0.001^*$	$z=16.196$, $p=0.001^*$			
T7: *Ring* M=5.02, SD=1.39	$z=-8.262$, $p=0.001^*$	$z=-14.84$, $p=0.001^*$	$z=-12.122$, $p=0.001^*$	$z=-5.145$, $p=0.001^*$	$z=0.543$, $p=1.00$	$z=-15.622$, $p=0.001^*$		
T8: *Rested Cont.* M=4.35, SD=1.44	$z=1.218$, $p=0.95$	$z=-5.417$, $p=0.001^*$	$z=-2.668$, $p=0.16$	$z=4.349$, $p=0.001^*$	$z=10.036$, $p=0.001^*$	$z=-6.214$, $p=0.001^*$	$z=9.471$, $p=0.001^*$	
T9: *Mid-air Cont.* M=3.73, SD=1.56	$z=10.51$, $p=0.001^*$	$z=3.895$, $p=.0032^*$	$z=6.643$, $p=0.001^*$	$z=13.618$, $p=0.001^*$	$z=19.236$, $p=0.001^*$	$z=3.094$, $p=0.051$	$z=18.66$, $p=0.001^*$	$z=9.297$, $p=0.001^*$

5.3 Body-, Device-, Environment-Based Interactions (User, Bystander, Combined)

A post hoc test revealed that body-based interaction techniques were perceived as the least comfortable compared to device- and environment-based techniques. Device and environment-based techniques, however, did not differ significantly from each other. A summary of the results is shown in Table 3. We ran a separate analysis for bystander and performer, yielding the same results, so we include the results for both grouped together.

Table 3. Social Comfort grouped by Interaction Technique Type (Body/Device/Environment-based)

Technique Type	**Device Based**	**Body Based**
Device Based: M=4.53, SD=1.53		
Body Based: M=4.21, SD=1.48	z=10.30, p=.001*	
Environment Based: M=4.58, SD=1.45	z=1.13, p=.493	z=8.98, p=.001*

6 DISCUSSION

6.1 Limitations and Caveats

Our participants experienced virtual recreations of real passenger contexts in video form, going a step further than portrayals previously used in research [41]. Mixed reality compositing enabled us to portray interactions within a breadth of simulated usage contexts that would be impractical to capture in reality. Compared to modelling an animated virtual avatar, this procedure is lower in cost and avoids uncanny valley side-effects [61, 111] ensuring a high degree of realism in the portrayal of the user/performer's actions. That our findings largely reflect what could be expected (discreet interactions being more socially comfortable; interactions being more socially comfortable in more private seating) suggests this approach has merit in supporting formative explorations of social comfort where real-world footage of the context/environment cannot be used. However, our clips did not fully simulate the dynamic social passenger environment. The real-life scenario would be replete with various real passengers that would react differently to imagined expectations, and whose reactions in-turn might alter bystander attitudes. Whilst our approach gives us valuable insights into the broad strokes of what is or is not socially comfortable, some nuances may still be missed, and would require further in-lab or in-situ studies to explore.

The method in this survey also shows some notable advantages over lab and *in situ* studies. For *in situ* studies, whilst an interaction could be tested, the seating locations themselves occur across a wide range of transports, and some of these are commonly used only in a subset of countries. Consequently, it would be extremely difficult to recreate this study with the same seating layouts. For in-lab studies, we could envisage using the same travel environments in VR headsets to immersively place users into the context directly [54, 97]. However, the breadth of contexts and interaction techniques would render a lengthy and prohibitive study. Video survey methodology, in contrast, allowed us to quickly ascertain a high-level overview of what passengers would be comfortable with regarding AR interactions. And such methodology has been used extensively [41], with recent work, for example showing immersive video surveys retain ecological validity in stated preference surveys [87]. By incorporating the passenger context, we were able to replicate and expand on results obtained from previous in-lab studies on social comfort of interaction techniques [4], which would have been difficult to replicate in both in-lab and *in situ* studies with sufficient detail. While there are limitations to our video-survey methodology, as it is not possible to see what the performer or bystander is seeing, our work manages to explore an extensive number of possible interaction techniques across a breadth of transit seating locations. This would not be practical or feasible for *in situ* research due to the complexity and costs associated with such an in-the-wild study design. We also highlight that our work can inspire and inform future work by supporting studies with a narrowed-down scope based on our findings, which could in-turn facilitate more feasible use of higher validity in-lab or *in situ* passenger AR evaluations.

Finally, regarding our respondent demographics, the vast majority came from a Western cultural context (U.K, France, U.S.A.). This means that we cannot account for cultural differences in this survey alone, with future work being required to consider a cross-cultural survey and the effect this would have on passenger social comfort. Moreover, we cannot account for varying experience with/exposure to different seating configurations in real-life and the impact this may have had on the perceived comfort of the presented locations in the survey.

6.2 Addressing Research Questions

6.2.1 RQ1: Impact of Seating Layout on Social Comfort of Interaction Technique. The social context directly affected overall social comfort. Facing another passenger strongly affected the users' comfort levels, with Single-Row and Multiple-Row arrangements being considered more socially acceptable than arrangements where participants are seated face-to-face from each other. However, when interaction techniques are analysed separately, no significant variation in social comfort between locations was found. The interaction technique itself had a greater contribution to perceived social comfort in public settings. This behaviour is even more prominent when we observe the variation in social comfort ratings across the different interaction techniques. Interaction techniques where users remained within their personal space, appropriating seat elements (such as the armrest) or even using lower attention-grabbing body parts (e.g. fingers and wrists), were seen as more socially acceptable. In locations where users were seated face-to-face, such as L5 (Multiple F2F far), techniques were typically rated more unacceptable.

6.2.2 RQ2: Social Acceptability of Interaction Techniques by Seating Location. Social comfort between interaction techniques did not substantially vary between locations. However, when users were not facing each other, techniques involving controllers and gestures in mid-air were more socially acceptable than in other locations. These locations also had overall better social comfort scores for interacting with vertical and horizontal physical surfaces such as tray tables and seat-backs, which were considered as not socially acceptable in other seating arrangements.

6.2.3 RQ3: Attitudes Towards Body / Device / Environment-based Interactions. We found evidence that the categorisation of body/device / environment-based input directly impacted social comfort. Body-based techniques were perceived as less socially comfortable compared to both device- and environment-based techniques. Whilst the cause of and motivation behind the perceived social discomfort of these interaction techniques requires further study, we can nonetheless reflect on the potential reasons why these differences arose. For body- and device-based techniques, techniques that use highly visible body parts were perceived as less comfortable than lower visibility ones such as fingers, wrists, and legs. Whilst visually discreet, foot-tapping was more discomforting than most techniques, potentially due to concerns regarding how socially disturbing the noise of such an action might be or reflecting existing interpretations of foot-tapping, e.g. as a signal of impatience.

In Environment-based interactions, social comfort also varied considerably. Users felt more comfortable in public settings when performing interactions that were less attention-grabbing and belonged to their personal space, such as the armrests, and less comfortable with seatbacks and horizontal tables. These surfaces offer significant advantages for AR interactions, offering a large surface area with haptic feedback and in-built haptic features [62, 63]. However, they also can potentially invade others' space (e.g., taking up more of the shared table than is considered fair) or otherwise negatively impact others' travel experiences (e.g. poking the seatback, resulting in the annoyance of the passenger in front). Future work should potentially explore the If we are to support socially acceptable and comfortable passenger AR, future work needs to bring together insights around acceptable interactions, as well as the impact of AR content layout, which has previously been shown to significantly impact social acceptance.

6.3 Difference Between Users and Bystanders

Both users and bystanders need to be considered for efficient and highly socially acceptable interaction techniques in public settings [4]. We noted, however, that when the techniques were compared in terms of social comfort between roles, only the Foot was significantly more comfortable when performing these actions rather than being observed. There is a question as to which perspective is perhaps most important - is it enough that they are comfortable to perform a given interaction despite their underlying attitude towards how others perceive this activity? While we argue that our approach is a step in the right direction, further work is still needed both in controlled and in-situ environments for more nuanced perceptions of the underlying factors that make an interaction technique socially comfortable for use in public spaces.

6.4 Social Discomfort Around AR Interactions

It is not our opinion that any of the interaction techniques discussed in this paper should be ruled out from passenger AR usage. Instead, we see two routes towards resolving social discomfort: being more selective about *when and to what extent* an interaction technique is used; and *addressing the underlying reasons for social discomfort.*

6.4.1 The Tension between Social Comfort and the Need for Mid-air Spatial Interactions in AR. Results from our study indicated that more discreet and less attention-grabbing techniques were the most socially acceptable on in-transit settings. This result corroborates previous work on the use of such techniques with body or device elements that are located in more discrete locations [34, 102, 103, 108]. Such techniques use small 2D surfaces, which by the nature of XR applications may not be enough to interact with 3D content [43]. A possible way to overcome this problem is by combining more socially acceptable techniques when interacting with 2D content and/or confirming selections [124] (i.e. armrest, ring and smartwatch-based interaction) with high interaction-fidelity techniques [59] such as direct mid-air touch for 3D content. These enable users to perform precise movements when strictly necessary (e.g. to interact with 3D content) while reducing the need for obvious interactions. Novel recent VR interaction techniques such as *FingerMapper* [101] further support this aim for supporting more discreet mid-air spatial interactions. We also see much promise in examining how the social acceptance of interaction techniques might vary across AR and VR headsets in the same passenger contexts, i.e. is there something inherent in the non-occlusive AR experience that makes visible interactions more or less acceptable to both users and bystanders?

6.4.2 Adapting Interactions to Overcome Discomfort. For some interaction techniques (e.g. mid-air controller), despite the perceived social discomfort of their usage, a solid rationale for their use may remain for a given context or use case (e.g. for gaming) given their capacity for supporting accurate and fine spatial interactions. This is particularly the case given we have little understanding about *why* mid-air interactions were perceived as problematic in the passenger context. Does this reflect the highly visible nature of such interactions? Or the risk posed by inadvertent interactions with other passengers (e.g. accidentally hitting another passenger) [116]? Or the perception of encroaching on another's public space [46, 62]?

For mid-air interactions in particular, some of the hypothesized reasons for why they are deemed less socially acceptable in passenger contexts could be resolved or lessened through interaction design. For example, Wilson *et al.* [116] examined adapting existing mid-air interaction techniques to work within constrained passenger spaces safely - such adaptations could lessen concerns related to infringing on others' personal space or causing accidental harm to other passengers. Similarly, if a technique may encroach on others' personal space, establishing AR safety boundaries may reassure users that their interactions will not inadvertently impact others [47, 60].

6.4.3 *Wave your Hands in the Air like you Just Don't Care - Familiarity and Normalisation.*

There is also the impact of familiarity [40] and the development of social norms to consider. The experienced interaction-based social discomfort may be transient - a symptom of the unfamiliar novelty and visibility of what is being proposed. For example, suppose the AR user can be assured that their actions will not physically interfere with other passengers. In that case, they may become more comfortable with the idea of appropriating the physical space in this way. The popularisation of VR devices in shared spaces such as the home might decrease any sense of discomfort and lead to the normalisation of these behaviours. In combination with the interaction technique adaptations discussed previously, this could lead to a scenario where passengers readily accept more energetic mid-air interactions in certain passenger contexts.

However, the emergence of such social norms is unpredictable, and our survey affirms that there still remains a need for more discreet, socially comfortable interactions for passenger AR, despite the current level of VR familiarity and adoption. Our research is the first to identify the social comfort gap around predominant mid-air interactions in a passenger context, considering both the users performing the interactions and bystanders. Our insights will help in understanding what interactions are currently suited to passenger contexts, and where further research is required to create more socially comfortable variants of problematic techniques.

7 CONCLUSION

AR headsets can significantly improve the passenger experience, moving away from the limited form factors of smartphones and seatback displays towards rendering virtual spatial content around the passenger. However, the constrained space of public transportation, and the varying proximity to other passengers, could have significant implications for how we interact with this spatial content - particularly if we are to avoid social rejection of AR technology. Using a novel mixed reality-composited video survey, we explored the social comfort of various AR-oriented interaction techniques (body-, device-, and environment-based) set across seven different public transport contexts, from the perspective of both bystanders and AR users. Our survey showed that the different seating arrangements significantly impacted overall social comfort between the tested techniques. In particular, respondents were uncomfortable with highly visible techniques and those with a high potential for encroachment into others personal space (e.g. mid-air interactions). We argue that addressing this discomfort will be crucial to ensure passengers can make the most of AR headsets and immersive, spatial content in constrained, shared public transport.

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